Simulating industrial symbiosis

Understanding and shaping circular business models for viable and robust industrial symbiosis networks through collaborative modelling and simulation

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Kasper Pieter Hendrik LANGE

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Dissertation

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Voor Liewe en Jelte

"We are will and wonder"

Tool - Pneuma[*]

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[*] Jones, A, Carey, D., Chancellor, J., & Keenan, M. (2019). Text fragment from *Pneuma* [Song]. On: Fear Inoculum performed by Tool. BMG Rights Management. This text fragment was used with permission from the authors.

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For my entire life, I have wanted to become both a scientist and an engineer. When I was six years old, I was fond of Carl Barks' and Walt Disney's stories of Gyro Gearloose, the absent-minded inventor whose machines always caused more trouble than relief. After high school, I decided to become an engineer and study at Delft University of Technology, graduating with a master's degree in Industrial Design Engineering. During my study, I increasingly became aware of grains of truth in the tales of Gyro. Although technologies can solve problems and increase users' comfort and well-being, these may cause undesirable environmental or social side effects.

At the time in the late 1990s, sustainability was not high on the global agenda of industries. Nevertheless, my professors and lecturers already taught Design for Sustainability, pushing students to think about ways to decrease environmental impact and enhance well-being while creating a viable business. After graduating, when I worked as an R&D engineer for the manufacturing industry, I found projects involving the recovery of materials and energy the most exciting. However, I also felt that we needed to make more effort to protect our habitat. I discussed this with many friends whom I had met in Delft. Some of them had already started and even finished a PhD journey, and they inspired me to pursue this challenge. So when I came across a vacancy for a researcher at the CleanTech Research Programme at the Amsterdam University of Applied Sciences (AUAS), I decided to devote my career to sustainable systems engineering research and education. Here we are now, at the end of a very inspiring and challenging PhD journey!

The completion of this dissertation would not have been possible without the help of many people, whom I would like to thank sincerely. First, I am highly grateful to my promotors for their supervision.

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Kasper Lange
Leiden, May 2022

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Glossary

Agent-based model	A computational model for simulating the effects of actions and interactions of individual agents on a complex adaptive system.
Business model	A description of a firm’s organisational and economical design, providing insights into how companies create, deliver and capture value.
Circular business model	Specific class of (sustainable) business models, aiming to create economic, environmental and social value according to the principles of the circular economy, often transcending internal business functions across supply chains and even industries.
Circular business model innovation	The process of redesigning linear business models into circular business models to create, deliver and capture value through slowing down resource flows and closing and narrowing loops.
Circular economy	An economic and industrial system based on the reuse and recycling of products and materials and the recovery capacity of natural resources.
Collaborative modelling methods	Modelling methods facilitating the Iterative collaboration among modeller(s) and stakeholders to create, calibrate, validate and use models.
Competencies	Combinations of applied knowledge, skills and attitudes.
Complex adaptive systems	Dynamic systems of elements that interact, which outcomes are not determined by single causes but by a combination of multiple factors that may reinforce or neutralize each other.
Complex adaptive socio-technical systems	“Systems composed of two deeply interconnected subsystems: a social network of actors and a physical network of technical artefacts” (Dijkema et al., 2015).
Design Interventions	The systematic set of technological and non-technological activities intending to impose a change from the existing to the desired situation.
Design science research	“Science that seeks to consolidate knowledge about the design and development of solutions, to improve existing systems, solve problems and create new artefacts” (Dresch et al., 2015, p. 15).

Eco-industrial park (EIP)	A geographical area containing several industrial symbiosis instances that allow energy and material exchanges amongst the different industrial enterprises to improve the actor's economic and environmental performances (Kuznetsova & Zio, 2016).
Game-based learning	Learning during and from serious gameplay.
Industrial symbiosis	[1] Collaboration between traditionally separate but geographically proximate economic and industrial agents, contributing to closing material, water, and energy cycles; *or; [2] s*cientific field studying the phenomenon of industrial symbiosis.
Industrial symbiosis network	"A collection of long-term, symbiotic relationships between and among regional activities involving physical exchanges of materials and energy carriers and the exchange of knowledge, human or technical resources, concurrently providing environmental and competitive benefits" (Mirata & Emtairah, 2005).
Linear economy	An economic system in which resources are extracted, turned into products, and the products are discarded.
Participatory modelling methods	See *collaborative modelling methods.*
Serious games	A class of games enabling players to experience situations in a virtual world, aiming to have a positive and meaningful impact on skills development. Serious games are often used to solve complex problems in collaborative settings.
Sustainable business model	A specific class of business models aiming to create economic, environmental, and social value.
Symbiotic urban agriculture network	A specific class of Industrial symbiosis Networks in the context of Urban Agriculture.
Urban agriculture	An agricultural industry located within (intra-urban) or on the fringe (peri-urban) of a town, a city or a metropolis, which grows or raises, processes and distributes a diversity of food and non-food products. The companies involved reuse resources, products, and services locally in the area.

List of acronyms

BM	Business model
CAS	Complex adaptive systems
CB	Current batch
CBM	Circular business model
CE	Circular economy
CIMO	Context, interventions, mechanisms, and outcomes
DSR	Design science research
EIP	Eco-industrial park
IE	Industrial ecology
IS	Industrial symbiosis
ISN	Industrial symbiosis network
SUAN	Symbiotic urban agriculture network
UA	Urban Agriculture
WI	Waste incinerator
WP	Waste processor
WS	Waste supplier

S

Summary

Samenvatting

Het doel van dit proefschrift is om circulaire businessmodellen in industriële symbiose netwerken (ISNs) beter te begrijpen en vorm te geven door middel van collaboratieve modelleer- en simulatiemethoden.

De wereldwijde consumptie van grondstoffen blijft groeien als gevolg van de groeiende bevolking en welvaart. Daarom krijgt de transitie naar een circulaire economie (CE), ook wel kringloopeconomie genoemd, steeds meer aandacht onder wetenschappers, bedrijfsleven, beleidsmakers en onderwijsprofessionals. De kringloopeconomie is een economisch en industrieel systeem dat is gebaseerd op hergebruik en recyclen van producten en materialen en de herstelcapaciteit van natuurlijke hulpbronnen. Het bedrijfsleven speelt een centrale rol in de transitie naar de circulaire economie, omdat hun kernactiviteiten veelal bestaan uit het omzetten van materialen en energie in producten en afvalstromen. Industriële symbiose netwerken bestaan uit bedrijven die samenwerken om economische, milieukundige en sociale waarde te creëren. De bedrijven in deze netwerken wisselen materialen, energie of informatie uit, waardoor kringlopen worden gesloten en de grondstofefficiëntie wordt vergroot. Daarom wordt industriële symbiose beschouwd als een essentiële manier om bij te dragen aan de circulaire economie op lokaal en regionaal niveau.

Ondanks de belofte ervan, ondervinden particuliere belanghebbenden echter moeilijkheden bij het implementeren en in stand houden van industriële symbiose. Circulaire businessmodellen stellen bedrijven in staat om nieuwe symbiotische samenwerkingen vorm te geven. Maar in de praktijk worden nieuwe circulaire businessmodellen vaak niet geïmplementeerd. Potentiële partners in ontluikende netwerken haken af of reeds deelnemende stakeholders verlaten het netwerk. De aarzeling van bedrijven kan worden veroorzaakt door dynamische omstandigheden en gedrag van actoren, wat leidt tot ongelijk verdeelde winsten en verliezen.

In lijn met het doel van dit proefschrift, beantwoordden we deze vragen:

1. Welke methode verschaft prescriptieve kennis, waarmee nieuwe businessmodellen voor robuuste industriële symbiose netwerken kunnen worden ontwikkeld?
2. Hoe beïnvloedt het netwerk en het gedrag van actoren de robuustheid van industriële symbiose netwerken tijdens het implementeren van kringloopsluiting?
3. Hoe kunnen circulaire businessmodellen voor levensvatbare en robuuste industriële symbiose netwerken voor implementatie worden getest en verbeterd door middel van collaboratieve modelleer- en simulatiemethoden?
4. Hoe kunnen collaboratieve modelleer en simulatiemethoden (toekomstige) professionals ondersteunen in het verbeteren van het ontwerp van industriële symbiose netwerken?

Het onderzoek heeft het volgende opgeleverd:

- Generieke inzichten in de complexiteit en dynamiek van industriële symbiose netwerken, inclusief de daarin aanwezige actoren en technologieën.
- Gezamenlijke methoden, modellen en gereedschappen, waarmee onderzoekers, werkveldprofessionals en opleiders gezamenlijk businessmodellen kunnen ontwerpen en verkennen die gericht zijn op levensvatbare en robuuste industriële symbiose.

- Aanbevelingen om de bijdragen uit dit onderzoek te gebruiken in leeromgevingen met meerdere actoren die ontwerpen van circulaire businessmodellen willen verbeteren.

Aanpak

Er wordt in dit onderzoek gebruik gemaakt van drie relevante theoretische invalshoeken: ontwerpgericht onderzoek (design science research), complexe adaptieve sociaal-technische systemen en circulaire businessmodelinnovatie. Literatuur over ontwerpgericht onderzoek en businessmodelinnovatie verschafte kennis en methoden op voor het gezamenlijk uitvoeren van onderzoek naar het (her)ontwerpen van businessmodellen richting circulariteit. Literatuur over complex adaptieve sociaal-technische systemen ondersteunde de ontwikkeling van digitale simulatiemodellen in nauwe samenwerking met belanghebbenden en studenten. Gedurende het onderzoek werden er agent-gebaseerde modellen ontwikkeld en gebruikt om te experimenteren met businessmodelontwerpen onder wisselende onzekere factoren, zoals verschillende soorten actorengedrag in diverse omgevingen. We hebben gebruik gemaakt van een palet aan verschillende onderzoeksmethoden, om vooringenomenheid te voorkomen en zowel relevantie als nauwgezetheid van het onderzoek te vergroten. Denk hierbij aan het open access publiceren van data, modellen en gereedschappen, en triangulatie van casussen, data, methoden, artefacten en uitvoerend onderzoekers. De gezamenlijk ontwikkelde artefacten bestaan uit twee agent-gebaseerde modellen, een bordspel voor de praktijk, en een educatief bordspel inclusief lesmateriaal. We hebben vier studies uitgevoerd in dit onderzoek.

In de eerste studie (hoofdstuk 2) hebben we een conceptuele ontwerpwetenschappelijke aanpak geconstrueerd voor het gezamenlijk ontwikkelen van een agent-gebaseerd model met belanghebbenden. De aanpak was gebaseerd op literatuur uit ontwerpwetenschappelijk onderzoek, complexe adaptieve systeemmodellering en participatieve modellering en geïllustreerd met een casestudie.

De tweede studie (hoofdstuk 3) was gericht op het begrijpen van het gedrag van industriële symbiosenetwerken en de bijbehorende actoren. De studie was de eerste die technische en sociale factoren combineerde in een agent-gebaseerd model van vijf symbiose-implementatiefasen. Met behulp van de voorgestelde ontwerpwetenschappelijke onderzoeksmethode uit hoofdstuk 2 werden een businessgame en een agent-gebaseerd model geconstrueerd met deelnemers in de casestudies in drie authentieke cases, experts en medeonderzoekers, ondersteund door studenten. Hoofdstuk 3 concentreert zich op het agent-based model en simulatieresultaten, het spel wordt beschreven in hoofdstuk 5. Op basis van de literatuur hebben we vijf implementatiefasen van industriële symbiose gemodelleerd: bewustwording, planning, onderhandeling, implementatie en evaluatie. We gebruikten de theorie van gepland gedrag (TPB) om het gedrag van belanghebbenden tijdens deze fasen te modelleren. We onderzochten de modeldynamieken met en zonder gedragsalgoritmen over een reeks mogelijke invoervariabelen. De simulatieresultaten lieten zien hoe het gemodelleerde geplande gedrag de cashflows van de sociale agenten en de robuustheid van het netwerk beïnvloedt.

De derde studie (hoofdstuk 4) presenteert een nieuwe systematische methode om circulaire businessmodellen te verkennen en te verbeteren voordat ze daadwerkelijk worden geïmplementeerd door middel van op agent gebaseerde modellering en simulatie. Voortbouwend op de aanpak en het model uit studies 1 en 2, hebben we op iteratieve wijze een nieuw model ontwikkeld, getest en gesimuleerd met deelnemers aan casestudies. Dit model simuleert een symbiose tussen GFT-leveranciers en een afvalverwerker met een anaerobe vergistingsinstallatie. Het nieuwe model werd vervolgens gebruikt om een ex-ante experimenteermethode te ontwikkelen en te valideren die systematisch de belangrijkste dimensies van bedrijfsmodellen dekt: de waardepropositie, de waardecreatie en -levering, en de waardevangst. We hebben simulaties gebruikt om te illustreren hoe circulaire bedrijfsmodelontwerpen zo gevormd kunnen worden, dat de opgebrachte waarde en het overlevingspercentage van het netwerk toenemen. Stakeholders kunnen de methode gebruiken om concrete voorstellen te doen om het circulaire businessmodel op individueel en gezamenlijk niveau te verbeteren.

De vierde studie toont aan hoe game-based learning kan helpen om huidige en toekomstige professionals te leren businessmodellen voor industriële symbiosenetwerken te ontwerpen. De business game, die voortkwam uit ons tweede onderzoek, werd iteratief doorontwikkeld tot een nieuwe educatieve game, inclusief les- en beoordelingsmateriaal. Vervolgens hebben we dit onderwijspakket gebruikt om een klassikaal experiment uit te voeren met twee groepen studenten. Alle studenten bestudeerden een reader en een persoonlijk toegewezen rol in het spel. Daarna vulden ze een circulair businessmodelcanvas in en reflecteerden op hun leerervaring. Een groep speelde het spel, bediscussieerde de uitkomsten ervan en werkte daarmee zowel het canvas als de reflectie bij. De controlegroep besprak en herzag hun werk, en speelde daarna pas het spel. De resultaten, bestaande uit teksten in businessmodelcanvassen en reflecties, werden geanalyseerd met een combinatie van *text mining* en kwalitatieve methoden. Bevindingen laten zien dat gameplay de studenten ondersteunde bij het doorontwikkelen van hun bedrijfsmodel en het vergroten van reflectieve vaardigheden tijdens het leren.

Wetenschappelijke bijdragen en aanbevelingen

De theoretische bijdragen van dit proefschrift zijn te vinden in onderzoek en onderwijs op het gebied van circulaire economie en industriële symbiose.

Dit proefschrift geeft wetenschappers in industriële symbiose een aanpak om de dynamiek van industriële symbiosenetwerken te kunnen modelleren en onderzoeken. De modellen uit de studies maken de integratie mogelijk van gegevens uit de casestudies over de context, beschikbare afvalstromen, hulpbronnenbehoeften en gepland gedrag. We stellen voor om het model te gebruiken om een beoordelingsmethode te ontwikkelen voor gedragsveranderingsbeleid in bestaande of toekomstige initiatieven voor industriële symbiose. We raden ook aan om het model verder te kalibreren door andere gedragstheorieën te vergelijken en te integreren.

Voor de onderzoeksgemeenschap die circulaire businessmodelinnovatie bestudeert, biedt dit proefschrift een methode voor het ontwerpen van, systematisch experimenteren met en verbeteren van circulaire businessmodellen op netwerkniveau. Hoewel de derde studie over experimenteren met businessmodellen alleen illustreert hoe industriële symbiose met uitwisseling van organisch afval en anaerobe vergisting kan worden verbeterd, is de methode breder toepasbaar. Het laat namelijk zien hoe digitale modellen aan de algemene dimensies van businessmodellen gekoppeld kunnen worden. Daarom stellen we voor om de methode verder te ontwikkelen in de context van andere duurzame businessmodelarchetypen waarbij samenwerking met belanghebbenden van belang is. Om ons begrip van de wisselwerking tussen businessmodellen en beleidsontwerpen te vergroten, stellen we voor om onze studies als startpunt te gebruiken om een bredere methode te ontwikkelen voor industriële symbiosenetwerken en andere circulaire toeleveringsketens.

Deze dissertatie draagt ook bij aan de onderzoeksgemeenschap die onderwijs in circulaire economie bevordert. Het laat zien hoe serious games ondersteunen in het onderwijzen van iteratieve ontwerpprocessen rondom industriële symbiose en circulaire businessmodellen. Bovendien laat het onderzoek zien hoe gemengde analysemethoden het begrijpen van inhoudelijke en persoonlijke leerresultaten.

Bijdragen en aanbevelingen aan de praktijk
Deze dissertatie draagt hoofdzakelijk bij aan ondersteuning van huidige en het opleiden van toekomstige professionals die levensvatbare en robuuste kringloopactiviteiten willen vormgeven en opzetten in netwerkverband.

De studies met agent-gebaseerde modellen (hoofdstukken 3 en 4) helpen belanghebbenden de ingewikkelde dynamiek van industriële symbiosenetwerken te verkennen, inclusief omgevingsvariabelen, gedrag en acties van actoren, technische specificaties en het ontwerp van businessmodellen. De businessmodel experimenteermethode in hoofdstuk 4 kan bedrijven richting geven bij het wegnemen van onzekerheden en het ontwerpen van samenwerkingen die circulariteit versterken. De agent-gebaseerde modellen uit dit proefschrift kunnen beleidsmakers ook ondersteunen bij het identificeren en vormgeven van gunstig gedrag en marktomstandigheden.
Het in dit onderzoek ontwikkelde bordspel (hoofdstuk 5) verschaft een aantoonbaar veilige en effectieve simulatie voor conceptualisering van industriële symbiose en de bijbehorende businessmodellen.

Bijdragen en aanbevelingen voor onderwijs
Dit proefschrift omvat open-access wetenschappelijke artikelen, bijdragen aan praktijkpublicaties, datasets, het educatieve spelpakket, twee agent-gebaseerde modellen en een methode voor ex-ante experimenten met circulaire businessmodellen. We stellen voor om deze artefacten te gebruiken om het onderwijs over het begrijpen en ontwerpen van industriële symbiose te verrijken. Het in dit onderzoek ontwikkelde spelpakket (hoofdstuk 5) is veilig en effectief gebleken om studenten te leren om industriële symbiosenetwerken en de bijbehorende businessmodellen te conceptualiseren. Het onderzoek in hoofdstuk 5 kan ook dienen als inspiratiebron voor het aanleren van inhoudelijke, persoonlijke, interpersoonlijke en design thinking-competenties met behulp van andere vormen van simulatie. We stellen voor om het gebruik en de verdere ontwikkeling van deze tools, modellen en methoden in onderzoeks- en onderwijsprogramma's voor de lange termijn te consolideren door ze te integreren met curriculumontwerpen.

Samengevat hebben we in dit proefschrift de uitdagingen aangepakt waarmee bedrijven worden geconfronteerd in de overgang naar een circulaire economie, met name voor bedrijven die industriële symbiose willen implementeren in onzekere omstandigheden. We hebben deze uitdagingen gekoppeld aan theorieën uit ontwerpwetenschappelijk onderzoek en collaboratieve modellerings- en simulatiemethoden. Het onderzoek voorziet wetenschappers, praktijkmensen en studenten (onze toekomstige leiders en praktijkmensen) van kennis, simulatiemodellen, games en een ex-ante experimenteermethode voor circulaire businessmodellen. Hiermee kunnen ze industriële symbiose verkennen vormgeven. In een breder perspectief vertrouwen wij erop dat we een inspiratiebron hebben geboden om te leren, samen te werken en te discussiëren over de toekomstige rol van bedrijven bij het vormgeven van een circulaire samenleving.

Summary

This dissertation aims to support researchers, professionals, and students in understanding and shaping circular business models for industrial symbiosis networks (ISNs) through collaborative modelling and simulation methods.

As the world's global resource consumption continues to rise due to growing populations and increasing welfare, the transition to a circular economy (CE) is increasingly gaining traction among scholars, practitioners, policymakers, and educators. The circular economy is an economic and industrial system based on the reuse and recycling of products and materials and the recovery capacity of natural resources. Industries play a crucial role in the transition towards the circular economy since their core activities often involve converting materials and energy into finished products and wastes. Industrial symbiosis networks consist of companies that collaborate to create economic, environmental, and social value. The companies in these networks exchange materials, energy or information, thereby closing loops and increasing resource efficiency. Therefore, industrial symbiosis is considered an essential contributor to the circular economy on local and regional levels.

Despite its promise, private stakeholders face difficulties implementing and sustaining industrial symbiosis. Circular business models allow companies to shape new symbiotic collaborations. However, in practice, novel circular business models are often not implemented. Potential partners in emerging networks drop out, or already participating stakeholders leave. The companies' hesitance may be caused by dynamic circumstances and actor behaviour, leading to unevenly distributed profits and losses.

In line with the aim of this dissertation, the questions we answered were:

1. What collaborative modelling and simulation method can facilitate designing business models for viable and robust industrial symbiosis networks?
2. How do network and actor behaviour affect the robustness of ISNs during implementation?
3. How can circular business models for viable and robust industrial symbiosis networks be tested and improved before implementation through collaborative modelling and simulation methods?
4. How can collaborative modelling and simulation methods support the learning of (future) professionals for improving industrial symbiosis network designs?

This research produced the following:

- generic insights into the complexities and dynamics of industrial symbiosis networks, their constituent actors and technologies;
- methods, models and simulation tools to enable researchers, practitioners, and educators to collaboratively design and explore business models aiming for viable and robust industrial symbiosis;
- recommendations to use the contributions of this research in multi-actor learning environments that aim to improve circular business model designs.

General approach

This work used three relevant theoretical perspectives: design science research, complex adaptive socio-technical systems, and circular business model innovation. Literature on design science research and circular business model innovation provided knowledge and methods to conduct collaborative research for redesigning business models towards circularity. Literature on complex adaptive socio-technical systems supported the development of computational simulation models in close collaboration with stakeholders and students. During the research, agent-based models were developed and used to experiment with business model designs under uncertain factors such as various actor behaviours in diverse environments. We used a mix of methods to avoid bias and increase both relevance and rigour, including open-access publication of data, models and tools and triangulation of cases, data, methods, artefacts, and researchers. The collaboratively developed artefacts comprise two agent-based models, a business game and an education game, including teaching material. We conducted four studies in this research.

In the first study (chapter 2), we constructed a conceptual design science approach for developing an agent-based model with stakeholders. The approach was based on literature from design science research, complex adaptive systems modelling, and participatory modelling and illustrated with a case study.

The second study (chapter 3) focused on understanding the behaviour of industrial symbiosis networks and their constituent actors. The study was the first to combine technical and social factors in an agent-based model of five symbiosis implementation stages. Using the proposed design science research method from chapter 2, a business game and an agent-based model were constructed with case study participants in three real-world cases, experts and coresearchers, supported by students. The model simulates compost production from local organic waste streams from companies. Chapter 3 focuses on the agent-based model and simulation results, and the game is described in chapter 5. Based on the literature, we modelled five industrial symbiosis implementation stages: awareness, planning, negotiation, implementation, and evaluation. We used the theory of planned behaviour (TPB) to model stakeholder behaviour during these stages. We explored model dynamics with and without actor behaviour algorithms across a range of possible input variables. The simulation results showed how the modelled planned behaviour affects the social agents' cash flow outcomes and the network's robustness.

The third study (chapter 4) presents a novel systematic method to explore and improve circular business models before actual implementation through agent-based modelling and simulation. Building upon the approach and model from studies 1 and 2, we iteratively redeveloped, tested, and simulated a new agent-based model with case study participants. This model simulates a symbiosis between organic waste suppliers and a waste processor with an anaerobic digester. The new model was then used to develop and validate an ex-ante experimentation method that systematically covers the key dimensions of business models: value proposition, value creation and delivery, and value captured. We used simulations to illustrate how to shape circular business model designs to increase the value captured and network survival rate. Stakeholders can use the method to make concrete proposals to improve the circular business model individually and collectively.

The fourth study shows how game-based learning can support teaching current and future professionals designing business models for industrial symbiosis networks. The business game, which originated from our second study, was iteratively redeveloped into a new educational game, including teaching and assessment materials. Next, we used this education package to conduct an in-class experiment with two groups of students. All students studied a reader and a personally assigned game role before gameplay. Then, they filled out a circular business model canvas and reflected upon their learning experience. One group played the game, discussed its outcomes, and updated the canvas and the reflection. The control group discussed and reviewed their work first and then played the game. The results, consisting of texts from business model canvasses and reflections, were analysed using a combination of text-mining and qualitative methods. Findings show that gameplay supported the students in redeveloping their business model and increasing reflective competencies during learning.

Contributions and recommendations to science
The theoretical contributions of this thesis can be found in research and education in the fields of circular economy and industrial symbiosis.

This dissertation provides industrial symbiosis scientists with an approach to model and explore the dynamics of industrial symbiosis networks. The models provided in the studies allow for the integration of case study data on the context, available waste streams, resource needs, and planned behaviour. We suggest using the model to develop an assessment method for behaviour change policies in existing or future industrial symbiosis initiatives. We also recommend further calibrating the model by comparing and integrating other behaviour theories.

For the research community studying circular business model innovation, this thesis provides a method for designing, systematically experimenting with, and improving network-level circular business models. Although the study only illustrates how to enhance industrial symbiosis with organic waste exchange and anaerobic digestion, the method is more widely applicable. It shows how digital models can be linked to the general dimensions of business models. Therefore, we propose developing the method in the context of other archetypes of sustainable business models involving collaboration with stakeholders. To increase our understanding of the interplay between business models and policy designs, we suggest using our study as a starting point to develop a broader experimentation method for industrial symbiosis networks and other circular supply chains.

This dissertation is also relevant for the research community furthering circular economy education. It shows how serious games teach iterative design processes involving industrial symbiosis and circular business models. Furthermore, the research demonstrates how mixed analysis methods improve an understanding of substantive and personal learning outcomes.

Contributions and recommendations to practice
This dissertation primarily contributes to supporting current and training future professionals that aim to shape and set up viable and robust circular activities in a network context.

The agent-based model studies (chapters 3 and 4) help stakeholders explore the intricate dynamics of industrial symbiosis networks, including environmental variables, behaviour and actions of actors, technical specifications, and business model design. The business model experimentation method in chapter 4 can guide companies in removing uncertainties and designing collaborations that enhance circularity. The agent-based models from this dissertation can also support policymakers in identifying and shaping favourable behaviour and market conditions. The board game developed in this research (chapter 5) provides a demonstrably safe and effective simulation for conceptualising industrial symbiosis and the associated business models.

Contributions and recommendations for education.
This dissertation includes open-access scientific articles, contributions to book chapters for practitioners, datasets, the education game package, two agent-based models and a method for ex-ante circular business model experimentation. We suggest using these artefacts to enrich education about understanding and designing industrial symbiosis. The game package developed in this research (chapter 5) was proven safe and effective for teaching students to conceptualise industrial symbiosis networks and the associated business models. The study in chapter 5 can also serve as a source of inspiration for teaching content-specific, personal, interpersonal and design thinking competencies using other simulation tools. We suggest consolidating the use and further development of these tools, models and methods in long term research and education programmes by integrating them with curriculum designs.

Overall, this thesis addressed challenges businesses face in the transition towards a circular economy, specifically those aiming to implement industrial symbiosis under uncertainty. We have connected these challenges with theories from design science research and collaborative modelling and simulation methods. The research equips scientists, practitioners and students (our future leaders and practitioners) with knowledge, simulation models, games and an ex-ante experimentation method for circular business models. From a broader perspective, we trust in having offered a source of inspiration for learning, collaborating, and discussing the future role of businesses in shaping a circular society.

1

Introduction

This chapter explains the circular economy transition and the role of industrial symbiosis with companies as key actors in this transition. The state-of-the-art literature is discussed, leading to a knowledge gap. To bridge this gap, a central research objective of this dissertation is stated: "To develop tools and participatory methods for understanding and shaping industrial symbiosis networks". Four research questions and a research design to answer these questions are introduced.

1.1 Background

1.1.1 From linear to circular: industries in the transition towards a circular economy

As the world's global consumption continues to rise due to growing populations and increasing welfare, the transition to the circular economy (CE) is increasingly gaining traction among scholars, practitioners and policymakers (PBL Netherlands Environmental Assessment Agency, 2021; Rizos et al., 2017). The circular economy, popularised a decade ago by The Ellen McArthur Foundation (EMF, 2013), is an economic and industrial system based on the reuse and recycling of products and materials and the recovery capacity of natural resources. A circular economy ultimately aims to create a long term regenerative economic, ecological and social environment.

The term circular economy was first used in the work of Pearce and Turner (1990). CE introduced a different mindset than the - at that time most common - linear way of take-make-use-dispose: extracting resources from the earth, transforming these resources into products, using the products, and disposing of the used products as waste. Instead, Pearce and Turner (1990) attempted to redesign the economic model in such a way that *"everything is an input to everything else"*. However, even then, the concept of closed-loop economic systems was not new at the time. Already in the sixties of the previous century, Boulding (1966) forewarned humankind that a shift towards closed-loops was inevitable, in what he called a *"spaceman economy"* - an economy that considers earth to be a closed system similar to a spaceship.

The linear economy is often coined as the opposite of the circular economy. In a linear economy, resources are extracted, turned into products, used, and discarded (EMF, 2013). Due to the abundance of resources, linear economy practices often contributed to companies' short-term profits (Sariatli, 2017). However, the linear economy is criticized more and more because it may lead to maximizing production and selling as many products as possible (Sariatli, 2017). The evidence of social, environmental and eventually economic disadvantages against these linear practices is omnipresent and increasing (e.g., EMF, 2013; Ghisellini, Cialani, and Ulgiati, 2015; Schroeder, Anggraeni, and Weber, 2019). Therefore, the circular economy is globally gaining attention as an alternative way to decouple economic growth from environmental impact and resource depletion (Ghisellini et al., 2015).

The environmental impact of materials that are regarded and treated as waste streams related to resource extraction and conversion of materials and energy into finished products and wastes is significant (Ayres, 1994). For example, Singh et al. (2014) estimated that mining and manufacturing industries globally generated 4 to 5 times more solid waste than municipalities, adding up to approximately 8.1 to 8.6 billion tonnes of solid waste per year. Therefore, industries play a central role in the circular and sustainable economy (Ayres, 1994).

Industries that commit to CE generally aim to develop business models to close, slow and narrow resource loops among networks of companies (Bocken et al., 2016). With closing loops, the authors mean the connection between post-use and production of new products. *Slowing cycles* refers to product life extension. By elongating operating time, new resource extraction or cycling activities are delayed avoiding unnecessary loss of value. With narrowing resource flows, Bocken et al. (2016) refer to increasing resource efficiency by using fewer resources per product.

In circular resource extraction and production processes, the focus lies on closing and narrowing loops to minimize waste and maximize resource efficiency among systems of industries and companies. Circularity requires all stakeholders in supply chains to treat and manage materials in such a way that potential cycling is supported. System-level innovations are needed to tackle the complex mix of values, norms, interests and motivations of the actors involved. Therefore, this dissertation focuses on system-level business model innovations for closing and narrowing loops: aiming to minimise waste and maximise resource efficiency.

1.1.2 Industrial symbiosis and its role in the circular transition

For the past decade, several local waste collection and treatment initiatives for industrial and company waste have emerged in The Netherlands. Many of these initiatives consist of networks of companies that aim to create value from their waste streams. The relationships between these companies are often compared to *"symbiosis"* in biology and ecology. The concept of *"symbiosis"* refers to relationships in which at least two different species both gain benefits by exchanging materials, energy, or information (Chertow, 2000). Scholars from the field of Industrial Ecology – which is considered one of the cornerstones upon which the circular economy is built (Ghisellini et al., 2015) – first coined the term industrial symbiosis (IS) (Chertow, 2000). Industrial symbiosis is the phenomenon of cooperation between previously separate industrial agents aimed at a mutual competitive advantage through the exchange of materials, energy, and information. By doing so, industrial symbiosis generally generates environmental and social benefits (Chertow, 2000).

In line with the aims of the circular economy, IS strives for the elimination of waste to create economic value and reduce environmental impact (Bocken et al., 2014; Graedel & Allenby, 2010). Thus, scholars and policymakers consider industrial symbiosis to be a major contributor to the design and implementation of the circular economy at city-district and network levels (e.g., EMF, 2013; European Commission, 2020; Ghisellini et al., 2015). Chertow (2000) stated, *"The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity"*. A key concept within this field is the eco-industrial park (EIP), a geographical area containing several industrial symbiosis instances that allow energy and material exchanges amongst the different industrial enterprises to improve the actor's economic and environmental performances (Kuznetsova & Zio, 2016).

Although, until a decade ago, the field primarily focused on geographic proximity for closing loops (Fernandez-Mena et al., 2016), industrial symbiosis is not necessarily limited to exchange and reuse in eco-industrial parks. Multiple scholars started to study the phenomenon from a dynamic and complex network perspective (e.g., Chertow and Ehrenfeld, 2012; Doménech and Davies, 2009; Lombardi and Laybourn, 2012). Instead of binding IS to geographical limits, they emphasize that system's boundaries may change over multiple dimensions. Hence, Lombardi and Laybourn (2012) redefined the term industrial symbiosis: "*IS engages diverse organizations in a network to foster eco-innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes.*" In this definition, they emphasize the diversity of organisations within a network context. Consequently, in the past years, scholars increasingly shifted the focus of interest from (eco-)industrial parks toward industrial symbiosis networks (ISNs), already defined by Mirata and Emtairah (2005) as *"a collection of* *long-term, symbiotic relationships between and among regional activities involving physical exchanges of materials and energy carriers as well as the exchange of knowledge, human or technical resources, concurrently providing environmental and competitive benefits"*.

Based on the literature, this dissertation presumes that industrial symbiosis emerges across a heterogenic set of networked companies and processes, involving (combinations of) material(s), energy or information exchanges.

1.1.3 Understanding the complexity of industrial symbiosis networks

Chertow and Ehrenfeld (2012) recognised that numerous industrial symbiosis processes evolve as self-organising complex adaptive systems. Complex adaptive systems (CAS) are dynamic systems of elements that interact. Outcomes are not determined by single causes but by a combination of multiple factors that may reinforce or neutralize each other (Byrne, 2002). Turner & Baker (2019) identified eight characteristics of complex adaptive systems: [1] path dependency, [2] systems having a history, [3] non-linearity, [4] emergence, [5] irreducibility, i.e., limited direct relationships between system and constituent elements, [6] adaptiveness, [7] order and chaos, and [8] self-organising. The central interacting components in CAS are called agents.

Firms operate in a complex and evolving environment, and their performance is influenced by many external and internal factors that they cannot manage (D'Souza et al., 2015). In order to create industrial symbiosis, merely connecting resources to needs is not sufficient: combinations of dynamic and transient social, technical and environmental conditions determine how the industrial symbiosis network evolves and whether it can survive (Chertow & Ehrenfeld, 2012). Hence, ISNs can be considered complex adaptive socio-technical systems (Dijkema et al., 2015), defined *as "systems composed of two deeply interconnected subsystems: a social network of actors and a physical network of technical artefacts"*.

In this dissertation, we study ISNs from the perspective of socio-technical complex adaptive systems theory. This perspective allows us to explore and integrate the interactive dynamics of the environment, social agents, technical agents (artefacts), and the organisational design of the network.

1.1.4 Shaping robust industrial networks through circular business model innovation

In self-organising industrial symbiosis networks, companies are the key players determining implementation dynamics (Tao et al., 2019). Many empirical studies have found that implementing and sustaining industrial symbiosis networks is not easy (e.g., Chopra & Khanna, 2014). Unexpected events may cause the symbiotic collaborations to end and the network to collapse (Boons & Spekkink, 2012; Chertow & Ehrenfeld, 2012; Chopra & Khanna, 2014; Yap & Devlin, 2016). 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 (Lange, Korevaar, Nikolic, et al., 2021c). While traditional supply chains regularly suffer from instability by disappearing partners, industrial symbiosis networks are even more vulnerable because of their scale, lack of flexibility, redundancy, multifunctionality and a high degree of interconnectedness (Chopra & Khanna, 2014). Disruptions between one industry's outputs result in accumulating adverse impacts of partnering industries in symbiosis (Chopra & Khanna, 2014). Because of this vulnerability of symbiotic linkages and networks, some scholars started to approach industrial symbiosis from a process perspective to find recipes for successful symbiosis. For example, Boons et al. (2016) identified several typologies of industrial symbiosis dynamics based on empirical evidence.

Because of their complex adaptive socio-technical nature, industrial symbiosis networks are shaped and adapted by contextual factors and 'local' rules, i.e., rules that apply to agents (Westhorp, 2012). The context in which the ISN is situated is affected by technical, economic, geospatial, and institutional factors. In this dissertation, the local rules can be shaped through what we call (design) interventions, defined as *the systematic set of technological and non-technological activities that intend to impose a change from the existing situation to the desired situation.*" (Lange et al., 2017). Design interventions for shaping robust ISNs thus require rethinking the whole business logic, traditionally described in business models (Teece, 2010). Designing business models for industrial symbiosis requires an understanding that transcends businesses, traditional supply chains and even industries or sectors (Bocken et al., 2015). Hence, network-level business model innovation is seen as a critical pathway for the transition towards a circular economy (De Angelis, 2016; Schenkel et al., 2015).

Although business model innovation for industrial symbiosis uncovers novel opportunities for companies to create value, many are hesitant to implement novel business models. Many companies raise questions about the feasibility of the pursued impacts (Bocken et al., 2019). Their hesitance is often caused by uncertainties about various new roles, the stakes, opinions, and behaviour of other actors, and the dynamics of the companies' environment. Therefore, partnering companies require iterative testing, evaluating and reshaping (Baldassarre et al., 2019). Hence, learning plays a crucial role in circular business model innovation.

1.1.5 Facilitating circular business model innovation in multi-actor learning environments

Multi-actor learning environments, where learners from different societal roles develop knowledge and solutions to problems, effectively support transformative actions (de Vries & Hoosbeek, 2019; Geerling-Eiff et al., 2007; Maas et al., 2017). In this context, the triple (Etzkowitz & Leydesdorff, 2000), quadruple (Miller et al., 2016) and quintuple helix (Carayannis & Campbell, 2010) frameworks are widely used. These frameworks describe the variety of actors that interact to develop knowledge for systemic innovation for sustainable development, i.e., public, government, industry, university and environment. Often, universities use living labs, defined as virtual or physical nodes, for exploration, experimentation, design and co-creation for knowledge development and practical application by students, educators, researchers and practitioners (Maas et al., 2017; Sol, 2021). Next to living labs, the terms open research facilities, field labs (de Vries & Hoosbeek, 2019) and knowledge arrangements are often coined to describe slightly different knowledge and innovation initiatives with the same purpose: researchers, societal partners (public, private, civil) and education (teachers, students) collaborate to develop knowledge and innovations. For researchers, multi-actor learning environments offer opportunities to increase societal relevance and scientific rigour through validation. From the educational perspective, collaborations in these environments support concrete and authentic learning opportunities, paving the way for students to become future researchers or practitioners. Industrial symbiosis networks are multi-actor systems by definition. We conjecture that a multi-actor learning environment offers learning opportunities for system-level circular business model innovations.

1.1.6 Design science research using collaborative modelling and simulation methods

Design science research as a problem-solving research paradigm

A methodological approach that serves theoretical rigour and practical relevance is needed to support circular business model innovation. The design science research (DSR) paradigm provides such a prescriptive approach that brings together theory and practice.

In contrast to traditional analytical research, which generally aims to explore, describe, explain and/or predict, DSR is fundamentally oriented towards problem-solving (Dresch et al., 2015). DSR is coined by Dresch et al. (2015, p. 59) as *“science that seeks to consolidate knowledge about the design and development of solutions, to improve existing systems, solve problems and create new artefacts*”. Key aspects of design science are found on multiple levels (Dresch et al., 2015). The *purpose* of design science is to devise new or change human-made systems, such as technologies or organisations within a complex world with limited information to achieve specific preconceived results. The *view of knowledge* is pragmatic; knowledge needs to serve action. Normative and synthetic thinking are the foundations of knowledge creation. Participation and discourse are an integral part of creating interventions and pragmatic experimentation. The *objects* of interest, human-made systems, are meant to contain descriptive and imperative properties, targeting an ideal situation. *Theory development* focuses on creating and evaluating a set of alternative solutions to complex problems, with multiple stakeholders and a lack of information, through grounded technological rules (Dresch et al., 2015; Van Aken & Andriessen, 2011). In contrast to analytical sciences, DSR also focuses on developing *artefacts* to solve problems. These artefacts must be developed and justified by both practice and theory (A. Hevner & Chatterjee, 2010). Artefacts in DSR can be produced in different forms and shapes, as long as they improve situations towards the desired states or theory. Artefacts can be physical constructs, models, methods or instantiations (March & Smith, 1995). Typical examples of artefacts are products, technologies, organisational designs, computational models, conceptual models, and working procedures.

Learning and designing through collaborative modelling and simulation methods

In line with the spirit of design science research, collaborative modelling and simulation methods facilitate hybrid learning in multi-actor stakeholder environments (Voinov et al., 2016; Voinov & Bousquet, 2010). These methods do not merely explain historical events from cases. They also provide opportunities to explore and learn about the dynamics of multi-actor industrial symbiosis networks in multiple possible futures (Batten, 2009). According to numerous scholars, collaborative modelling and simulation efforts and activities support both the researchers and the participating stakeholders (e.g., Chu et al., 2012; Holtz et al., 2015; Voinov et al., 2016). Thus, from a DSR perspective, we can consider the model as the artefact that facilitates problem-solving and theory development (Venable, 2006). In general, participation in modelling enables stakeholders to make decisions, increase knowledge among the stakeholder group through social learning, and increase the model validity in terms of quality, acceptance and integration of cross-sectoral perspectives (Hare, 2011). For example, during such a modelling process, stakeholders are pushed to identify and define concrete and latent assumptions regarding actor behaviour in transition processes (Holtz et al., 2015). By doing so, participating researchers and stakeholders reach consensus or identify disagreements and understand the broader effects of their decisions, providing solutions. Thus, the evolving models facilitate the dialogue between different perspectives (Holtz et al., 2015), making it possible to understand mechanisms in systems that are yet to be realised.

We thus presumed that collaborative modelling and simulation methods could offer opportunities to experiment with circular business models before implementation.

Scholars in the domain of socio-technical systems modelling use several terms for stakeholder involvement. The main reason for this is that different stakeholder motivations, expectations, levels of engagement, and activities can be applicable (Basco-Carrera et al., 2017; Voinov et al., 2016). In their study, Chu et al. (2012) present a methodology for the participatory design of an agent-based model. Barreteau (2003) also included simulation in the process by coining the term companion modelling: "*a cycling approach, in interaction with field processes, including discussion of assumptions and feedbacks on the field process*". More recent work by Smetschka & Gaube (2020) shows how participatory modelling can move the research process beyond transdisciplinary and interdisciplinary boundaries. Some scholars strictly distinguish between collaborative and participatory modelling, for example, by classifying stakeholder involvement into types and degrees of participation (e.g., Basco-Carrera et al., 2017; van Bruggen et al., 2019). This study recognizes the opportunities for collaborative and participatory modelling and simulation methods to create knowledge and solutions for viable and robust industrial symbiosis. However, we do not aim to contribute further to the theoretical development of typologies of approaches with stakeholder involvement. Hence, we refer to *collaborative or participatory modelling methods* instead of participatory (or collaborative) modelling in this thesis to avoid any confusion.

1.1.7 Knowledge gap

Given the need for a swift transition towards the circular economy, it is crucial to support the development of viable and robust industrial symbiosis networks. Merely analysing existing networks is insufficient: stakeholders who aim to become part of industrial symbiosis need to know where and how to intervene. The mechanisms and impact of their behaviour on the performance at both individual and network levels need to be understood to make informed decisions. In addition, novel circular business models need to be designed, bearing in mind that changes may occur in both environment and actor behaviour. Collaborative modelling and simulation methods in multi-actor learning settings offer opportunities to this end. These methods can support researchers, practitioners, educators, and students in exploring pathways towards robust industrial symbiosis networks. Currently, these methods and accompanying models are lacking.

1.2 Research objectives and questions

1.2.1 Relevant theoretical fields

This dissertation supports understanding and shaping industrial symbiosis to speed up the circular economy transition. Based on the background study of section 1.1, this work brings together three theoretical perspectives: design science research, complex adaptive socio-technical systems, and circular business model innovation, see Figure 1-1.

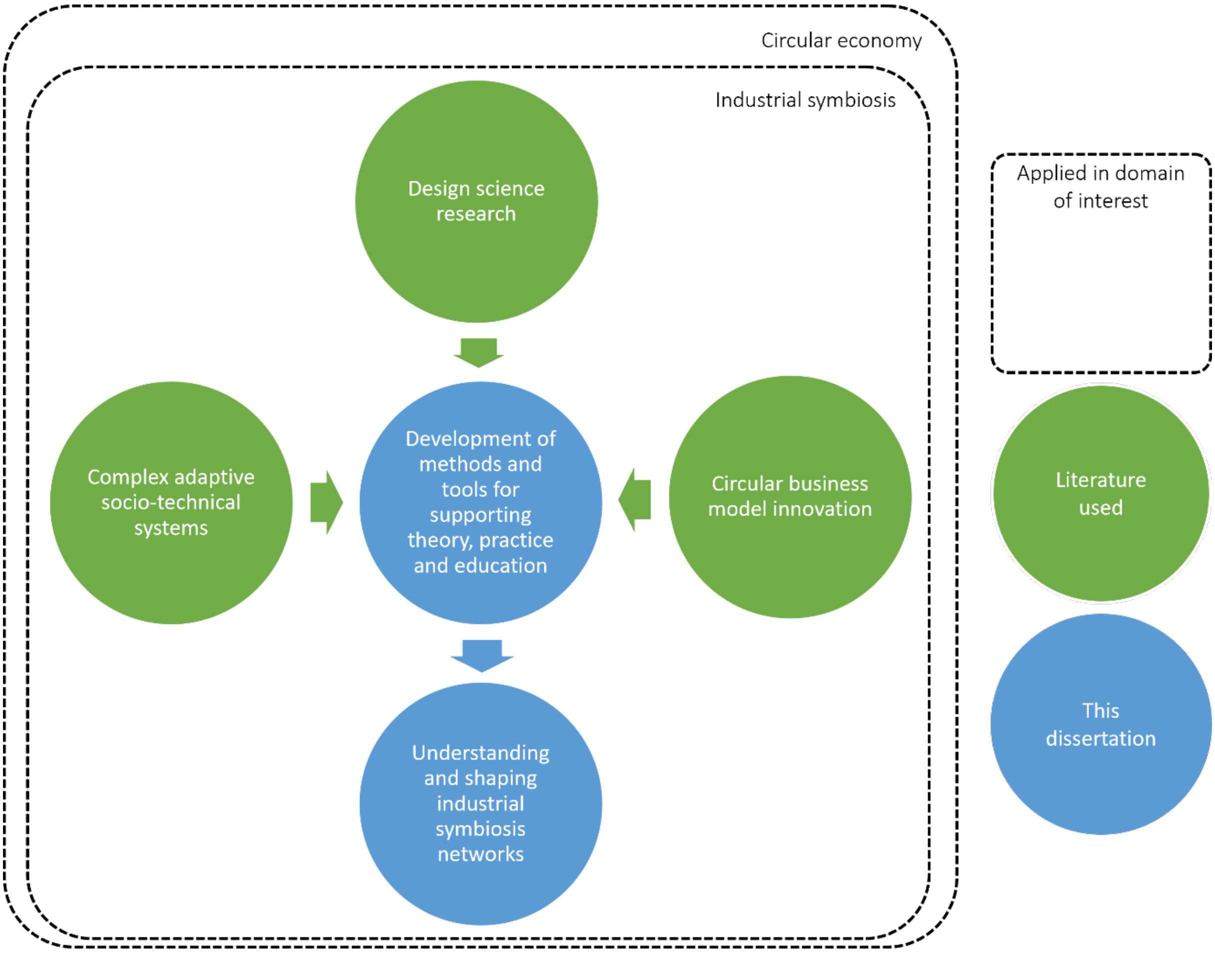

Figure 1-1 Relevant theoretical perspectives applied within industrial symbiosis and circular economy research domains.

Design science research

Design science research is prescriptive, aiming to develop knowledge and solutions by using and creating artefacts. Combining knowledge and solution development from grounded theory and stakeholder involvement serves theoretical rigour and practical relevance. DSR contributes to gaining context-specific insights on the efficacy of design interventions such as organisational changes and technological innovation (Denyer et al., 2008; Dresch et al., 2015; Van Aken & Andriessen, 2011).

Circular business model innovation

Design interventions for industrial symbiosis require an understanding of actors, technologies and accompanying actions and interactions. The required knowledge transcends businesses, traditional supply chains and even industries or sectors (Bocken et al., 2015). Business models describe a firm's organisational and economic design, providing insights into how companies create, deliver and capture value (Teece, 2010). Hence, network-level business model innovation is considered a key pathway for the transition towards a circular economy (De Angelis, 2016; Schenkel et al., 2015). To shape robust ISNs, business models that serve the individual and network levels must be redesigned and tested. Literature about circular business model innovation provides qualitative frameworks for designing network-level business models, which can be co-created and tested in design science research (Baldassarre et al., 2019).

Complex adaptive socio-technical systems

Most research on circular business model innovation and experimentation drew on empirical and qualitative design research. These studies merely provide knowledge limited to the cases (Yap & Devlin, 2016). Literature on complex adaptive socio-technical systems provides compelling socio-technical modelling and simulation methods and tools. Simulation tools such as agent-based modelling enable computational experimentation with design interventions, actor behaviour, and contextual boundary conditions, i.e., Monte Carlo simulation (Van Dam et al., 2013). Developing and using socio-technical modelling and simulation for business model innovation offers opportunities to gain more generic insights on the efficacy of design interventions under uncertain conditions.

1.2.2 Research objectives

Following the knowledge gap and theoretical perspectives, the main goal of this research is:

"To develop methods and tools for understanding and shaping viable and robust industrial symbiosis networks."

This dissertation aims to create the following contributions:

- insights into the complexities and dynamics of industrial symbiosis networks, their constituent actors and technologies;
- methods, models and simulation tools to enable researchers, practitioners, and educators to collaboratively design and explore business models aiming for viable and robust industrial symbiosis;
- recommendations for using and furthering the methods, models and tools to improve circular business model designs in multi-actor learning environments.

1.2.3 Research questions

As stated in the knowledge gap, business model innovations, behaviour of actors, and the environment are three essential elements that determine the successful implementation of robust symbiosis networks. However, the role and relationships among these elements have not been well understood until now. Methods and tools are needed to deepen knowledge about these elements and broaden design competencies that address these elements. We derived four questions to guide our research to reach our main research goals.

To identify which literature is relevant, we employ a research method to guide us in studying and improving industrial symbiosis networks (company networks aiming for closed and narrowed material cycles) using collaborative modelling and simulation methods. Hence, our first question is:

> **RQ1: What collaborative modelling and simulation method can facilitate designing business models for viable and robust industrial symbiosis networks?**

Next, using such collaborative modelling and simulation methods, we aimed to understand the complex mechanisms in ISNs and their constituent actors to determine how these affect the robustness of the networks. Our second question is:

> **RQ2: How do network and actor behaviour affect the robustness of industrial symbiosis networks during implementation?**

The third question addresses the assessment of network-level business model designs that aim to increase the robustness and viability of industrial symbiosis. Therefore, our third question is:

> **RQ3: How can circular business models for viable and robust industrial symbiosis networks be tested and improved before implementation through collaborative modelling and simulation methods?**

Lastly, we needed to show how collaborative modelling and simulation can support learning and designing ISNs. Consequently, our fourth question is:

> **RQ4: How can collaborative modelling and simulation methods support the learning of (future) professionals for improving industrial symbiosis network designs?**

1.3 Research design

This section introduces the general research approach, including the used methods for modelling and simulation and practical knowledge development. Then the research process and timeline are presented, including the connections between several studies, research questions and developed artefacts (models, methods and tools). Furthermore, an analytical framework is presented, which guides us in answering our research questions in chapter 6. The section concludes with a process overview and thesis outline

1.3.1 General research approach

The researchers, partners and students followed a design science research approach and iteratively explored the ISN dynamics, created business model designs and assessed the efficacy of these designs on network robustness and viability. This process is illustrated in Figure 1-2.

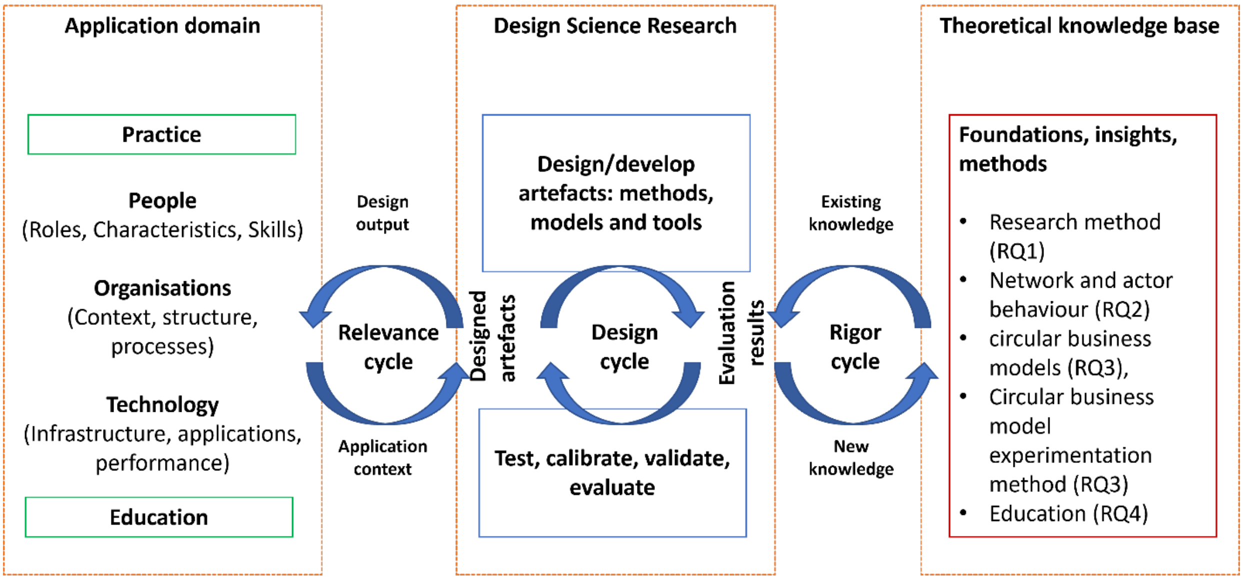

Figure 1-2 The design science research approach as applied in this dissertation, inspired by Hevner (2007).

Context, interventions, mechanisms, and outcomes as fundamental elements in design science research

In general, design science research aims to understand and develop four essential elements of the problem: Context, Intervention, Mechanisms and Outcomes or CIMO in short (Denyer et al., 2008; Holmstrom et al., 2014; Van Aken & Andriessen, 2011):

- The context describes internal and external factors that influence the behaviour of the system of interest.
- Interventions that stakeholders can impose on the system of interest, aiming to transform the system into the desired state.
- Mechanisms emerge as a result of the combination of context and interventions. In general, these are changes in interaction behaviour or interim states of actors and objects that affect the course of events.
- Outcomes emerge from the mechanisms imposed by context and intervention.

During design science research, these four CIMO elements are run through to iteratively explore, develop, evaluate, and redevelop knowledge and solutions.

Role of the researcher

Researchers in design science research (DSR) fulfil different roles than those in analytical research: they act both as observers and participants in the research process, facilitating a stakeholder discourse to create solutions. During the process, iterative analysis and synthesis steps are taken to simultaneously develop the problem description and matching solution(s) (Dresch et al., 2015; Rittel & Webber, 1973). While doing so, DSR researchers move in cycles between practical and theoretical knowledge flows, thus contributing to both practical relevance and scientific rigour.

Rigour and relevance

Design science research should always be performed with a strong emphasis on research rigour (Gibbert & Ruigrok, 2010) and practical relevance (Gregor & Hevner, 2013; A. R. Hevner, 2007). Objectivity is critical as the researcher has separate roles with different interests, such as facilitator, observer, analyst, modeller, student mentor, and client. Therefore, we used a mix of methods to decrease bias and increase both relevance and rigour:

- case and data triangulation: we use various cases and data sources to calibrate our models and simulation tools;
- method triangulation: multiple methods of data collection and analysis throughout the process. Examples of different collection strategies are interviews, surveys, observations and show and tell methods;
- artefact triangulation: we developed multiple artefacts to increase communicability among participating stakeholders;
- researcher triangulation: we aimed to decrease researcher bias by involving other researchers in interview sessions and students for data collection, modelling and data analysis;
- open-access publication of articles, data, models and tools to reconstruct the research process (Yin, 2009).

1.3.2 Collaborative modelling and simulation methods

Design science research aims to produce practical artefacts to find solutions for relevant and significant practical problems. In a scientifically rigorous and sound DSR, the designed artefact's efficacy, quality, and utility must be validated. Only if this is demonstrated to both theoretical and practical audiences, the artefacts enable us to expand our knowledge (Gregor & Hevner, 2013; A. R. Hevner, 2007). In this research project, the models and games for simulating ISNs are the artefacts that support knowledge development while solving problems. Each chapter explains how these artefacts are validated, elaborating their scientific, practical and educational value at the time of publication.

Here, we elaborate on two types of artefacts that allow for modelling and simulating complexity: agent-based models and serious games.

Agent-based models

Agent-based models (ABMs) are widely used to model and simulate complex adaptive systems. In ABMs, the interactions between autonomous actors and artefacts are modelled to enable dynamic simulation over time, allowing for heterogeneity and flexibility of subsystem agents and rules (Borshchev & Filippov, 2004). Despite the advantages of using ABM for modelling complexity, only a few ABM studies concerning industrial symbiosis have been conducted (Ajisegiri & Muller, 2020). The few existing studies indicate that agent-based models are powerful tools to facilitate the exploration and shaping of industrial symbiosis networks, e.g., Albino et al. (2016); Batten (2009); Camparotti (2020). Some scholars, however, also identified some disadvantages to ABM. For example, the process of agent-based modelling is very time- and labour intensive, and stakeholder participation requires stakeholders to commit to the research (Bas, 2017). In addition, model code may be difficult to communicate to stakeholders unfamiliar with programming.

Using serious games to facilitate collaborative agent-based modelling

To overcome barriers in communicating about agent-based models and their outcomes, simpler forms of communication during the modelling processes can be helpful. The advantage of using serious games is that it enables players to experience concrete and hands-on situations in a virtual world to create meaningful and desirable impacts in the real world (Susi & Johannesson, 2007). Serious games are widely used to solve complex problems in collaborative settings (Geurts et al., 2007). They provide a safe virtual learning environment and allow participants to make mistakes without risk (Tobias et al., 2014).

Several collaborative studies on other sustainability transitions used serious games and agent-based modelling, or combinations of both, e.g., Lagabrielle et al., 2010; Rouan et al. (2010); Simon & Etienne (2010); Souchère et al. (2010); Worrapimphong et al. (2010). Therefore, we decided to use a combination of these two types of modelling and simulation - ABM and serious gaming - as exemplary methods to understand and shape industrial symbiosis networks.

1.3.3 Practical knowledge development in the application domain

Case studies

In line with the purpose of design science research, we aimed to ensure that the research objectives and the developed artefacts remained relevant and that the stakeholders were committed to contributing to the research. To this end, we set up two practice-oriented research projects in which we based our research on questions from case study participants (Mulder et al., 2018, 2020). This section explains why the chosen cases were relevant to fit our research goals and how we collected data in these cases.

In the research projects, we executed three in-depth case studies involving networks of companies that aimed to exchange and process local organic waste (Mulder et al., 2018, 2020). In each initiative, the participants wanted to know which technologies should be used to turn waste into valuable resources. In addition, they asked what technology and organisational design was needed and to what extent the choice of partners in terms of collaborative intentions would affect the implementation and survival of the symbiosis initiatives. Two case studies primarily focused on creating concepts for a specific class of Industrial symbiosis Networks in the context of Urban Agriculture (Schrik et al., 2017), which we called Symbiotic Urban Agriculture Networks or SUANs (Lange et al., 2017). One case study involved a collective of creative pioneering and service companies situated in a former shipyard in Amsterdam (Lange, Korevaar, Oskam, et al., 2021; Mulder et al., 2020). In general, all cases were chosen because they aimed for economic and environmental impact through narrowing and closing organic material loops. The companies were geographically near each other but not yet working together in symbiotic relationships for value creation.

Although the research objectives addressed in this dissertation do not merely entail biobased materials, all our case studies involved solid organic waste streams from the (peri-) urban environment, such as pruning materials, grass cuttings and food waste. Here we explain why studying biobased material recovery is still representative for modelling and simulating symbiosis.

Biobased materials cycles in industrial symbiosis and the circular economy

Scholars and professionals from various academic fields, such as urban planners, economists, and agronomists, identify the recovery and reuse of organic waste flows, also known as the biobased or biotic circular economy, as one of the main priorities (e.g., Agudelo-Vera et al., 2012; EMF, 2013; European Commission, 2014, 2020). There are several types of biobased materials, such as sewage streams, agricultural waste, and food waste. In the Netherlands alone, 1,5 million tons of organic waste is annually collected from households and companies and processed in 26 bulk conversion systems (i.e., anaerobic digestion and composting) (Rijkswaterstaat, 2014).

Biobased streams are produced by many diverse actors, varying from the food and beverage industry, the paper industry and agriculture to households. Hence, organic waste has a heterogeneous chemical composition. The quality of the waste is often fluctuating and low (Vereniging Afvalbedrijven, 2013, 2014, 2015) since the total quality of the waste in a treatment plant depends on the most inferior quality of input. Incineration and conversion into compost and biogas for energy are the most common types of organic waste treatment (Vereniging Afvalbedrijven, 2013, 2014). The composition of solid organic waste is highly variable, but it generally contains crucial elements for food production, such as carbon, nitrogen, phosphorus and potassium. The access, use and disposal of these elements are closely related to various environmental and social issues. For example, disturbances in the earth's nitrogen cycles negatively affect the natural environment, human habitat and health

(Gu et al., 2012). Closing carbon and nitrogen cycles and recovering phosphorus are top priorities for global sustainable food production. Developing systemic solutions to exploit recovered nutrients from solid organic waste is thus evidently crucial for a sustainable society (Bastein et al., 2013; European Commission, 2020).

Organic material cycles are highly relevant to achieving circularity. However, the high variety of material quality and quantity, combined with low economic value, creates challenges for businesses to create viable and robust value chains. Most circular business practices (PBL Netherlands Environmental Assessment Agency, 2021, p. 141) and education programmes (Ellen MacArthur Foundation, 2021) focus on elements of the technical cycle. Our three case studies face additional economic viability, complexity, and knowledge development challenges. Therefore, we considered these cases as representative examples of challenging industrial symbiosis networks in the making.

1.3.4 Educational knowledge development

In this dissertation, we integrated education with the development of the facilitation methods and tools for industrial symbiosis by creating thesis assignments on modelling and simulation and data collection and business modelling at the university. These assignments were given to students in Master’s and Bachelor’s degree courses at a university of technology and a university of applied sciences. In case we needed knowledge on biobased materials and processes, we set up student collaborations with ‘green’ universities and education programmes. Furthermore, we created assignments for data science students to contribute to our data analysis. Vice versa, based on the methods and tools devised in this research, we iteratively developed, improved, and tested teaching materials. By doing so, the research activities benefited from and delivered to education.

1.3.5 Research process

Figure 1-3 shows the studies we performed and how these studies were related to the research questions.

Study 1 entailed a literature review to explore what method could provide prescriptive knowledge that facilitates designing viable and robust industrial symbiosis networks, thereby answering research question 1.

The second and third studies both entail the development of simulation models and methods to capture the dynamics and complexities of our case studies. Study 2 focused on understanding the behaviour of ISNs and their constituent actors through the collaborative development of an agent-based model, contributing to solving research question 2. During the study, a business game was developed to facilitate the communication process during modelling with stakeholders. It used the research method from study 1 to build and simulate the model.

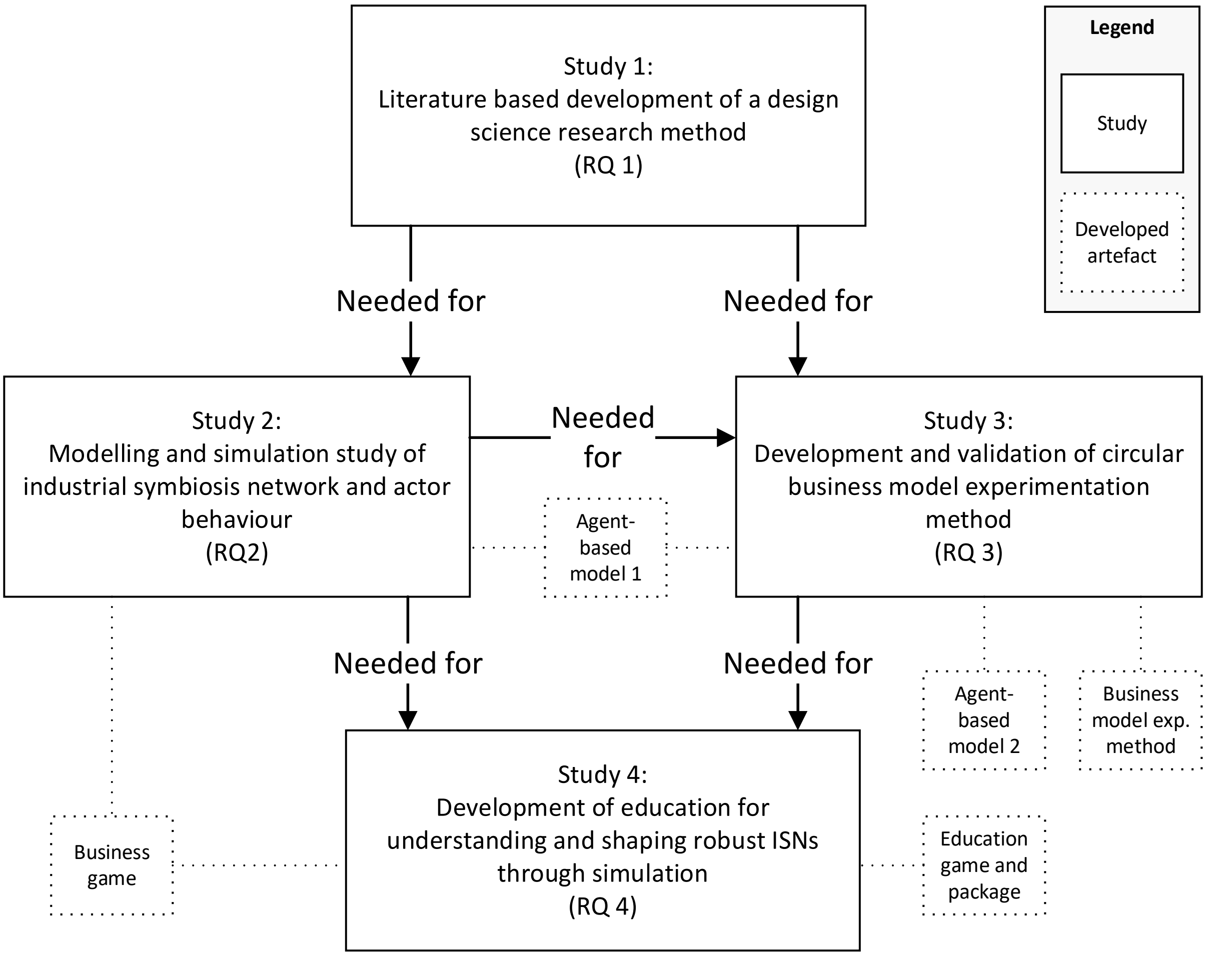

Figure 1-3 Studies and their relations to the research questions (RQ) and developed artefacts.

Next, the model from the second study was iteratively redeveloped and used to create a new agent-based model. This model was used for developing an ex-ante experimentation method in study 3. This study aimed to explore how businesses can manage uncertainties and improve circular business model viability, bearing the complexities and dynamics of ISNs and their actors in mind. Thereby study 3 built upon studies 1 and 2 and contributed to answering research question 3.

Study 4 contributed to research question 4. Using simulation methods, it aimed to show how current and future professionals can be supported in the ISN design process. A business game developed to facilitate case study participants in exploring opportunities for symbiosis was redeveloped into an education game package for teaching circular business model innovation.

Appendix A provides a detailed timeline overview of the research process.

1.4 Analysis

Although there is no single formal definition agreed upon, analytical frameworks are generally considered effective and valuable for organising research by structuring a researcher's thinking and supporting logical thinking in a systemic manner (Coral & Bokelmann, 2017; Ostrom, 2009). Analytical frameworks can therefore be helpful to reflect upon how research is conducted, order the study results and check whether the scope of the study is met.

Many frameworks in the domain of design science research, such as those from Hevner (2007) and Van Aken & Andriessen (2011), position the researcher in and between theory and practice. However, these frameworks were not meant to include the role of education. In line with our primary research objective (section 1.2), stating that there is a need for swift knowledge development in education, we propose an analytical framework that includes this knowledge flow, as seen in Figure 1-4.

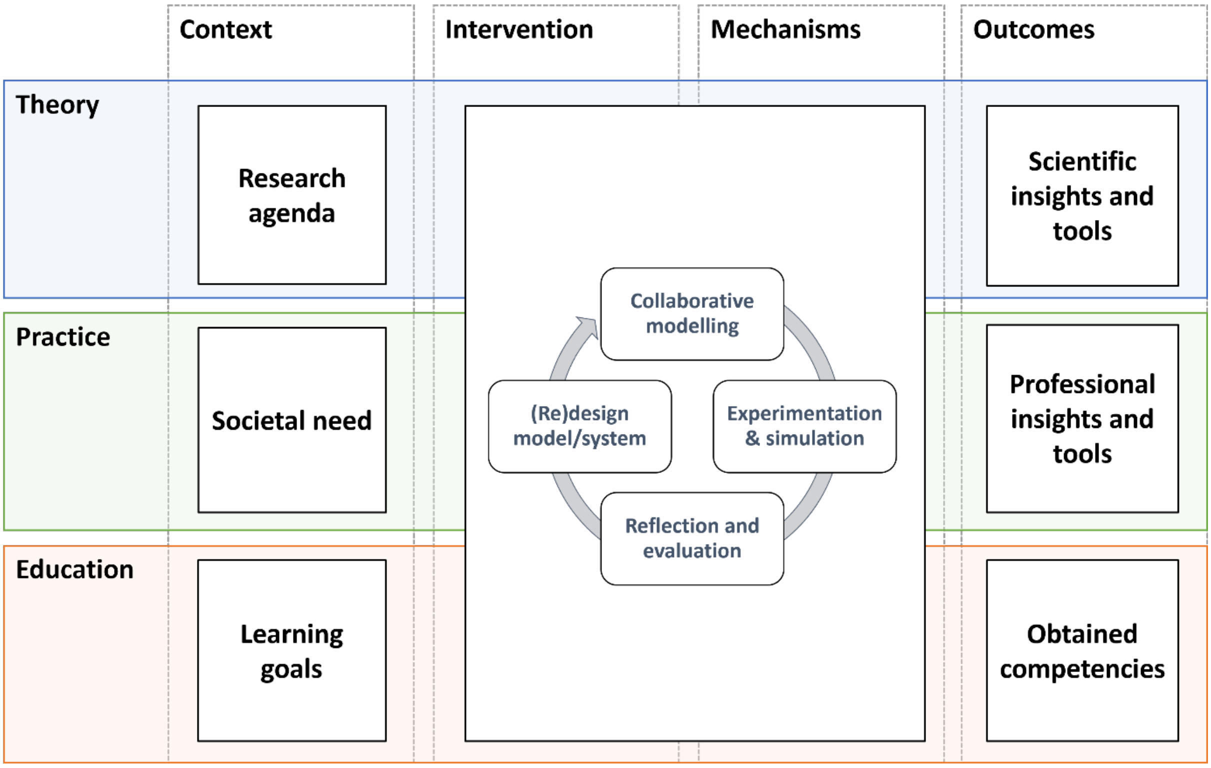

Figure 1-4 The proposed analytical framework.

The framework represents iterative and simultaneous knowledge and solution finding by collaborative modelling and simulation and its contributions to the three knowledge flows – theory, practice, and education – following CIMO logic. Hence, the framework consists of two axes covering the main elements of our research:

1. The x-axis shows how the CIMO-logic (section 1.3.2) is embedded in the design science research process.
2. The y-axis shows how the knowledge evolves from the three perspectives theory, practice, and education.

In chapter 6, we used the framework to visualise how and to what extent our studies covered the key research elements, which supported us in answering each research question.

1.5 Dissertation structure

The structure of this dissertation follows the studies as presented in section 1.3.5.

Chapter 2 contains a literature review study to explain why a design science research approach is needed for understanding and developing industrial symbiosis networks. The study presents a case study, a research approach with research topics relevant to designing viable and robust ISNs.

An agent-based model and its simulation outcomes are presented in chapter 3, using the case study provided in chapter 2. The model offers insights into the effect of individual actor behaviour on the robustness of industrial symbiosis networks (chapter 3).

Based on the agent-based model of chapter 3, a new model was iteratively constructed in chapter 4 and validated with a different case study. The study presents an approach to performing ex-ante circular business model experimentation.

During agent-based modelling, we codeveloped a serious game with experts to help practitioners explore possibilities for symbiosis. Chapter 5 describes how we iteratively redeveloped the serious game to teach students about circular business model innovation.

Chapter 6 comprises conclusions using the analytical framework as presented in chapter 1 and discusses the contributions to theory, practice and education. Furthermore, it includes reflections and recommendations.

2

Study 1

Developing and understanding design interventions in relation to industrial symbiosis dynamics

This chapter[1] explores what method provides prescriptive knowledge for designing robust and viable industrial symbiosis networks (RQ1). Private stakeholders face difficulties in the implementation of industrial symbiosis. Their challenges are attributable to the complex and dynamic nature of the context, i.e., the environment in which the industrial symbiosis networks operate and the various roles, stakes and opinions of the participating stakeholders. Therefore, companies need to understand how and to what extent technological and organisational designs and interventions contribute to robust and viable symbiosis. Most existing research on designing industrial symbiosis networks originated from the field of Industrial Ecology, mainly providing design knowledge based on historical data from specific cases. This approach often resulted in knowledge with limited relevance to other cases and contexts.

Based on literature from design science research, complex adaptive systems modelling, and participatory modelling methods, this chapter proposes a conceptual Design Science approach, aiming to develop an empirically grounded and tested agent-based model with stakeholders. This model aims to enable exploring design rules under varying circumstances in which industrial symbiosis networks run. It offers opportunities to explore the efficacy of industrial symbiosis designs more generically. The approach is illustrated using a case study of networked stakeholders in an urban agriculture area, which in this chapter is referred to as a Symbiotic Urban Agriculture Network (SUAN).

This study complements the existing analytical work in Industrial Ecology by adding a Design Science approach, thereby bridging the gap between industrial symbiosis dynamics theory and practical complex design issues. It proposes a methodical approach to gain insights and design viable and robust industrial symbiosis networks.

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[1] This chapter was published as: 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.

The first author conceptualised and performed the research. The other authors had an advisory role. Several textual edits have been made to ensure alignment of the published paper into this dissertation.

The original article contained a research agenda, which is currently outdated. Therefore, we have removed the research agenda and references to it to avoid confusion with the research topics addressed in chapter 1. The initial research agenda can still be found in appendix B.

2.1 Introduction

Urban planners, economists, and agronomists identify the recovery and reuse of organic waste flows, the biotic circular economy, as one of the main priorities to foster a transition towards a circular economy (Agudelo-Vera et al., 2012; Bastein et al., 2013; EMF, 2013; European Commission, 2014; Hajer & Dassen, 2014; McKinsey Global Institute, 2011). User-driven, self-organising, and decentralized symbiotic networks are emerging, in which stakeholders are aiming to create economic, environmental, and societal value by closing materials, energy, and water loops (Schenkel et al., 2015; Weijnen et al., 2004). A specific type of symbiotic network is being developed for closing loops in Urban Agriculture. In principle, Urban Agriculture discerns itself from traditional agriculture by its embeddedness and interaction with the local or nearby urban metabolic flows, i.e., by in-situ or nearby organic waste processing and reuse of urban nutrients, materials, water, and energy (RUAF Foundation, 2016). Based on the study of Mougeot (2000, p.10), we define Urban Agriculture (UA) as follows: *"UA is an industry located within (intra-urban) or on the fringe (peri-urban) of a town, a city or a metropolis, which grows or raises, processes and distributes a diversity of food and non-food products, (re-)using largely human and material resources, products and services found in and around that urban area, and in turn supplying human and material resources, products and services largely to that urban area"*.

The need to develop closed-loop systems in Urban Agriculture is stimulated by the idea that a multi-objective business model is crucial to making Urban Farming economically, environmentally, and socially sustainable (Koppius et al., 2011; Metaal et al., 2013; Schenkel et al., 2015). This chapter focuses on reusing organic waste, such as vegetable waste from (peri-) urban agriculture, forestry, and food production, processing, and consumption. Although it is already regularly technologically and economically feasible, these types of urban organic waste flows are not often treated as a valuable local source for new materials and energy, e.g., through composting or biodigestion (Bastein et al., 2013; European Commission, 2014; McKinsey Global Institute, 2011). Urban Agriculture stakeholders are reluctant to change the technological and organisational design of the system because they lack knowledge of the effect of these design interventions in combination with uncertain events that may occur in the system. These stakeholders hesitate because of uncertainties regarding their financial viability (Fichtner et al., 2005; Metaal et al., 2013). A relevant field of literature for this research topic is Industrial symbiosis (IS). IS aims to understand how collaboration between traditionally separate but geographically proximate economic industrial agents may contribute to closing material, water, and energy cycles (Chertow, 2000). Chertow (2000, p. 313) states, *"The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity"*. Gibbs & Deutz (2005, p. 542) add that Industrial symbiosis projects *"must be designed to allow for a gradual approach, and each phase needs to be financially viable"*. While looking at the definition of Urban Agriculture from the perspective of IS, it is quite evident that an urban farm, a location where Urban Agriculture takes place, can be considered a specific type of eco-industrial agent. Such an agent interacts with nearby partners within the urban ecosystem, thus creating what we will call a Symbiotic Urban Agriculture Network (SUAN). These SUANs facilitate local production and use a combination of crops, materials, water, and energy through a strategy of optimal high-value multi-sourcing, cascading, reuse, and recovery. The composition of organic waste changes quickly due to biological processes (e.g., decay or fermentation) (Pfaltzgraff et al., 2013). Hence, Industrial symbiosis, focusing on a decentralized and local approach, appears to be particularly promising for agile and high-value reuse and recycling of organic waste. In practice, this implies that SUANs are dynamic networks consisting of actors executing nearby separation and collection of organic waste and local cascading and/or processing into valuable resource materials or energy.

In the real world, SUANs, and other symbiotic networks, are continuously developing over time; for example, stakeholders enter or leave the SUAN or change their roles, organisational structure, and use of technologies. Symbiotic networks are considered socio-technical Complex Adaptive Systems (Dijkema & Basson, 2009). Complex Adaptive Systems are defined as systems that consist of heterogeneous components that adapt as they interact (Boons et al., 2014; Chertow & Ehrenfeld, 2012; Holland, 2006; Spekkink et al., 2016). Bauer and Herder define socio-technical systems as systems where *“technology is central for their operations”* (Bauer & Herder, 2009, p. 602). Dijkema & Basson (2009) consider the socio-technical system a dynamic, complex system that consists of both a technical and a social network that interacts with a continuously changing context. Therefore, a particular strand of IS literature studies IS dynamics; it conceives IS as a interact (Boons et al., 2014, 2016; Chertow & Ehrenfeld, 2012; Spekkink et al., 2016). The recent comparative framework by Boons et al. (2016), which provides a set of IS dynamics typologies, is based on historical data. According to Yap & Devlin (2016), historical data from case studies provide an initial common explanation. However, it gives no insights into IS dynamics in new case studies since different combinations of factors lead to different network behaviour. Hence, the analytical research approach can benefit by adding a prescriptive approach, in which we can build on an understanding of how certain events and actions influence the IS network development in specific contexts.

Design Science is particularly useful for prescriptive driven design issues (Denyer et al., 2008). Scholars widely accept participatory methods in modelling as ways to encourage co-evolutionary learning among stakeholders during the process of designing context-specific solutions (Hare, 2011; Holtz et al., 2015). As a result, to improve the understanding of technological and organisational design intervention effects in symbiotic networks, we propose to combine literature on IS dynamics with methods and perspectives from Design Science and participatory modelling. In this chapter, we do so by studying the literature from these three fields of literature, IS dynamics, design science research methods, and participatory methods in modelling, and by proposing an iterative design science research method.

This research contributes to understanding IS dynamics by bridging the gap between history-based IS dynamics theory and design intervention issues in current and future case studies. The study, therefore, provides a literature-based conceptual Design Science method, illustrated with a practical agricultural network example in the city of Amsterdam, The Netherlands.

2.2 SUANs, Complexity and Design Interventions

This section starts with defining the newly introduced concept of SUANs, being a suitable case for improving insights on design mechanisms and outcomes in technological innovation and organisational structures in IS dynamics. Then, we explain the role of design interventions in IS dynamics. In the following sections, we elaborate on the concepts of Design Science and participatory methods in modelling. Finally, the state-of-the-art IS dynamics will be discussed on applicability from a design science research perspective, and a novel conceptual research method will be presented.

SUANs are heterogeneous: there are different types of urban, industrial, and civil actors involved, as well as a variety of material, energy, and information flows (e.g., food, wood, leafy greens, compost, biogas, digestate). Both quantity and quality of these flows are essential aspects that influence the reuse potential in terms of business value.

We created a simple model of flow exchanges between actors in SUANs, including their resources and waste flows (see Figure 2-1). We used the conceptual frameworks of Despeisse et al. (2012) and Leigh & Li (2014) as a source of inspiration and literature by Bastein et al. (2013) and Metaal et al. (2013) on respectively urban organic material loops and Urban Agriculture. Note that actors can play more than one role within the network. For instance, a restaurant owner may simultaneously act as a food processor and a distributor; or an urban farmer may also act as a waste processor when using composting heaps or biodigesters. It is important to note that the actors in Figure 2-1 do not represent the exhaustive set of stakeholders involved in influencing the SUAN's dynamics.

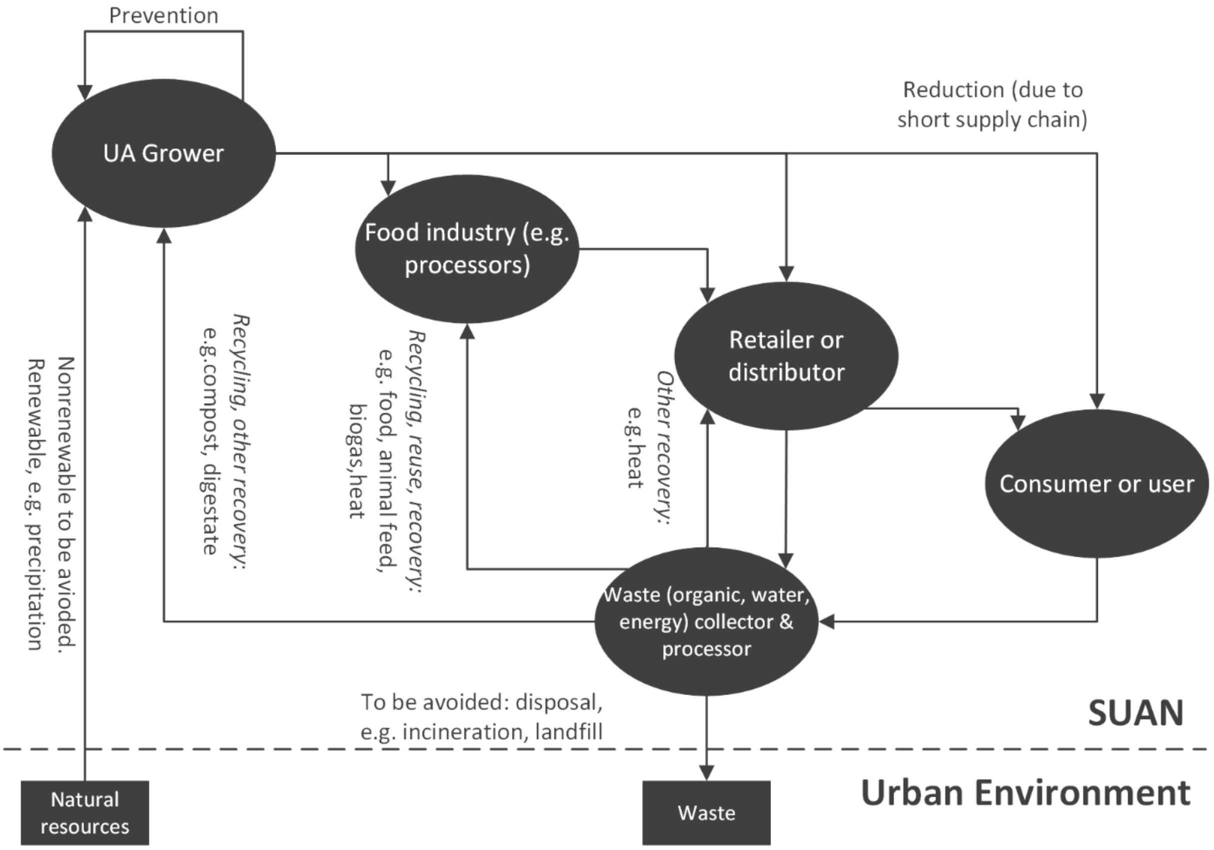

Figure 2-1 Simple generic model of day-to-day resource and waste flows in a Symbiotic Urban Agriculture Network. SUAN = Symbiotic Urban Agriculture Network.

In this research, the concept of industrial symbiosis as a socio-technical Complex Adaptive System is studied from a design perspective and the traditional explanatory approach. Transforming analysis methods into design interventions regarding economic and sustainable development in practice is an essential aspect of the field's right to exist (Graedel & Allenby, 2010). In line with Pugh (1990), we define design interventions as *the systematic set of technological and non-technological activities that intend to impose a change from the existing* *situation to the desired situation*. This definition of design interventions explicitly recognises and accepts that emergent and disruptive contextual behaviour may occur; sudden changes in the context may influence the effects of the design intervention in an unintended way. Therefore, this definition distinguishes itself from comprehensive design or planning, of which Desrochers states that it "is unlikely to live up to the expectations of its proponents" (Desrochers, 2001, p. 1099).

2.3 Design Science, Modelling and Stakeholder Participation

Many studies on the concept of IS can be considered analytical and description-driven, whereas explanatory sciences aim to describe, explain, or predict phenomena. Typical examples of the analytical approach in industrial symbiosis dynamics can be found in explanations through ex-post evaluations of the development of symbiotic systems (e.g., in single case studies or generic comparative studies). The analytical sciences provide explanations through causal models through hindsight. Design science provides a set of alternative solutions through grounded technological rules (Van Aken & Andriessen, 2011).

Dresch et al. (2015, p. 59) define design science as *"science that seeks to consolidate knowledge about the design and development of solutions, to improve existing systems, solve problems and create new artefacts*". Design science research has also been termed practice-oriented, applied or evidence-based management research or innovation action research (Denyer et al., 2008; Holmstrom et al., 2014; Van Aken, 2004; Van Aken & Andriessen, 2011). These terms are all used for research in which prescriptive knowledge on solving practical problems is obtained through artefacts rather than providing generic explanations of phenomena through causal models. Dresch et al. (2015) emphasize that even though design science differs from traditional analytical sciences, they complement each other because of their different objectives. Design science aims to pragmatically develop grounded and tested solutions and rules for 'wicked problems': complex problems with little information available, multiple stakeholders including their plural and sometimes contradictory perspectives and goals and endless possible solutions (Dresch et al., 2015).

While in traditional science the researcher acts as an observer, in Design Science, the researcher instead participates by facilitating a discourse in which stakeholders strive for pragmatic solutions for a particular class of problems through iterative analysis and synthesis steps (Dresch et al., 2015). Hence, the problem description and matching solutions are simultaneously and iteratively developed in Design Science (Rittel & Webber, 1973). Four key concepts play a crucial role in Design Science: Context, Interventions, Mechanisms, and Outcomes (CIMO). An explanation of these key concepts is given in Table 2-1.

Table 2-1 Context, Interventions, Mechanisms, and Outcomes (CIMO) explained, inspired by Denyer et al. (2008), Boons et al. (2016), and Holmstrom et al. (2014).

Concept	**Explanation**
Context	Internal and external technical, economic, geospatial, and institutional factors and the nature of human actors influence the behavioural transformation of the socio-technical system.
Interventions	Interventions available within the power of the design participants, aiming to influence behavioural change of the socio-technical system.
Mechanisms	Mechanisms provoked by the design intervention in the specific context. For example, changes in interaction behaviour between agents or changes in interim states which influence the course of events.
Outcome	The outcome of the intervention in its (intended and unintended) aspects, such as the impact on environmental impact, network structure changes, or performance changes in terms of network function. In the case of SUANs (among other symbiotic networks), the intended outcome would be a network that creates business value through symbiosis.

Hypothesized and testable design propositions are a central component of iterative design science research methods (D. Jones & Gregor, 2007). A typical feature that contributes to the design process is the prescriptive design hypothesis consisting of CIMO-logic: *"Use for this type of problems within Context, this type of Intervention, for starting this Mechanism, in order to realize this Outcome"* (Denyer et al., 2008, p. 395). Applying a design hypothesis enables the reflection on possible mechanisms and outcomes that can be observed and evaluated through iterative and incremental design interventions in similar contexts (Holmstrom et al., 2014). According to Yap & Devlin (2016), the analytical approach to IS dynamics provides a scientifically sound explanation of historical events, but it has no predictive power. Although the Design Science approach does not offer comprehensive predictions on IS dynamics, it does contribute to gaining context-specific insights on how specific design interventions within the context influence the symbiotic network behaviour and vice versa. It also provides insights into behavioural changes in similar contexts, leading to empirical design rules for organisational changes and technological innovation (Denyer et al., 2008; Dresch et al., 2015; Van Aken & Andriessen, 2011). If a similar set of stakeholders turn out to be successful in multiple cases, it is likely to be successful in other similar cases as well. One might think about a particular group of stakeholders that are able to turn organic waste into a successful business case for local compost production. Modelling and simulation provide very powerful tools to play with network configurations, agent behaviour, and contextual boundary conditions, i.e., through Monte Carlo simulation (Van Dam et al., 2013).

Agent-based models (ABMs) are considered most suitable for modelling socio-technical Complex Adaptive Systems when (1) each actor acts autonomously, (2) subsystems operate in a dynamic environment, (3) subsystem (agent) interaction is characterized as flexible, and (4) agents are heterogeneous (Van Dam et al., 2013). Design interventions in the case of SUANs match these conditions, which is in line with a recent study on socio-technical aspects of agro-industrial ecological systems by Fernandez-Mena et al. (2016). Nevertheless, up to now, the amount of ABMs that can be found on the topic of industrial symbiosis dynamics is currently limited to a few: examples are Cao et al. (2009), Bichraoui et al. (2013), Ligtvoet (2010), and Batten (2009). Batten (2009, p211) states: *"The purpose of an ABM is not to predict the future but to explore the alternative futures that might develop under different conditions"*. ABMs enable us to show which transition pathways are likely to occur in specific design intervention scenarios and whether these pathways are stable or not. Thus, agent-based modelling is a promising tool for evaluating technological and organisational design decisions in symbiotic networks.

It is essential to build models that are accurate and transparent enough to increase insights, provide communication, and foster social, co-evolutionary learning (Batten, 2009). Participatory methods in modelling are particularly helpful in clarifying and identifying fundamental and latent assumptions and behaviour of real-life agents (Holtz et al., 2015). Other types of socio-technical Complex Adaptive Systems have successfully been developed and evaluated using participatory modelling techniques for ABMs, e.g., in resource and water management (Hare, 2011; Hare et al., 2003; Newig et al., 2008). However, we found only one article by Batten (2009) on participatory modelling of ABMs in IS. Participatory methods are suitable for Design Science: while the modelling participants iteratively impose design interventions, its mechanisms and outcomes are evaluated to develop generic knowledge further to resolve the problem. Considering the need for prescriptive knowledge on design interventions and coherent with observations by Holtz et al. (2015), Batten (2009), and Hare (2011), participatory modelling methods can be used to:

- facilitate stakeholder processes through social learning during the collective iterative modelling, simulation, evaluation, and reflection processes; and
- improve the model, e.g., for quality improvement, stakeholder acceptance, and system integration through active participation of stakeholders in iterative modelling, simulation, evaluation, and reflection.

Current analytical methods in IS primarily intend to understand organisational phenomena by uncovering general patterns and influences in industrial ecosystems through hindsight observations. We are convinced that understanding IS dynamics would benefit from a pragmatic approach through Design Science. Aiming to develop pragmatic grounded solutions simultaneously in running case studies will likely provide generic design rules that can be applied in different contexts. An iterative design science research method, using participatory methods to establish ABMs, is likely to contribute to scientific and practical knowledge development concerning technological and organisational design interventions in IS dynamics.

2.4 Conceptual design science research method development

Based on the literature review presented above, we expect that the Design Science approach helps scientists and practitioners to facilitate social learning processes among stakeholders in industrial symbiosis. In order to respond to this gap, we combined the participatory methods by Hare et al. (2003) and the agent-based modelling methods of Van Dam et al. (2013). We placed these in the context of the Design science research methodology by Van Aken & Andriessen (2011) and the CIMO-logic by Denyer et al. (2008), resulting in Figure 2-2. The proposed conceptual methodology shows that generic knowledge development is reached through an iterative multiple case study analysis. Each tab represents a single case study in which the design science research methodology is applied. In the model, CIMO logic is represented throughout the phases.

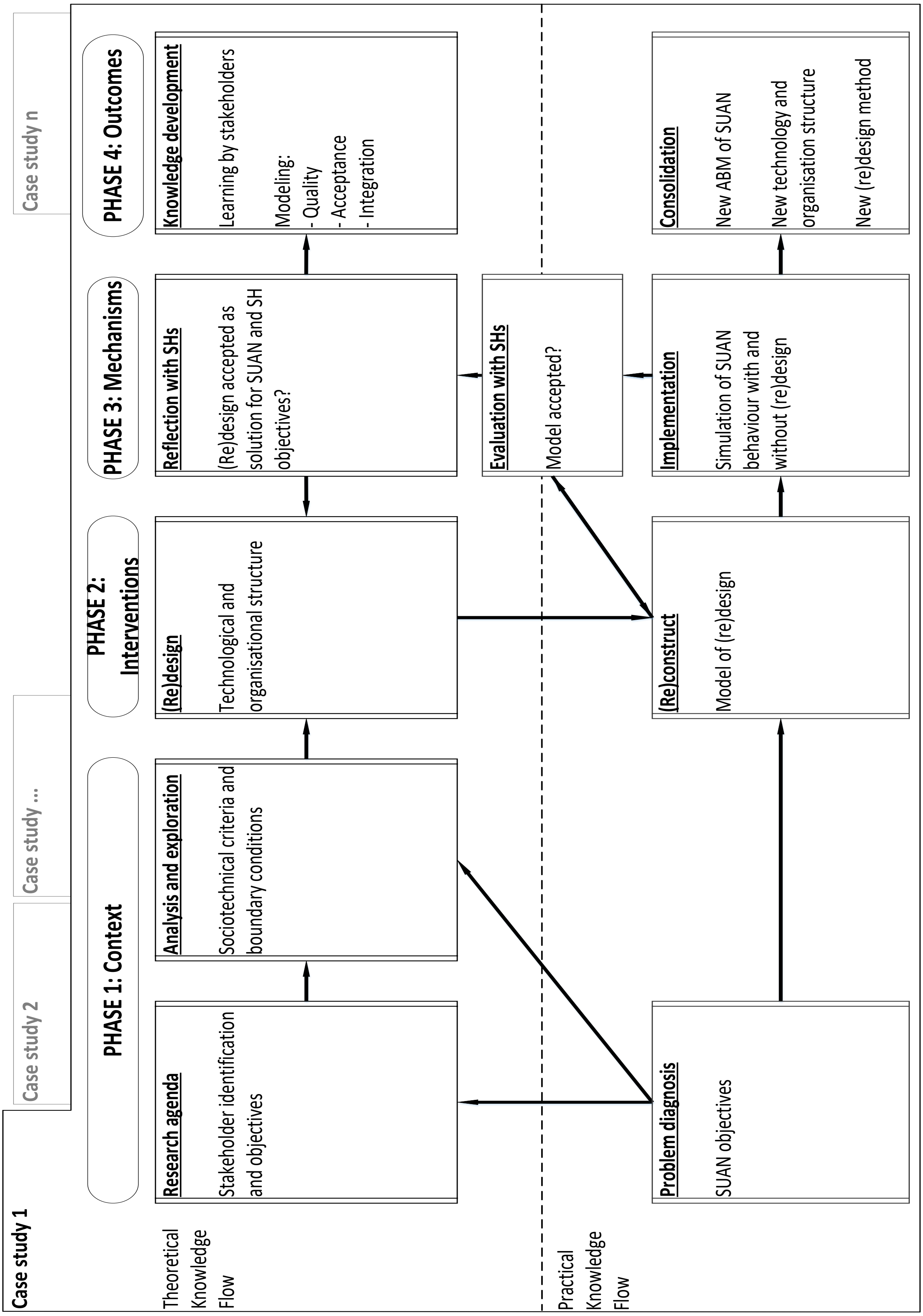

Figure 2-2 Conceptual design science research method for facilitation of design interventions regarding technology and organisational structure in SUANs. SUAN = Symbiotic Urban Agriculture Network; SH = stakeholder; ABM = Agent-based model.

Existing theories and methods from IS and IS dynamics help communicate, model, and analyse simulation results. Zhu & Ruth (2014) provide a method to translate three typologies (i.e., self-organisation, facilitation, and governmental planning) into simulated growth patterns in ABMs based on historical data. IS dynamics literature can therefore be used as a point of departure for basic assumptions on the behaviour of social agents. IS literature provides many analytical methods and indicators based on historical data that may be of use while analysing and evaluating the mechanisms and outcomes of the IS dynamics simulations. Zhang et al. (2015) did an extensive review of the theory and methodology of industrial symbiosis research. They provide an overview of theoretical frameworks, analytical methods, indicators, and examples useful during data collection and network development analysis. The researcher should actively select and present relevant information understandably to the participants to facilitate discussions on the simulated course of events. For example, Fichtner et al. (2005) provide an overview of personal, enterprise-level, and inter-organisational barriers that prevented stakeholders from closing loops in 25 historical case studies. These barriers may be helpful to consider as variables in the ABM. The researcher may use this knowledge to reflect on empirical data in the new case study and translate this into an initial set of agent states and rules. Then, the real-world stakeholders must be involved in an iterative validation of the model and reflect on the simulation results. If the model does not accurately simulate the real world, the model must be updated in terms of technical, geo-spatial, social, institutional, and economic conditions. If the stakeholders agree upon the accuracy and embeddedness of the model, the second question is whether the simulated mechanisms imposed by the design intervention lead to the desired outcome. Comparative IS dynamics typologies such as those perceived by Boons et al. (2014) may help communicate the simulation results to the stakeholders. Along the process, the researcher or facilitator observes the participation process during concept evaluation through the development and use of an ABM. It will result in insights into the role of design interventions (connected to participatory agent based modelling) and on institutional learning during this design process.

To conclude, we define design interventions in IS dynamics as: “the systematic set of technological and non-technological activities that intend to inhibit and support the physical and social growth and development of symbiotic networks”. This definition does not explicitly include any exceptions on who is performing the design intervention activities. It implies that design activities may mainly be executed by independent stakeholders (e.g., in self-organisation), facilitators (e.g., knowledge institutes, governmental, or private facilitators), or external planners (e.g., governmental command and control). In order to provide empirically grounded design intervention rules in the context of IS dynamics, we argue that the field of IS would benefit from iterative studies that use the Design Science approach.

2.5 Case Study

This section describes a case study to give illustrative insights into applying the proposed methodology. Our project 'Re-Organise' aimed to stimulate the collaboration between local small and medium-sized enterprises (SMEs) and higher education institutions. The proposed methodology was fully implemented during the project at SUANs in Amsterdam, The Netherlands (Mulder et al., 2018). One particular consortium of companies consists of SMEs located on the fringe of Amsterdam West. The goal for the stakeholders was to critically reflect on design scenarios around the organisational network structures regarding the use of new biodigestion systems.

The area consists of several urban farming companies for local production (e.g., local to local vegetable production, fruit gardens, and beekeepers), food service, the hospitality industry (e.g., cafes and restaurants) and a sustainability consultancy and networking company. Farmers produce vegetable and animal products for the local market, such as food service companies in and just outside the area. The companies need energy products for cooking and heating and material products, such as fertilizers and animal feed. The site has a rich development history and is therefore dependent on a heterogeneous group of internal and external stakeholders, such as multiple departments of the city of Amsterdam, the municipality of Haarlemmermeer, the Province of Noord-Holland, several regional water authorities, private companies, such as Schiphol Group, and civilians.

The intended mutual stakeholder dependency was to become cooperative. For example, some parts of the area were owned by public stakeholders. These public institutions intended to give the farmers the right to maintain the area while handing over local resources (e.g., grass, wood). This dependency could also become competitive: some internal and external parties, for example, wanted to expand at the expense of the current landowners. The design science research of this case study followed the phases of Figure 2-2: Context, Intervention, Mechanisms, and Outcome. We here describe what the CIMO logic looked like in this particular case study.

<u>Phase 1: Context</u> started with gaining insight through a series of unstructured and semi-structured interviews with initially committed stakeholders (Mulder et al., 2018). For stakeholders interested in participation, the available technologies, business activities, input and output flow, geospatial information (e.g., location, size, and type of terrain) and institutional factors (e.g., relevant legislation, taxes, subsidies, area development plans) were collected. The previous activities resulted in practical individual questions around stakeholder problems and opportunities regarding the socio-technical aspects of the current technologies and organisational structures (see Table 2-2).

Table 2-2 Initial questions by stakeholders involved at the SUAN in Amsterdam West (Circle Economy et al., 2015; Gemeente Amsterdam, 2014; Mulder et al., 2018).

Stakeholder	Practical question
Fruit garden owner	"What is the quantity and quality of the products (biogas, digestate) produced by my biodigestion system, and how can I use this technology to meet the market's demands to improve my revenues?"
Sustainability consultant	"Which ecological and economical business values and usage possibilities can be identified? How should the stakeholders in the area work together?"
Urban farmer	"To what extent is my company able to work together with surrounding companies to close organic nutrient and waste loops? How can we systematically accomplish this? What costs and benefits are involved?"
City of Amsterdam	How to facilitate a transition to closed-loop systems for a maximized eco-efficiency and economic value through recycling and upcycling, particularly in the food sector?

An initial practical diagnosis of a research agenda was set up by combining keywords in Table 2-2. We formulated a case-specific question that was shown to and approved by all stakeholders after several iterative steps (Mulder et al., 2018): "*Can we process and reuse the local organic waste in a decentralized biodigestion system to increase economic and ecological value?*" Then, materials, water energy and information demands and supplies were mapped using material flow accounting methods. Data was iteratively collected from existing geographic and commercial data on materials, stocks, processes and symbiotic potential, in-situ observations, and interviews during day-to-day handling. The individual questions and the mapped data were translated into a case-specific description of the SUAN's objectives through iterative brainwriting and participatory meetings. It resulted in a prescriptive design hypothesis: "*Use biodigestion systems to produce and exchange local biogas and fertilizers from public, private, and civil organic waste to realise the economic value and soil improvement for the stakeholders*".

In phase 2: Interventions, the case-specific information on and demand and supply potentials of relevant organic materials (e.g., tons/month), water (e.g., tons/month), and energy (e.g., kWh/month) for biodigestion was used to develop a socio-technical design through stakeholder participation. In addition, inspired by the work of Boons et al. (2016) and Zhu & Ruth (2014), IS dynamics typologies were used to propose initial states and rules in model agent behaviour. It resulted in:

1. a list of relevant agents, including descriptions of their properties and behavioural rules regarding actions and interactions; and
2. a description of the environment and its interaction with the agents.

The agents, behaviour specifications, and environment description are checked for approval with the stakeholders through showing and telling and were put in a schematic model layout for further development of the ABM, using the methods of Van Dam et al. (2013). Table 2-3 shows the steps for building an ABM, including the extent of stakeholder participation and the intended result. This ABM was used to experiment with case-specific design interventions: different plausible organisational structures concerning implementing decentralized biodigestion systems.

Table 2-3 ABM modelling steps, inspired by Van Dam et al. (2013).

Step	Methods	Intended Result
Concept formalization	Iterative model conceptualisation and show-and-tell participation methods	A precise description of the conceptual model: software data structure, ontology
Model formalization	Iterative model conceptualisation and show-and-tell participation methods	Model narrative and pseudo-code (who does what and when)
Software implementation	Software choice Software model	Software model
Model verification	Iterative model testing, debugging, single-agent interaction, multi-agent interaction	Tested model
Experimentation	Scenario building and experimentation. It may include the effect of a specific organisational or technological design in different contexts. Such as worst-case scenarios in internal (e.g., bankruptcy) and external factors (e.g., disruptive technology)	ABM scenario simulation of the socio-technical system

In phase 3: Mechanisms, first, the model was evaluated on quality, such as accuracy, acceptance by stakeholders, and system integration (completeness) based on the theory by Hare (2011). It led to an additional model improvement step, for example, a more accurate description of the context or intervention. Once the model was accepted, the stakeholders participated in an interactive reflection of the simulation results to improve the mutual understanding of the design intervention effects concerning the intended SUAN scenarios. Depending on the model's results or the lessons learned, phase 1 or 2 was iteratively repeated, until the end of the project, ending with phase 4.

As Boons et al. (2016) described, the emerging mechanisms took the form of typologies and could be evaluated in terms of a series of events. During the participatory modelling of the system, the stakeholders were allowed to steer the intervention between facilitation and self-organisation or governmental planning. The model helped them understand which dynamic was most appropriate in their case. The researcher was to conclude how the dynamics have been interpreted over time and resulted in the desired design outcome. For example, the events that occur in simulated mechanisms can be described using the institutional levels of Williamson (1998) and Bauer & Herder (2009). It contributed toward understanding how interventions shaped the network within the abilities of the SUAN stakeholders. These iterative design optimization steps took place in phase 4, but only after the acceptance of the model.

In phase 4: Outcomes, the lessons learned were used as a learning tool for optimization experiments by practitioners in the specific case. Phase 4 allowed for simulating contextual adjustments over time, investigating whether the design intervention remained pragmatically valid in terms of the intended outcome despite emerging contextual changes. For example, reasons for discontinuance could be simulated. The ABM allows for studying the gradual effect of both the context and design interventions on network collaboration and individual financial viability. These indicators remain crucial to successfully implementing symbiosis (Gibbs &

Deutz, 2005). If combined with other cases, the case-specific outcomes may lead to generic recommendations for improvement of participation and modelling methods or even the methodology as a whole. In addition, the ABM can be used to set up a generic ABM for SUANs, which may be helpful for modelling and social learning in other cases.

2.6 Concluding Remarks

In order to advance the facilitation of design interventions in dynamic symbiotic networks, a literature-based design science research method for further method development was proposed in this chapter. The study complements analytical work based on historical data by adding the Design Science approach that bridges the gap between IS dynamics theory and practical complex design issues. This method provided a different understanding of mechanisms and outcomes through ABMs based on literature and new empirical data. The methodology, therefore, led to improved insights into IS dynamics and its typology arrangement. In addition, it provided a way to take technological and organisational design interventions and complex institutional behaviour into account.

In general, design science research methods are promising for uncovering prescriptive knowledge on design interventions for IS. It is important to note that the research using this method does not result in a single comprehensive set of rules that leads to the successful development of IS networks. However, the research contributes to the development of design rules for different cases in which contextual similarities and differences may be identified, and the effect of interventions may be evaluated.

From a societal perspective, the different types of stakeholders, with their different perspectives and aims, wish to translate the knowledge of IS dynamics into grounded and tested design rules instantly. We believe that the Design Science and participatory ABM perspectives may contribute to a broader understanding of meeting these societal demands. We are also convinced that participatory modelling methods are likely to encourage potential participants to engage in IS because of their power to elicit discussions among the participants. In addition, the approach may contribute to other fields as well, for example, by adding the newly developed design intervention facilitation method for participation in modelling to existing methodologies in the field of participatory urban planning or resource management.

To conclude, this chapter shows how design science research methods combined with participatory modelling can provide practical and theoretical knowledge on IS dynamics. The generic agent-based models developed in the following chapters were built using this method. These provided more precise insights on how network environment, actor behaviour and interventions in business model design influence IS dynamics.

3

Study 2

Actor behaviour and robustness of industrial symbiosis networks: an agent-based approach

In practice, industrial symbiosis networks (ISNs) regularly fail when partners leave and residual streams remain unrecovered. Regarding the current societal need for a shift towards sustainability, ISNs should not fail. Failures of ISNs may be caused by environment dynamics and actor behaviour, leading to unanticipated economic losses. This chapter[2] *explores the effect of these behaviours on ISN robustness by using an agent-based model (ABM).*

Using the proposed design science research method from chapter 1, a business game (see chapter 5) and an agent-based model were constructed based on insights from both literature and participatory modelling in three real-world cases. The chapter focuses on the agent-based model and simulation results. Although initially, the case participants were interested in studying biodigestion (chapter 2), this agent-based model eventually simulated the implementation of synergies for compost production from local waste. The Theory of Planned Behaviour (TPB) was used to model agent behaviour in time-dependent bilateral negotiations and synergy evaluation processes. We explored model behaviour with and without TPB logic across a range of possible TPB input variables. The simulation results show how the modelled planned behaviour affects the cash flow outcomes of the social agents and the robustness of the network.

The study contributes to the theoretical development of industrial symbiosis research by providing a quantitative model of all ISN implementation stages, in which various behavioural patterns of entrepreneurs are included. It also contributes to practice by offering insights on how network dynamics and robustness outcomes are related to context and ISN design, and actor behaviour (RQ1 and 2).

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[2] This chapter was published as: Lange, K.P.H., Korevaar, G., Nikolic, I., Herder, P.M., 2021. 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.

The first author conceptualised and performed the research. The other authors had an advisory role. Minor textual edits have been made to ensure alignment of the published paper into this dissertation.

3.1 Introduction

Within the context of the circular economy, self-organised industrial symbiosis networks (further abbreviated as ISNs) have gained much interest in science and practice as a means to increase social, environmental and economic sustainability (Ghisellini et al., 2015). Firms within ISNs exchange information, materials and energy to primarily create economic benefits while also contributing to sustainability (Chertow, 2000; D. R. Lombardi & Laybourn, 2012).

ISNs consist of social entities and technical objects, such as waste streams, contracts and technologies, which are interdependent and evolving over time (Mannino et al., 2015). Technologies, business models, policies and actor behaviour affect the emergence, growth and decay of ISNs. Only a few types of ISNs can be successfully sustained (Yap & Devlin, 2016), and for example, small networks are particularly vulnerable to falling apart (Tudor et al., 2007). The most successful ISNs are generally self-organising networks (Chertow & Ehrenfeld, 2012).

Understanding the behaviour of firms improves the effectiveness of decision making in the transition towards circular systems (Verzijl et al., 2019). Therefore, the behaviour of firms is increasingly being studied in the context of ISNs, e.g., by Spekkink et al. (2016).

This study aims to explore under which conditions, how and to what extent the robustness of ISNs is influenced by actor behaviour during the implementation of by-product exchanges in ISNs. It is built upon key elements that determine ISN dynamics and survival: this concerns all stages of industrial symbiosis implementation from the perspective of each firm in the network, including actor behaviour.

Since real-world experimentation is impracticable for exploring many parameters and actor behaviours, we have used agent-based modelling to explore this relationship. Compared to other methods, agent-based modelling is particularly suitable for studying complex cooperation dynamics among firms (Bonabeau, 2002; Giannoccaro, 2015). To adequately capture the real-world dynamics of interactions among ISN firm representatives, we have utilized a participatory modelling process in multiple real-world case studies.

3.2 Background

Following the key elements indicated above, this section discusses the importance of each firm's perspective, modelling all stages of industrial symbiosis implementation and understanding how actor behaviour affects network performance.

3.2.1 The firm's perspective

In self-organising industrial symbiosis, companies are the key players determining implementation dynamics (Tao et al., 2019). Each company plays at least one, but possibly more roles, such as waste supplier or processor (Mulder et al., 2018). Economic costs and benefits firstly accrue to the firms and then to the network (Chertow, 2000). When costs for individual firms are too high or their benefits too low, they tend to pull out, resulting in a higher probability of other firms leaving the network. This failure phenomenon has a severe negative impact on the survival probabilities of ISNs (Wang et al., 2017; Zeng et al., 2013). ISN dynamics are strongly determined by the decisions of individual firms (Tao et al., 2019). Hence, reasoning from the individual firm’s perspective is crucial to shaping ISNs towards a robust state.

3.2.2 Modelling all ISN implementation stages

Academic literature suggests that the development of ISNs should be considered a process based on broad economic, environmental and social aspects (Chertow & Ehrenfeld, 2012; Lambert & Boons, 2002). Based on the experience of ISN firms, Tao et al. (2019) developed such a broad ISN implementation framework from the perspective of firms. According to this framework, ISN firms go through the following stages: [1] awareness, [2] planning, [3] negotiation, [4] implementation and [5] evaluation. However, existing studies that model ISNs address the implementation stages only partially. Zhu & Ruth (2013, 2014) explored ISN evolution under different external disruptions and institutional settings. Mantese & Amaral (2017, 2018) used an ABM to study ISN indicators. Bichraoui et al. (2013) explored several scenarios of cooperation and learning in the context of ISNs. Albino et al. (2016) explored the role of contracts. These papers all touch upon ISN implementation stages 2, 4 and 5, excluding the awareness and negotiation stages. Zheng & Jia (2017) explored opportunities for closing loops by using innovation diffusion theory in their model. This work includes the awareness stage but excludes negotiation.

Some existing ABMs regarding ISN development include negotiation but exclude other stages such as awareness or evaluation. Examples of these studies are the energy system model by Batten (2009), the industrial coal system model by Gang et al. (2014), the biogas network model of Yazan et al. (2018), the strategic cooperation model by Yazan et al. (2020), and the model of the construction material recycling network by Knoeri et al. (2014).

3.2.3 Actor behaviour

The behaviour of actors in firms plays an essential role in ISN formation, development and survival. Among others, Krueger Jr. et al. (2000) show that representatives of firms that engage in industrial symbiosis act as entrepreneurs and tend to behave in a planned and informed way. The Theory of Planned Behaviour (TPB) proposes a model that describes how individual actors can make informed decisions (Ajzen, 1991). In TPB, actors show a behaviour which is described by three variables: the Attitude (abbreviated as A), the belief of other actors’ approval called the Subjective Norm (SN), and the perception of being able to implement their intentions, the Perceived Behavioural Control (PBC). According to Ajzen (1991), the Behavioural Intention (BI) of an actor encapsulates PBC, A and SN. In addition, BI is an indicator of behavioural performance (B) if the behaviour can be decided as planned (Ajzen, 1991). TPB is regarded as a significant predictor of entrepreneurial intentions and behaviour (Iakovleva & Kolvereid, 2009; Kautonen et al., 2013) and has been used in many studies to clarify this behaviour (e.g., Iakovleva & Kolvereid, 2009; van Asselt et al., 2012). It is also used to study the firm’s efforts to take environmental measures (Sánchez-Medina et al., 2014) and explore its readiness towards the circular economy (M. P. Singh et al., 2017). Ghali et al. (2017) show that TPB can be used to model the development of self-organised industrial symbiosis as randomly pre-defined synergies between pairs of actors.

3.2.4 Knowledge gap, study objectives and contribution

Interest in the effect of actor behaviour on the ISN evolution is growing among ISN practitioners and researchers. Echoing the recommendations in research by Ghali et al. (2017), there is a need for comprehensive models that enable us to study ISN dynamics and failure mechanisms from behavioural and contextual perspectives.

Our study brings together theory from behavioural sciences and industrial symbiosis into an agent-based model (ABM). Since ISNs involve real-world stakeholders, the ABM is grounded on literature findings and discussions with stakeholders in our case studies to increase the realism and verifiability of the model narrative, the chosen variables, and inputs. Thus, we show how an agent-based modelling and simulation approach allows us to study the effect of behaviour across all ISN implementation stages of Tao et al. (2019).

3.3 Conceptualising a Model Using Case Studies

We executed three in-depth case studies with stakeholders in ISNs in Amsterdam, the Netherlands. Each case involves the exchange and processing of organic waste within collectives of companies. Organic waste treatment is particularly interesting for our study since it entails a changing seasonal supply quantity, physical degradation of the waste, and a heterogeneous chemical composition. It all imposes a dynamic supply in terms of quantity and suitability for the transformation process from waste to product. The participants wanted to know how their waste could be turned into valuable resources in each initiative. They also wanted to know to what extent the behaviour of potential partners in the ISN would increase or decrease the robustness of the ISN.

The first case involves a large-scale symbiosis network of around 700 hectares of agricultural area, situated directly in the polders on the outskirts of Amsterdam. The participating companies consist of 16 firms, such as small-scale arable farmers, livestock farmers, fruit growers, gardeners, allotment gardens, hospitality businesses, and offices in a nearby business park. Companies in the area maintain the publicly owned land. Annually, thousands of tonnes of organic material, mainly grass, reed and leaves, are removed from the area as waste. The companies are members of a business association which aims for sustainable entrepreneurship. Some prominent members of the association set up a composting collective when we performed our research. Since then, the collective has allowed for the storage and processing of 600 m^3 of organic materials (Mulder et al., 2018).

The second case involves a small-scale urban agriculture area focusing on sustainable food production and recreation. The area is situated in a former sports park area on the north side of Amsterdam. Along with other firms, small scale hospitality businesses, urban farmers, a beer brewer, a consultancy firm, a beekeeper, a carpenter, and a daycare centre are in the area. The firms are part of a foundation that aims to exemplify circular economy practices. In the area, tons of organic materials, consisting mainly of leafy greens, pruning residuals, and brewers' grains, leave the area yearly. Some small compost heaps have been set up to handle these residual streams and produce soil improvement material for their own use (Mulder et al., 2018).

The third case involves a business park in the former wharf area on the north side of Amsterdam's waterfront, the IJ. A foundation represents a few hundreds of SMEs in the creative and hospitality industry in the area. A smaller number of companies is also represented by an energy cooperation, aiming for local and renewable energy production. A few years ago, the foundation performed a study to explore the possibilities of setting up a network for anaerobic digestion (or biodigestion) to process the organic residuals into biogas. However, the biogas network never took off. The involved participants considered the network too small to establish a robust network (Mulder et al., 2020).

In all cases, we gathered information about waste streams, needs and motivations through stakeholder interviews. In the first two case studies, we developed a serious game in which stakeholders played their own role in the network and in which they had to set up new ways of connecting residual waste streams with their needs. We used the game and interview data to create the model narrative, describing how stakeholder awareness was raised, how possible synergies were planned, how negotiations took place, how deals were closed, and how the synergy was implemented (Mulder et al., 2018). The game was also used to cross-check the interview data (for example, demand and supply), which was used to parameterize the simulation. We iteratively conceptualized, formalized, implemented, and verified the model using the participatory method proposed in earlier work (Lange et al., 2017). In addition to the case study data, we used literature regarding the ISN implementation stages, bilateral negotiation tactics and planned behaviour to set up the model narrative, which was calibrated with stakeholders, market experts and peers in participatory workshops and interviews. Data from the first case study was used to define the moderating variables for this chapter's experiments regarding TPB.

3.4 Model

This section briefly presents our conceptual model and the agent-based model. An extensive description using the ODD protocol by Grimm et al. (2020), including source codes, flowcharts, input data, results, and analysis information, can be found in the repository, see appendix C (Lange, Korevaar, Nikolic, et al., 2021a).

3.4.1 Conceptual model

Figure 3-1 shows an overview of the conceptual model and how it is related to the ISN implementation stages as proposed by Tao et al. (2019).

The case studies involved local exchanges and processing instead of bringing the waste to a centralised incinerator. Hence, three types of social agents are implemented in the model: the waste suppliers (WS), the local waste processor (WP) and the external waste incinerator (WI). The social agents interact during (de-)implementation of symbiosis.

The awareness stage consists of waste created by the suppliers and the determination of the value of the waste. The planning stage comprises composting and selling compost by the waste processor. The suppliers that already have a contract with the local processor deliver the waste according to the contract. A critical restriction in the model is the maximum capacity of the local processor, which may, for example, be imposed by a hygiene policy. If the processor is not full yet, the waste processor agent invites supplier agents to negotiate a new contract. If an agreement is concluded, this new contract directly results in waste exchanges between the waste supplier and the processor during the implementation stage. Another essential factor is *waste quality*, in our model defined as "*the fitness to process the waste*". Only if the waste quality is high enough the processor agent decides to use the waste for composting. In the final stage, evaluation, the waste supplier agents and the processor agent evaluate the outcomes and update their technical and behavioural parameters.

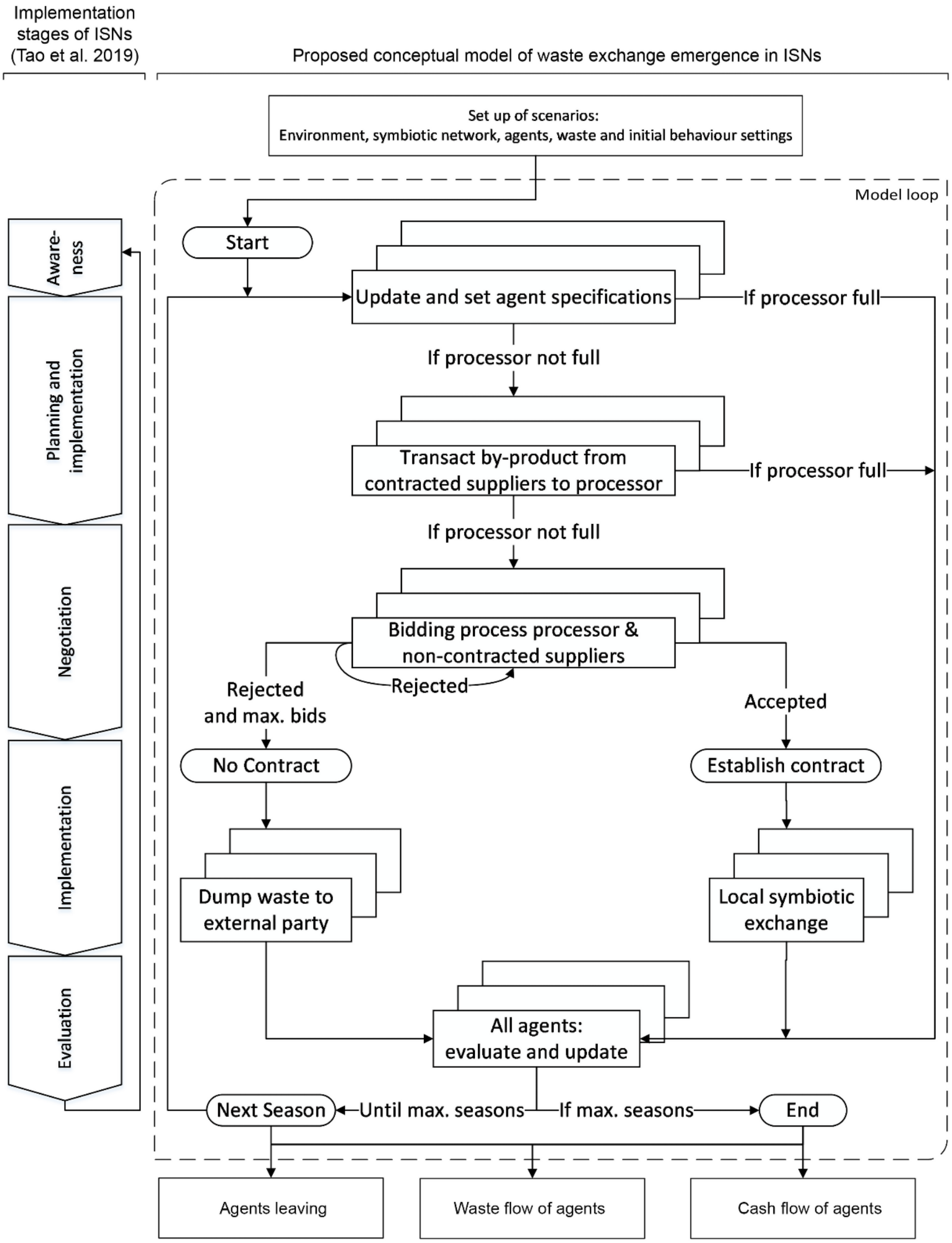


Figure 3-1 Overview of the model (right) compared to the industrial symbiosis implementation stages of Tao et al. (2019) (left).

Model assumptions (based on the cases):

- each social agent represents one actor's role. It means that different agents cannot represent the actors in our model;
- negotiations are bilateral;
- communication between suppliers and processor is honest and transparent;

- both parties agree upon the quality and quantity of the waste. However, the value of the waste is perceived differently;
- there are no intruders from outside the ISN. Hence, there is no network growth;
- WP and WS are allowed to leave the network. They do so when they consider the operational or economic results of symbiosis insufficient. External factors, such as bankruptcies, do not play a role in leaving the network;
- since the physical distances are less than 5 km, we assume these distances are negligible. Therefore, transportation costs or boundary conditions related to logistics are not modelled;
- after breaking open a fixed contract with WI, the waste supplier is allowed to negotiate and establish a contract with WP at any time;
- according to the contract, the waste transaction to WI and WP is unhindered and flawless. The contract between WS and WP allows WS to deliver a flexible amount of waste each season, up to a maximum agreed amount of waste. This maximum amount is based upon the amount of waste accepted when the contract was established;
- WP always accepts the agreed amount of waste when a contract is established. WP may redirect the waste to the incinerator based on capacity and waste quality;
- if WS can deliver more waste than agreed upon in the contract with WP, WS may enter another round of negotiations to establish an additional contract;
- after the contract between WS and WP expires, WS has to renegotiate a new contract with WP;
- contracts with WI make use of the waste market price;
- contracts with WI do not include a maximum agreed amount of waste; and
- all ripe compost is sold at a fixed market price.

The model allows for simulating this process with or without Theory of Planned Behaviour (TPB) algorithms to study the effect of planned behaviour. The behaviour of interest in this particular case is described according to Ajzen’s TACT elements (Ajzen, 2002, p. 2): *implementing a symbiotic link to exchange waste for composting during the next season(s), preferably for the creation of one’s economic benefits.* Figure 3-2 shows how the different TPB elements should be interpreted for this case.

Based upon interviews with case study participants and from the literature, i.e., Chertow (2000), we assumed that symbiosis primarily aims to create a competitive advantage. Thus, the model focuses on the effect of TPB on the economic results and vice versa, i.e., the effect of evaluating the economic outcomes on the behaviour of interest. In the model, each agent’s attitude, control belief, and subjective norm value affect the actors' intention and actual behaviour during the negotiation stage. In addition, the individual economic outcomes are assumed to influence the agent’s attitude, control beliefs and subjective norms during the evaluation stage.

3.4.2 Agent-based model

Based on the conceptual model, the ABM was constructed and verified according to Van Dam et al. (2013, p. 98).

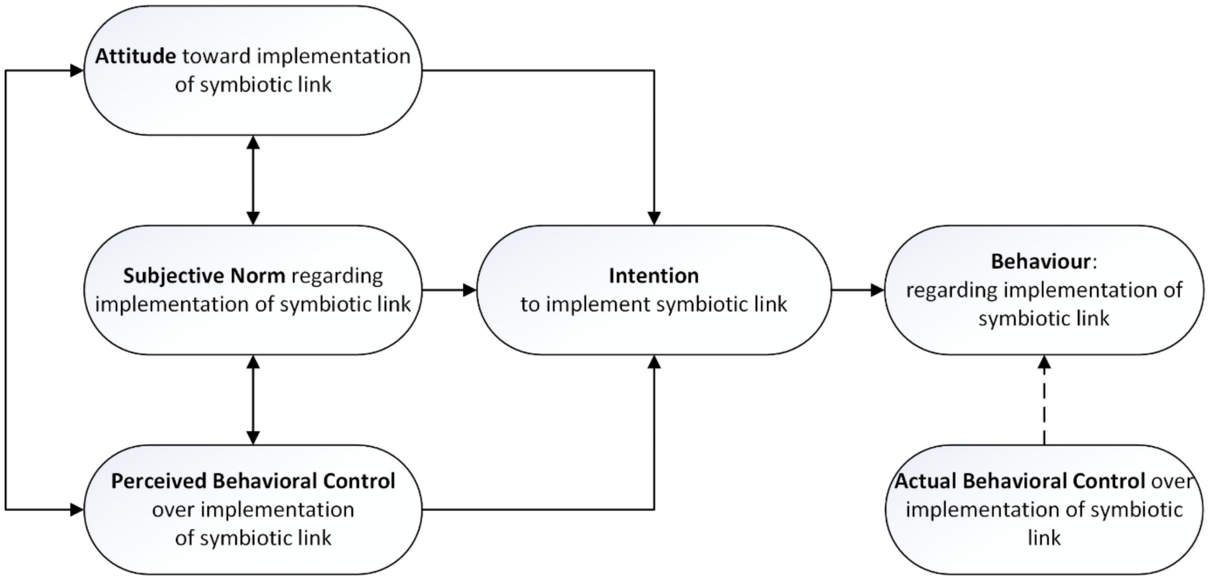


Figure 3-2 Use of TPB in the context of this study.

Given the *purpose* of this study, the TPB parameters can be adjusted freely to test different types of agent behaviour, and we also allow for model runs without this TPB implementation. The waste incinerator (WI) acts as the infinite sink of all waste flows in the external environment, so the social behaviour of WI is not included.

The *model dynamics and outcomes* are also affected by contextual factors and organisational design (Lange et al., 2017). The organisational design is modelled as technological and operational parameters, such as quality control, quantity control, or contract conditions.

Performance indicators in this study are the cash flows of WS and WP and the network's survival. Based on the experience of the case study participants, we considered a network to be robust when it was sustained for a minimum of 10 years. Waste supplier and processor agents that leave the network may cause a network to fail. Agents leave the network after many cumulative negative cash flows. The processor agent can also leave the network when the input is too low for half a year. Cumulative losses shape agent memory in our model. If an agent makes a profit due to local waste exchanges, the chance of leaving reduces over time since the agent 'remembers' that it previously made a profit.

The recursive model narrative, based on the implementation stages in Figure 3-1, and including the TPB implementation, is as follows:

1) <u>Awareness stage</u>: waste suppliers first produce waste and determine the waste value. This value depends on the type of organisational design set, either *waste-as-waste* or *waste-as-by-product*. When waste is treated as waste, the local waste value is determined by the global waste market price, the waste quality and the local availability during the season. We assume that if waste is treated as a by-product, it is seen as a source of income for the supplier. In that case, the price of a substitute product is used instead of the waste market price. WS makes efforts to increase the waste quality, resulting in an overall economic value increase. Based on the case studies, waste quality and quantity are set as normally distributed values.
2) <u>Planning & implementation stage:</u>
    a. The waste processor produces compost and sells it; see equation 3-1:

Eq. 3-1: $CF_{WP} = (\Sigma M_{CB} * P_{compost}) - (\Sigma M_{CB} * C_{proc} / A_{IO})$

in which:

CF_{WP}: Cash flow for WP

$P_{compost}$: Market price for compost per mass unit [Euro/tonne]

ΣM_{CB}: Sum of masses of ripe compost batches (heaps)

ΣC_{proc}: Processing costs per mass unit [Euro/tonne]

A_{IO}: Mass input-output ratio of conversion process

Each period, the compost heap ripens. Since part of the mass in the composting process is turned into gasses that are emitted into the air (Dhamodharan et al., 2019), the mass of the heap decreases according to a set input-output ratio. When the compost batch (CB) age equals the retention time, the batch is ripe and sold at the market price.

b. Transaction processes from contracted suppliers. WS is allowed to deliver less waste than agreed upon in the contract, but not more. Therefore, WP asks contracted suppliers if and how much they can deliver according to the contract. WP then checks the quality of the waste offered. To do so, WP compares the waste of the contracted suppliers by calculating which transaction leads to the highest economic waste stock value as perceived by WP (WV_{WP}). WV_{WP} is determined by the actual waste quality (Q_{WS}) and quantity (M_{WS}) each WS can offer at that point in time; see equation 3-2:

Eq. 3-2: $WV_{WP} = Q_{WS} * M_{WS}$

The contracted supplier with the highest WV_{WP} is permitted to make the first transaction. Next, the contracted WS with the second-highest WV_{WP} is allowed to transact waste to WP. This process continues until all contracted suppliers have delivered their waste according to the contract. The cash flow for WS is then calculated; see the transaction process equations in Table 3-1. Revenues and avoided costs are calculated as relative cash flows compared to bringing the waste to the incinerator. During the model setup, the cash flows are set at 0.

c. WP accepts all transacted waste. WS does not make (deliberate) mistakes in the delivery, and WP does not reject any waste of contracted suppliers. However, not all accepted waste is necessarily used for processing. During the waste acceptance process, WP first makes two decisions:
    i. WP determines whether the quality of the transacted waste exceeds a given threshold. WP redirects it to the waste incinerator (WI) if the quality is too low.
    ii. Next, WP determines whether its capacity is expected to be exceeded. WP only fills the compost heap up to the maximum capacity. If there is still some waste left, WP redirects it to WI.

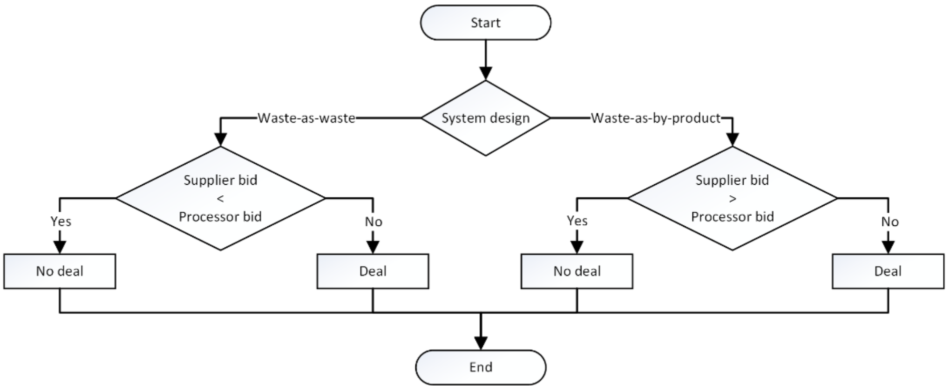
d. WP's cash flow is calculated; see the transaction process equations in Table 3-1. The revenues and avoided costs are calculated as relative cash flows, as these are compared to transactions with WI.

Table 3-1 Cash flow equations for the two different organisational designs during a waste transaction.

Agent	**Organisational design**	**Contract with incinerator**	**Eq.nr.**	**Cash flow calculation**	**Explanation of variables**
Waste processor	Waste-as-waste	WI payment per mass unit	(3-3)	$CF_{WP} = M_{WS} * P_{contract} - M_{WS} * P_{contract} * A_{IO} * (1 – RS_{wp}) + M_{WS,WP} * P_{waste} * (1 - CS_{WS}) - M_{WP,WI} * P_{waste}$	A_{IO}: processor mass input-output ratio CF_{WP}: Cash flow of WP [Euro] CF_{WS}: Cash flow of WS [Euro] CS_{WS}: Cost-share ratio assigned to WS [-] M_{WS}: Waste mass quantity from WS [tonne] $M_{WS,WP}$: Waste mass flow from WS to WP [tonne] $M_{WP,WI}$: Waste mass flow from WP to WI [tonne] $P_{contract}$: Agreed price for local waste treatment per mass unit [Euro/tonne] P_{waste}: Market price for waste treatment per mass unit [Euro/tonne] RS_{wp}: Revenue share ratio assigned to WP [-]
		WI payment per season	(3-4)	$CF_{wp} = M_{WS} * P_{contract} - M_{WS} * P_{contract} * A_{IO} * (1 – RS_{wp})$	
	Waste-as-by-product	WI payment per mass unit	(3-5)	$CF_{wp} = - (M_{WS} * P_{contract}) - M_{WS} * P_{contract} * A_{IO} * (1 – RS_{wp}) + M_{WS,WP} * P_{waste} * (1 - CS_{WS}) - M_{WP,WI} * P_{waste}$	
		WI payment per season	(3-6)	$CF_{wp} = - (M_{WS} * P_{contract}) - M_{WS} * P_{contract} * A_{IO} * (1 – RS)$	
Waste supplier	Waste-as-waste	WI payment per mass unit	(3-7)	$CF_{WS} = -(M_{WS} * P_{contract}) + M_{WS} * P_{contract} * A_{IO} * (1 – RS_{wp}) + M_{WS,WP} * P_{waste} * CS_{WS}$	
		WI payment per season	(3-8)	$CF_{WS} = -(M_{WS} * P_{contract}) + M_{WS} * P_{contract} * A_{IO} * (1 – RS_{wp})$	
	Waste-as-by-product	WI payment per mass unit	(3-9)	$CF_{WS} = M_{WS} * P_{contract} + M_{WS} * P_{contract} * A_{IO} * (1 – RS_{wp}) + M_{WS,WP} * P_{waste} * CS_{WS}$	
		WI payment per season	(3-10)	$CF_{WS} = M_{WS} * P_{contract} + M_{WS} * P_{contract} * A_{IO} * (1 – RS_{wp})$	

3) <u>Negotiation stage:</u>
   a. Based on its capacity, WP determines whether new suppliers are required. If so, WP checks which suppliers might potentially be interesting partners to negotiate with. The suppliers that are not bound to a fixed contract with the incinerator are asked how much waste they have available and at what quality. Again, WP determines which supplier is most suitable by calculating the potential economic value of the supplier's waste stock, see equation 3-2.
   b. A bilateral negotiation is started with the supplier with the best waste stock value. The negotiation process consists of two parties making alternating offers. Bidding occurs according to time-dependent negotiation, with a linear concession curve (Chongming Hou, 2004). In the *waste-as-waste* design, the model treats the waste supplier as a buyer and the processor as a seller of a waste collection service. In the *waste-as-by-product* design, the model treats the waste supplier as the seller, and the processor as a buyer of resource materials, see Table 3-2.

Table 3-2 Different agent roles and model algorithms for the waste-as-waste and waste-as-by-product designs.

		Waste-as-waste	**Waste-as-by-product**
Waste-processor	Role	Seller (of waste management services)	Buyer (of resources for production process)
	Aim	Target price as high as possible	Target price as low as possible
Waste supplier	Role	Buyer (of waste management services)	Seller (of resources for production process)
	Aim	Target price as low as possible	Target price as high as possible
Negotiation process			

During negotiations, buyer and seller determine their limit price based on the best alternative to a negotiated agreement (BATNA). When TPB is turned on, the behaviour value (B) modifies the limit price; see Figure 3-3 and Table 3-3.

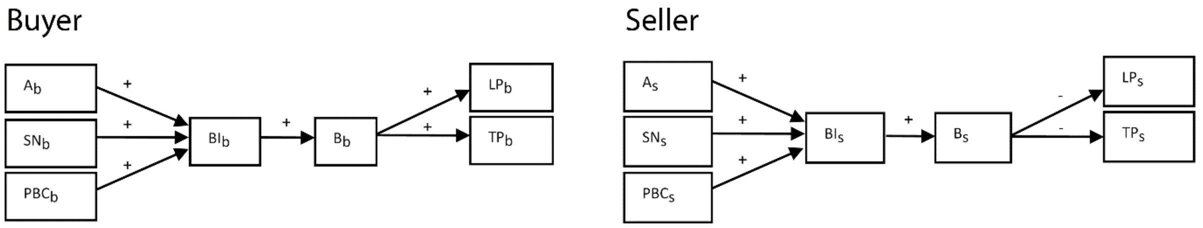


Figure 3-3 Influence of TPB-values on the limit prices (LP) and target prices (TP) of the buyer and the seller in the negotiation process.

Table 3-3 How the Theory of Planned Behaviour is integrated into the model's time-dependent negotiation.

Eq.nr.	**Main variable**	**Code**	**Values**	**Explanation**
(3-11)	Behavioural Intention (BI)	$BI = (A * W_A) + (PBC * W_{PBC}) + (SN * W_{SN})$	$0 \leq A \leq 1$; $0 \leq PBC \leq 1$; $0 \leq SN \leq 1$	Inspired by Ajzen (2002)
(3-12)	Behaviour (B)	If else BI >= 0.5 [let A ((10 + random 11) / 10) set B ((A * (BI - 0.5) ^ 2) + 0.5)] [let A -2 set B ((A * (BI - 0.5) ^ 2) + 0.5)]	$0 \leq BI \leq 1$	Sheeran (2002) points out a difference between intentions and behaviour. To address this gap, Webb & Sheeran (2006) showed that a medium-to-large change in intention leads to a small-to-medium shift in behaviour. A small change in intention hardly leads to behaviour change. Negative intentions are more correlated to negative behaviour than positive intentions to positive behaviour. Therefore, we modelled the relationship between BI and B as a randomized quadratic equation for positive BI values and a quadratic equation for negative values.
(3-13)	Buyer Limit Price (LP_B)	$LP_B = V_W + (V_W * (B_B - 0.5))$	$0 \leq B_B \leq 1$	V_W: Market value of waste or by-product [Euro/tonne] B_B: Behaviour value of buyer [-], inspired by Ajzen (1991)
(3-14)	Buyer Target Price (TP_B)	$TP_B = LP_B - 0.5\ LP_B$		Assumption
(3-15)	Seller Limit Price (LP_S)	$LP_S = V_W - (V_W * (B_S - 0.5))$	$0 \leq B_S \leq 1$	B_S: Behaviour value of seller, inspired by Ajzen (1991)
(3-16)	Seller Target Price (TP_S)	$TP_S = LP_S + 0.5\ LP_S$		Assumption

With B >= 0,5, a negotiating agent behaves more in favour of the opponent, trying to influence the achievement of local waste exchanges positively. With B < 0,5, the agent negotiates more firmly, negatively affecting the achievement of local waste exchanges. The target price depends on the limit price. We assumed that the target price of sellers is 50% higher than the limit price, aiming for higher income. The target price is assumed to be 50% lower than the limit price for buyers, aiming for lower purchasing costs.

   c. After the first bid, the opponent accepts or rejects the offer by comparing it to its own bid. If there is no deal, both agents make a new offer, which is one step closer to the limit price. WS and WP continue to negotiate until the maximum number of bids is reached, or a contract is established.
   d. The negotiation process is repeated for all potential WS partners unless the compost heap is full.

4) <u>Implementation stage:</u>
   a. When WP and WS reach an agreement, they establish a contract. The contract stipulates an agreed maximum waste delivery, price per mass unit and a contract duration.
   b. After establishing the contract, waste is transacted according to the contract. After this, monetary transactions take place. This process is similar to the steps described in step 1 and Table 3-1.
   c. All available waste that is not processed locally is sent to waste incinerator WI.
5) <u>Evaluation stage</u>:
   a. WS and WP evaluate the economic and operational outcomes (cash flows and processor use) and update TPB variables based on evaluation variables (E); see Table 3-4 and Table 3-5.
   b. Based on the outcomes, WS and WP decide whether they are still willing to participate in the ISN or not. WS and WP can leave the ISN when they lose too much money, set by input parameters *WSStepOutMoney* and *WPStepOutMoney*. WP can also leave when the amount of input waste remains too low for a certain period (input parameter *WPStepOutEmpty*). With TPB algorithms turned on, WS and WP do not directly leave the initiative. They first adjust their TPB behaviour value due to the aforementioned economic or operational outcomes. It is done by lowering the behaviour value (using parameters *WSEBFailure* for WS and *WPEBFailure* for WP). The resulting behaviour value is then compared to a behaviour threshold of each agent (*WSStepOutB* for WS and *WPStepOutB* for WP).
   c. If WP leaves, the ISN fails.
   d. Existing contracts expire after a set period. We assume that a new contract can only be established after acceptance in a new bidding process.

Table 3-4 Agent behaviour changes by altering the TPB values after periodic evaluation of the individual outcomes. Note. All TPB values remain between 0 and 1.

Agent	Evaluation of periodic outcome per agent	New TPB value after evaluation	Eq. nr.
Waste supplier	No local waste exchange contract AND profit	$A_{WS} = A_{WS} - E_{A,WS}$	(3-17)
		$PBC_{WS} = PBC_{WS} + E_{PBC,\,WS}$	(3-18)
	No local waste exchange contract AND loss	$A_{WS} = A_{WS} + E_{A,WS}$	(3-19)
		$PBC_{WS} = PBC_{WS} - E_{PBC,\,WS}$	(3-20)
	Local waste exchange contract AND profit	$A_{WS} = A_{WS} + E_{A,WS}$	(3-21)
		$PBC_{WS} = PBC_{WS} + E_{PBC,\,WS}$	(3-22)
	Local waste exchange contract AND loss	$A_{WS} = A_{WS} - E_{A,WS}$	(3-23)
		$PBC_{WS} = PBC_{WS} - E_{PBC,\,WS}$	(3-24)
	Avg. $B_{actors \in ISN} \geq SN_{WS}$	$SN_{WS} = SN_{WS} + E_{SN,WS}$	(3-25)
	Avg. $B_{actors \in ISN} < SN_{WS}$	$SN_{WS} = SN_{WS} - E_{SN,WS}$	(3-26)
Waste processor	Enough waste in the processor	$PBC_{WP} = PBC_{WP} + E_{PBC,\,WP}$	(3-27)
	Not enough waste in the processor	$PBC_{WP} = PBC_{WP} - E_{PBC,\,WP}$	(3-28)
	Profit	$A_{WP} = A_{WP} + E_{A,\,WP}$	(3-29)
	Loss	$A_{WP} = A_{WP} - E_{A,\,WP}$	(3-30)
	Avg. $B_{actors \in ISN} \geq SN_{WP}$	$SN_{WP} = SN_{WP} + E_{SN,\,WP}$	(3-31)
	Avg. $B_{actors \in ISN} < SN_{WP}$	$SN_{WP} = SN_{WP} - E_{SN,\,WP}$	(3-32)

3.5 Simulation Experiments

We posed three questions to the model, to explore how and to what extent planned behaviour theory affects the model outcomes in terms of network robustness, and cash flow outcomes for the social agents:

1. How does the modelled *planned behaviour* affect the *network robustness*?
2. How does the modelled planned behaviour affect the cash flows of each individual actor?
3. How does the modelled *planned behaviour* affect *the overall cash flow* for the ISN as a whole?

In this section, we explain the input and output values in detail. The experiment results, discussion, and conclusions can be found in the following sections.

3.5.1 Independent variables: planned behaviour

We executed simulations with two types of *independent input variable sets*, see Table 3-5. The first input set does not employ the TPB algorithm (*TPB OFF*). The second input set includes the TPB algorithm to regulate the agents’ behaviour (*TPB ON*).

Given the scope of this study, and for the sake of conciseness, we only show experiments from the *waste-as-waste* design. We repeated each simulation 500 times to obtain statistical significance.

In the *TPB OFF* input set, all TPB behaviour values are not applicable since the model bypasses TPB algorithms. In the *TPB ON* input set, the model simulates variations in initial agent behaviour with undetermined causes. Thus, we approximated a uniform distribution of the broadest range of initial behaviour values (*initWSB* and *initWPB*) possible: between 0 and 1. We did so by setting PBC, A and SN at 0,5, randomising these values with σ=2, and randomly altering the accompanying weight factors from 1 to 7.

The chosen average values and standard deviations for evaluation parameters (*initWSESN* and *initWPESN*) and leaving parameters (*WSStepOutB*, *WPStepOutB, WSEBFailure* and *WPEBFailure*) were determined by performing a sensitivity analysis and calibrating the outcomes based on information from case participants.

3.5.2 Moderating variables: design and context

The moderating variables consist of organisational design (Table 3-6) and context variables (Table 3-7). The effect of changing the organisational design is not explored in this study, and therefore the accompanying input variables were fixed. These values were based on the interviews with case participants.

Uncertain conditions were included in the simulations by randomising the context variables. Here, we explain why and how.

Some waste suppliers do not enter the ISN before their *existing contract with the incinerator* ends. Some suppliers are at the end of this contract, others halfway or at the beginning. To address this, the agents obtain a randomised contract duration with a maximum of 1 year during setup (Suez, 2020). After that period, the contracts are terminable, and the supplier starts participating in the ISN negotiations.

Market prices are set according to a randomised normal distribution based on recent market prices (Bruins en Kwast, 2019; Vereniging Afvalbedrijven, 2013) to account for realistic market prices in the simulation runs.

Each supplier's *waste quantity and quality* are based on measurements and estimations by participants in Mulder et al. (2018) case studies. These values were randomized according to a normal distribution with a standard deviation equal to 10% of the quantity at the beginning of every new season to account for quantity variations. The waste quality values are also randomized in each calculation step (between 0, worst quality and 1, best quality). These values were based on qualitative data from our case study (Mulder et al., 2018), using a normal distribution (σ = 0.3). We would like to stress that these assumptions on waste quantity and quality fluctuations only apply to these cases.

Table 3-5 Independent input variables sets.

Independent variable	**Input set *TPB OFF***	**Input set *TPB ON***		**Description**
	Input value	**Input value**	**σ**	
TPB?	FALSE	TRUE	n.a.	Determines whether to follow TPB algorithms or not
WSRNorm	-	2	n.a.	Standard deviation σ for randomizing PBC_{WS}, A_{WS} and SN_{WS}
initWSPBC	-	0.5	WSRNorm	Perceived behavioural control value of WS (PBC_{WS})
initWSWFPBC	-	Random 1 to 7	n.a.	Weight factor for PBC_{WS}
initWSEPBC	-	0.04	0.01	Evaluation variable $E_{PBC,WS}$, see Table 3-4.
initWSAtt	-	0.5	WSRNorm	Attitude value of WS (A_{WS})
initWSWFAtt	-	Random 1 to 7	n.a.	Weight factor for A_{WS}
initWSEAtt	-	0.04	0.01	Evaluation variable $E_{A,WS}$, see Table 3-4.
initWSSN	-	0.5	WSRNorm	Subjective norm value of WS (SN_{WS})
initWSWFSN	-	Random 1 to 7	n.a.	Weight factor for SN_{WS}
initWSESN	-	0.04	0.01	Evaluation variable $E_{SN,WS}$, see Table 3-4.
WSStepOutB	-	0.25, 0.45	n.a.	Behaviour-based leaving threshold for WS to leave the ISN
WSEBFailure	-	0.3	0.1	Agent behaviour reduction value
WPRNorm	-	2	n.a.	Standard deviation σ for randomizing PBC_{WP}, A_{WP} and SN_{WP}
initWPPBC	-	0.5	WSRNorm	Perceived behavioural control value of WP (PBC_{WP})
initWPWFPBC	-	Random 1 to 7	n.a.	Weight factor for PBC_{WP}
initWPEPBC	-	0.04	0.01	Evaluation variable $E_{PBC,WP}$, see Table 3-4.
initWPAtt	-	0.5	WSRNorm	Attitude value of WP (A_{WP})
initWPWFAtt	-	Random 1 to 7	n.a.	Weight factor for A_{WP}
initWPEAtt	-	0.04	0.01	Evaluation variable $E_{A,WP}$, see Table 3-4.
initWPSN	-	0.5	WSRNorm	Subjective norm value of WP (SN_{WP})
initWPWFSN	-	Random 1 to 7	n.a.	Weight factor for SN_{WP}
initWPESN	-	0.04	0.01	Evaluation variable $E_{SN,WP}$, see Table 3-4.
WPStepOutB	-	0.25; 0.45	n.a.	Behaviour-based leaving threshold for WP to leave the ISN
WPEBFailure	-	0.3	0.1	Agent behaviour reduction value

Table 3-6 Moderating variable settings concerning organisational design. Assumptions were calibrated by showing the effects of input changes to case study participants and experts in organic waste management.

Moderating variable settings concerning organisational design for both TPB OFF and TPB ON input sets			
Variable	**Value**	**Unit**	**Remark**
Residue treatment			
Waste_as_by-product?	False	[-]	Model assumption
Quality control			
WSWQualRNorm	0.3	[-]	Model assumptions
WPQualThresholdPerc	0.5		
WSQualPenalty?	false		
Quantity control			
WPMinProcThreshold-Perc	0.1	[-]	Model assumption
WPProcThresholdPerc	0.95	[-]	Model assumption
MaxQuantityAllowed	480	[Tonnes]	Mulder et al. (2018, p. 54)
Leaving the network			
WSStepOutMoney	-1500	[Euro]	Model assumptions
WPStepOutMoney	-1500	[Euro]	
WPStepOutEmpty	2	[Seasons]	
Contractual agreements ISN			
Contract length	1	[Seasons]	Model assumptions
PercAvoidedWaste-Costs2WS	1	[-]	
PercProductYield2WP	1	[-]	
Process technology			
Compost retention time	2	[Seasons]	Van der Wurff et al. (2016, p. 23)
I/Oratio active composting	0.5	[-]	Vlaco (2009, p. 5)
Composting costs per tonne	33	[Euro/tonne]	LCA-LCC tool by Mulder et al. (2020)
Negotiations			
MaxOfferCounter	5	[Bids]	Model assumption

3.5.3 Dependent variables: network robustness and cash flows

ISN Robustness. In our simulation results, we define a network to be robust when it can run for ten years without falling apart due to leaving agents. Thus, the experiments were run over 40 steps (1 step per season).

Individual cash flows. We have measured the cash flow outcomes of each supplier and processor. Every agent deals with different amounts of exchanged waste, and therefore we normalized the outcomes to cash flow per tonne of waste.

*Table 3-7 Moderating variable settings concerning the ISN context. Grey cells are randomized during model setup. * Normal distribution with μ = market price and standard deviation σ = 0.2μ. **Inputs from CSV, normal distribution with μ = quantity and σ = 0.1μ ***Inputs from CSV, normal distribution with μ = quality value and σ = WSWQualNorm (Table 3-6).*

Moderating variable settings concerning the ISN context for both *TPB OFF* and *TPB ON* input sets			
Variable	**Value**	**Unit**	**Remark**
Existing contracts with incinerator			
WSWIMaxfixedContractLength	Random 0 to 4	[Seasons]	Suez (2020)
Contractual agreements with incinerator			
FlexMassWIContract?	True	[-]	Model assumption; WI charges per mass unit waste (Euro/Tonne)
Market prices			
Cprice	15*	[Euro/tonne]	Bruins en Kwast (2019)
BPPrice	0*		Model assumption
Wprice	40*		(Bruins en Kwast, 2019; Vereniging Afvalbedrijven, 2013)
Waste supplier quantity			
Each waste supplier	Varying**	[Tonne / season]	Determined per waste supplier. From CSV, waste quantities from: Mulder et al. (2018)
Waste quality variables			
Ditch cuttings	0.55***	[-]	Model assumptions, based on The type of waste in: Mulder et al. (2018)
Farmland Waste	0.9***	[-]	

<u>Average total cash flow for the ISN as a whole.</u> To compare different network sizes, we expressed the total cash flow by normalizing it to the average cash flow per tonne of waste per agent. The average cash flows in the TPB OFF runs were used as a benchmark. The average cash flow difference was calculated according to:

Eq. 3-33: $\Delta CF = CF_{TPB\ ON} - CF_{TPB\ OFF}$;

in which CF is the average cash flow per mass unit per ISN actor (Euro/tonne of waste/agent).

Using this equation, we can compare the extent to which the *TPB ON* runs affect each agent's average economic outcomes.

3.6 Results

3.6.1 Effect of planned behaviour on the network robustness

Figure 3-4 shows that the network has a higher chance of failure during the first seasons and a lower chance of failure afterwards. This is particularly true when TPB logic is applied.

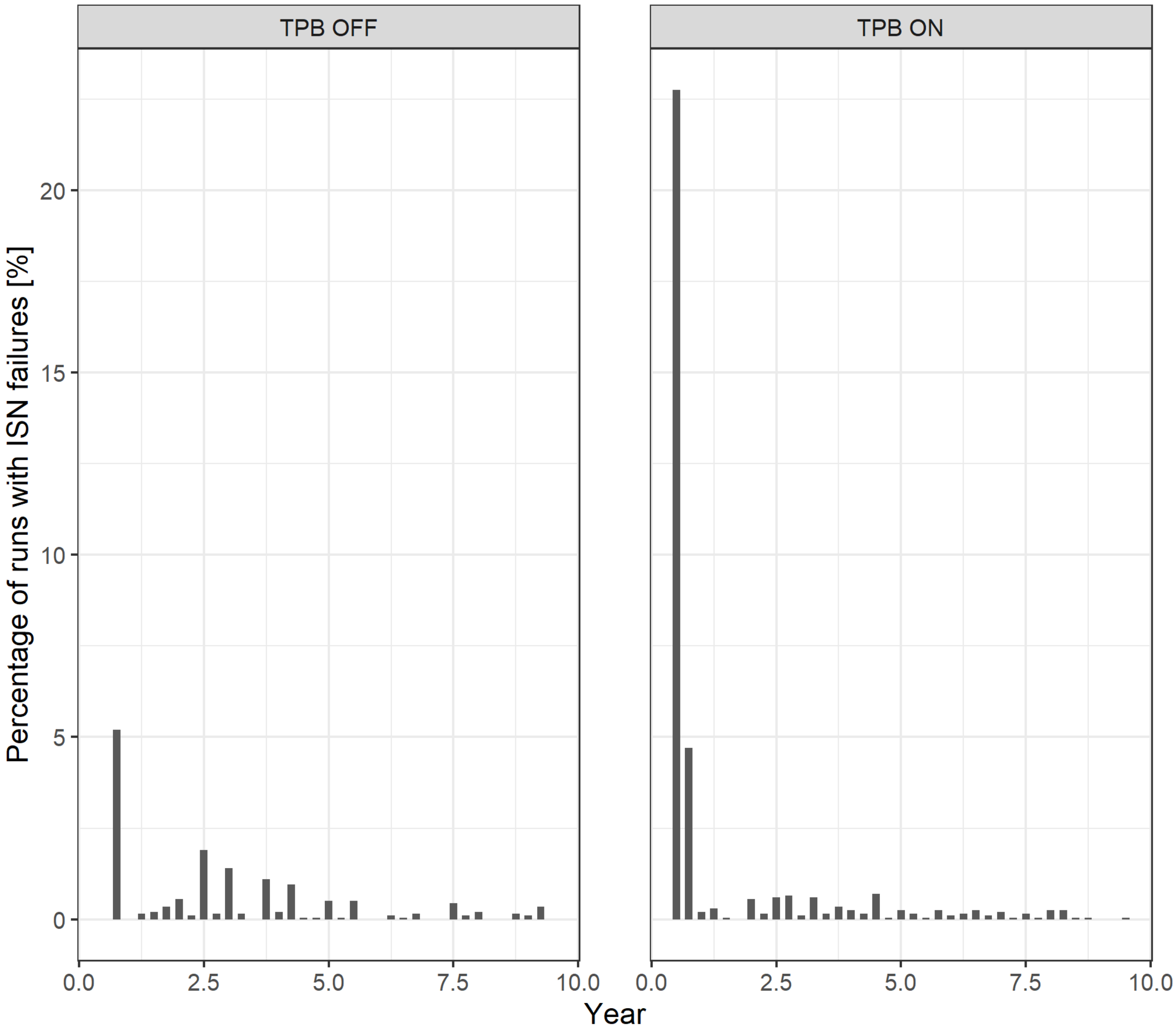


Figure 3-4 Industrial symbiosis Network (ISN) failures over time when TPB OFF and TPB ON input sets are used.

Figure 3-5 and Figure 3-6 show the percentage of runs with surviving networks after running both *TPB OFF* and *TPB ON* input sets. For the sake of conciseness, here we discuss two types of TPB variables that affect the network's survival: the initial behaviour values and the behaviour based leaving thresholds. Both figures show that mainly the waste processor behaviour parameters determine the robustness of the network.

Thus, in TPB OFF runs, influential mechanisms regarding ISN survival outcomes are lacking.

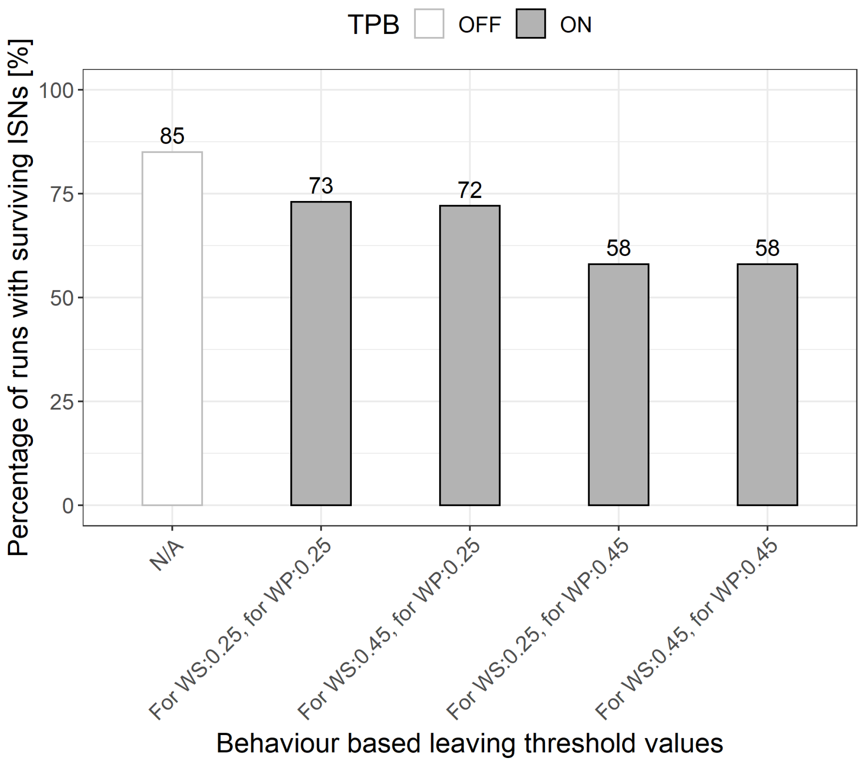


Figure 3-5 Comparison of ISN robustness as affected by the behaviour based leaving thresholds of WS and WP. ISN = industrial symbiosis network, TPB = theory of planned behaviour, WS = waste supplier, WP = waste processor.

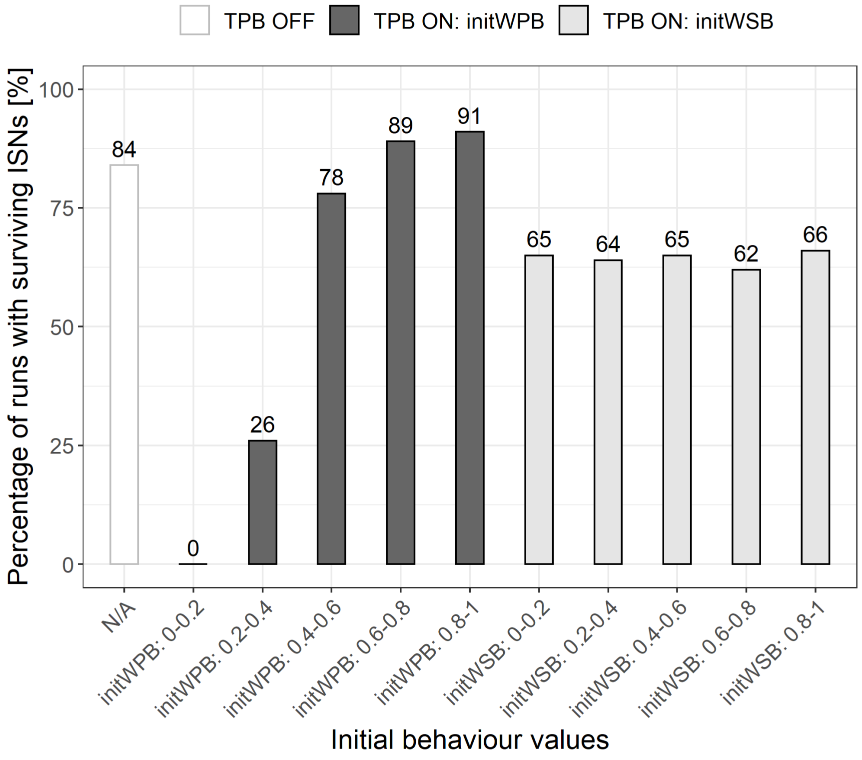


Figure 3-6 Percentage of runs resulting in robust industrial symbiosis networks using TPB OFF (utter left) versus TPB ON input sets. In the TPB ON runs, the percentage of robust networks is categorised by the initial behaviour values of the waste processor (initWPB) and the supplier (initWSB).

3.6.2 Effect of planned behaviour on individual cash flows

The supplier and processor's initial behaviour value and accompanying cash flows can be found in Figure 3-7 and Figure 3-8, respectively. Both boxplots follow standard Tukey representations. The results of accompanying Wilcoxon rank-sum tests - for not all samples can be assumed to be normally distributed - can be found in the repository (Lange, Korevaar, Nikolic, et al., 2021a), and appendix C.

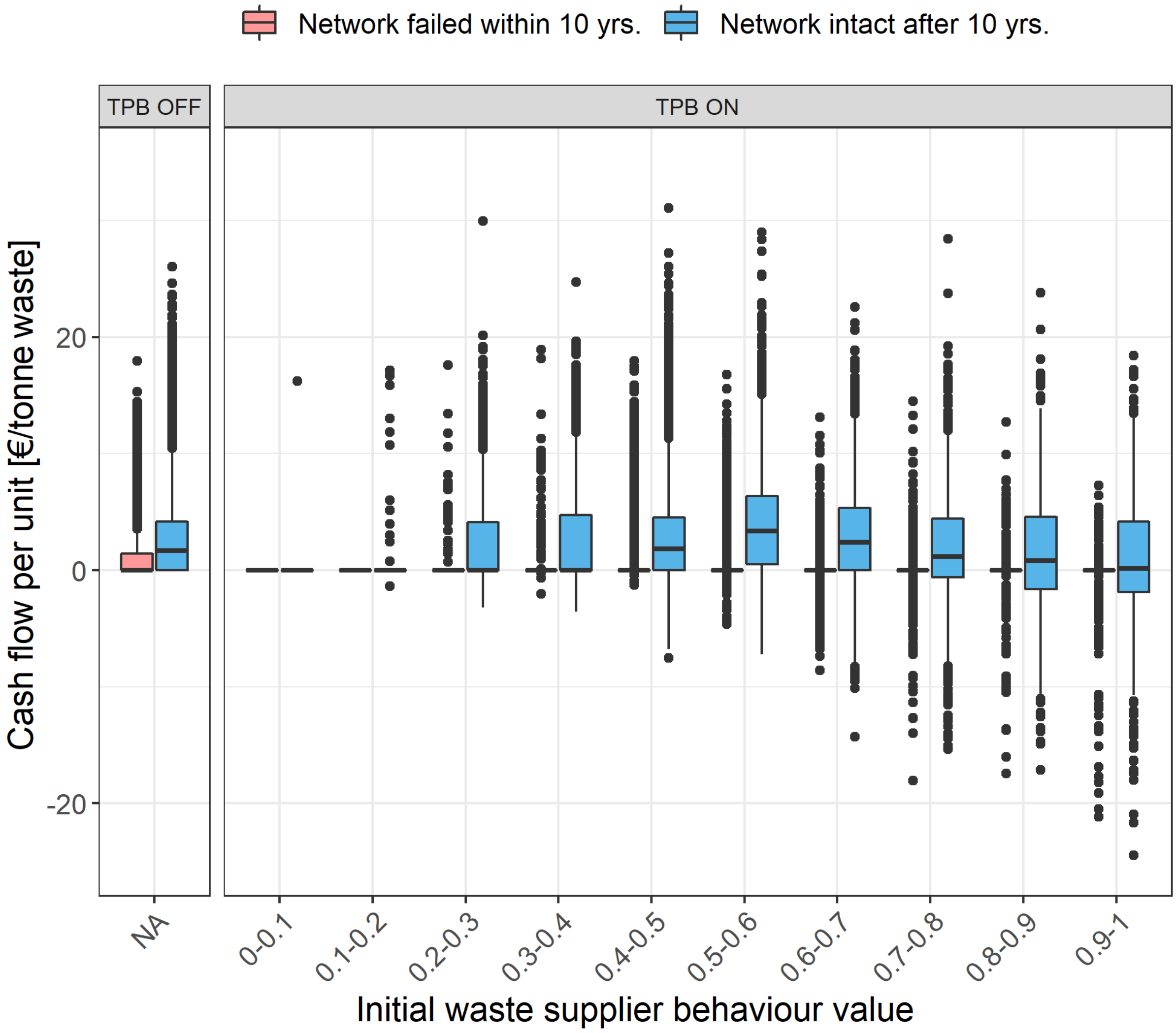


Figure 3-7 Initial ranges of waste supplier behaviour values (initWSB) compared to cash flow per unit waste.

Concerning the waste supplier, the results in Figure 3-7 allow us to make three comparisons (i.e., the differences between cash flow outcomes for $p \leq 0.05$):

a. There is a significant difference in cash flow outcomes between intact and failed networks.
b. *The TPB ON* model runs show a wide range of positive and negative cash flow outcomes, whereas the *TPB OFF* model runs only positive results.
c. *InitWSB* between 0.5 and 0.6 is correlated with the highest cash flows. At *initWSB* > 0.9, the average WS plays even.

Similarly, the waste processor results in Figure 3-8 show that:

a. There is a difference in cash flow outcomes between intact and failed networks. The failed networks show a wider variance in the *TPB OFF* runs than *TPB ON* runs.
b. *TPB OFF* and *TPB ON* runs with intact networks show quite similar cash flows, except for the runs with the lowest *initWPB* values.
c. Failed networks show a tipping point at the *InitWPB* value of 0.5.
d. All networks failed at *initWPB* between 0 and 0.1.

Thus, TPB OFF runs lack mechanisms that affect individual cash flow outcomes.

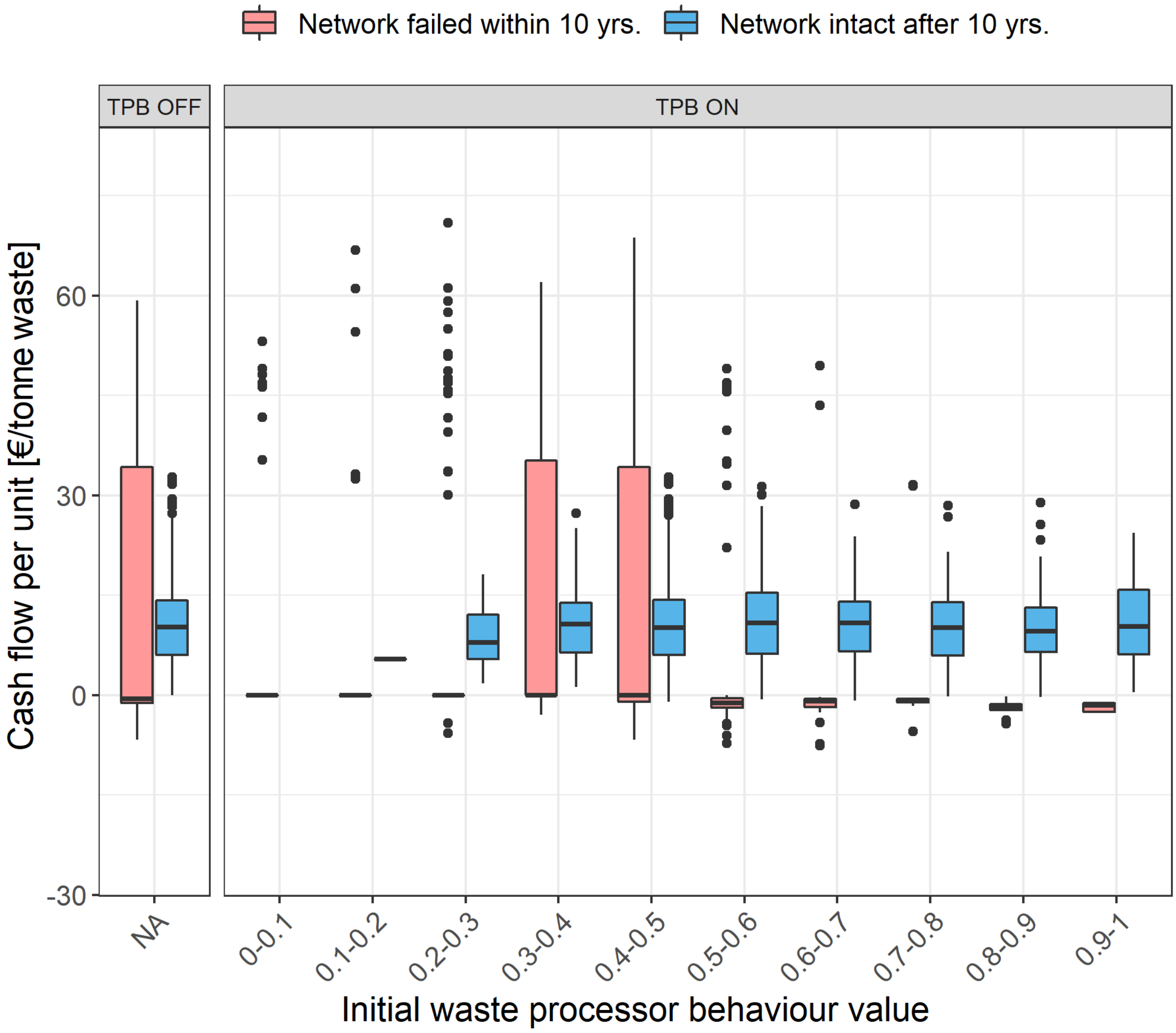


Figure 3-8 The waste processor's initial behaviour value (initWPB) compared to cash flow per unit.

3.6.3 Effect of planned behaviour on total ISN cash flow

Figure 3-9 shows how *TPB ON* runs affect each ISN actor's normalised average cash flow outcomes (surviving networks only). Four areas can be identified in this figure:

a. *Red* areas show which initial behaviour values correlate to economic disadvantages compared to TPB OFF runs.
b. In *purple areas,* there are higher economic benefits compared to TPB OFF runs.
c. In *white* areas, there is almost no difference between TPB ON and TPB OFF runs.
d. *Empty* areas: there are no surviving networks in the lowest combinations of initial behaviour values.

Thus, if the model does not include TPB algorithms, significant information regarding cash flow outcomes on the network level is lacking.

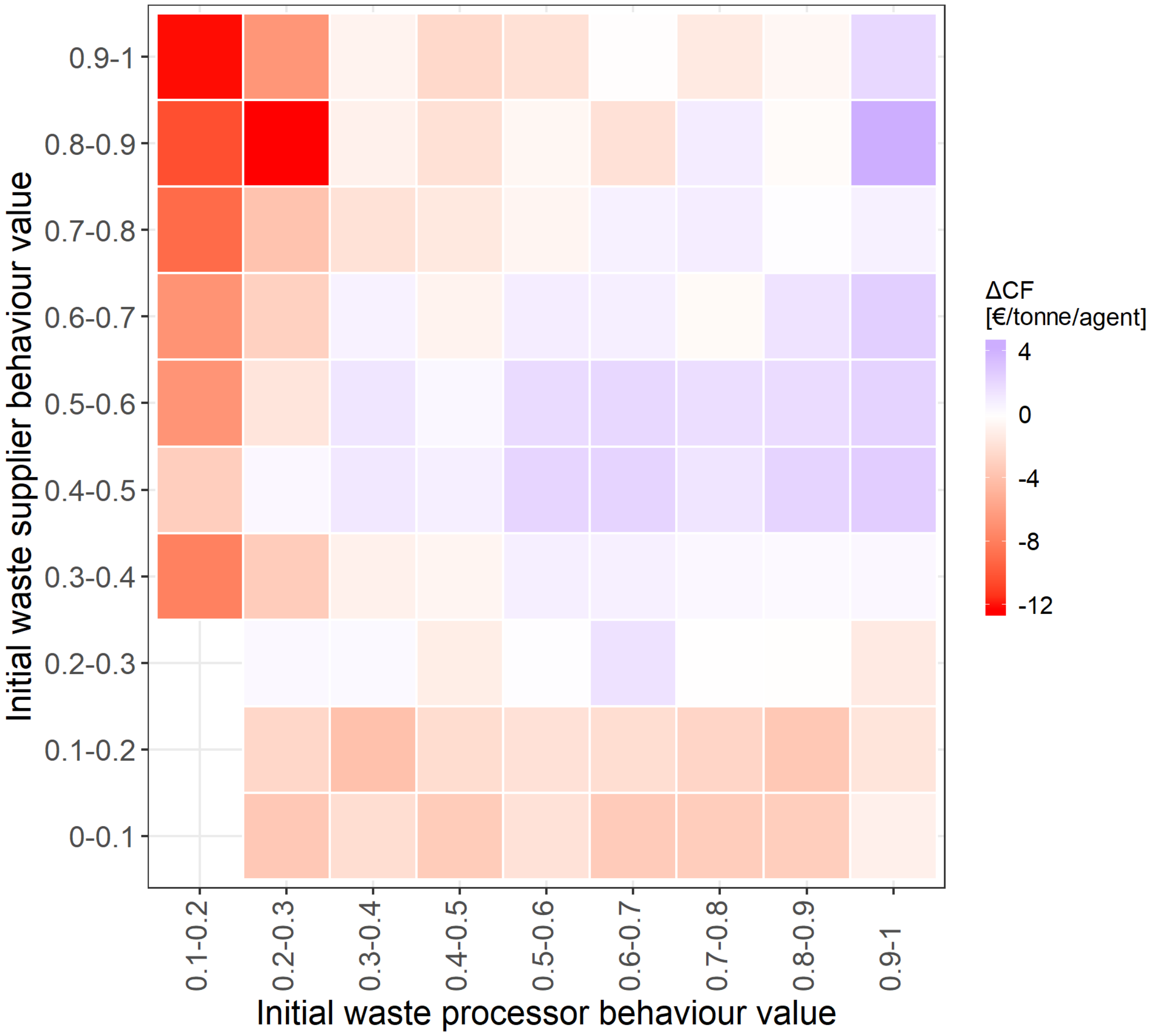


Figure 3-9 Average cash flow differences (ΔCF) between TPB ON and TPB OFF runs for each initial behaviour value. The average cash flows in TPB OFF runs were used as a benchmark.

3.7 Discussion, Conclusions and Future Work

3.7.1 Validation of mechanisms and outcomes

The model represents a socio-technical system, which implies that insights from the model affect the modelled system itself (Hodges, 1991). Classical validation, i.e., generating a model prediction and validating it with an empirical experiment, is impossible since the simulation outcomes represent possible futures. Therefore, the purpose of the model and its simulations is to explore and not to predict. However, we used two methods to increase the external validity of the model outcomes: expert validation and literature comparison (Van Dam et al., 2013, p. 127). In repeated consultation sessions with domain experts and case participants, we systematically went through the model assumptions, the simulation mechanisms and the outcomes. The results concerning ISN robustness corroborate observations by Chertow & Ehrenfeld (2012, p. 24); they observed that ISNs often fail to grow beyond their initial set of synergies. In addition, the costs and benefits outcomes are in line with the business reports and policy documents as referred to in Table 3-6 and Table 3-7.

3.7.2 Discussion

General contribution

The current model describes the planned behaviour of waste suppliers and processor in the context of all stages of industrial symbiosis implementation. By building the model, structural, transactional and link characteristics (Doménech & Davies, 2009) of the case were disclosed. The model includes network size, physical transfers of waste and money, information exchanges regarding the waste quantity and quality, and frequent negotiation and communication for setting up local collaborations. We described the agents from their specific symbiosis roles, i.e., waste supplier and processor. It allowed us to model agents that act and evaluate outcomes according to their intentions and behaviour regarding synergy creation or ending.

The model is generic and comprehensive so that all ISN implementation stages for firms in free-market waste management systems were included. The model was built using a comprehensive set of data on collaborative composting by including three cases. Organic flows have a relatively high quantitative and qualitative heterogeneity. Processor capacity and supply dynamics are therefore included. In addition, the quality of the waste was modelled as *'fitness for processing'*. By doing so, the model can also be applied to analyse other types of residuals and conversion processes with relatively small efforts and without significant change in model behaviour.

The purpose of the model was to ask *'what if'* questions about sensitivities regarding agent behaviour, combined with the ISN's organisational design and context. In our experimental design, we used Monte-Carlo simulations in which we repeatedly manipulated the non-controllable behavioural inputs, combined with randomized contextual inputs based on empirical data. This approach allowed us to assess the impact of TPB variables in the model.

Waste processor perspective

Planned behaviour of the waste processor affected the network's survival and economic benefits or losses. In some simulation runs, the *leaving threshold* of the waste processor played a significant role in the survival of the network. The *leaving threshold* can be considered an indicator of actor persistence as defined by Agarwal & Strachan (2006, p. 23); it causes the waste processor to respond more or less eager to adverse outcomes. Our results indicate that persistence of the waste processor influences the network robustness. It may be explained by the fact that the waste processor can choose between multiple waste suppliers. When too many waste suppliers decided to withdraw, the processor was forced to quit due to insufficient waste deliveries. These results are in line with, for example, Vurro et al. (2009), who state that an organisation with a relatively high degree of centrality can influence the network. A waste processor willing and acting to implement symbiosis from the start (modelled as *initWPB>0,5*) can expect higher network survival chances. When the waste processor acts unwillingly, it tends to overcharge the suppliers, leading to waste suppliers leaving, resulting in network failures. If an ISN survives, the waste processor's cash flow outcomes are not correlated with its initial planned behaviour. The actions of the modelled processor are considerably determined by choosing whom to negotiate with based on the highest potential economic value of the waste stock. Hence, in the case of ISN survival, economic behaviour dampens the influence of planned behaviour.

Waste supplier perspective

The waste supplier's modelled planned behaviour does not significantly affect the network’s survival, but it does affect its economic benefits or losses. Planned behaviour of the waste suppliers causes some agents to cooperate in ISNs without making a profit. In the experiments without planned behaviour, waste suppliers never obtain negative cash flow outcomes. Waste suppliers that are slightly willing to cooperate in ISNs (*initWSB* close to 0.6) obtain the most economic benefit per tonne of waste. For all waste suppliers, particularly those with large quantities, these benefits can make a difference in the low margin compost market.

ISN perspective

The modelled planned behaviour of both social actors affects the network robustness and cash flow outcomes. The simulation results show that motivating and supporting the processor as a key player are essential to improve both ISN robustness and economic outcomes on the network level. Therefore, future research on policy interventions to improve processor behaviour is warranted.

Modeller and practitioner perspectives

This study shows that essential mechanisms may be lacking if an ISN model does not include behaviour. In practice, modelled TPB values of suppliers and processors can be measured before and during the implementation of ISNs, for example, through questionnaires (Ajzen, 2002). Combined with evidence of economic outcomes, emerging synergies and disappearing synergies, this data allows us to calibrate our model further and increase its informative power. Eventually, this helps practitioners decide about joining an ISN or changing the organisational and technological design. Based on the model outcomes, we advise stakeholders to implement interventions that encourage the waste processor to stay in the network.

Study limitations

The model and simulation study also have their limitations. One limitation concerns the case study context. The modelled Dutch market for industrial and commercial waste management is free, and therefore waste suppliers can choose which processor to partner with. The model cannot be used to implement ISNs in government planned or non-market waste management contexts. In many cases, negotiation takes the form of an open auction rather than the modelled bilateral negotiations. In addition, the negotiation tactics can be modelled differently, for example, by implementing imitative negotiation tactics (Faratin et al., 2002). Another limitation is that the modelled behaviour focuses on joining ISNs for competitive advantage. Other drivers for behaviour, such as personal attitude and trust towards potential partners, are not included in the model. The model allows for testing two organisational designs, i.e., waste-as-waste and waste-as-by-product. However, since this chapter focuses on the behaviour of actors, only the waste-as-waste design was used in this study’s simulations. Given the emergence of circular economy research and practices, the efficacy of various organisational designs should be studied. Although the model allows for studying the effect of external disruptions, we did not include external events in our experiments for the sake of conciseness. External disruptions should be considered when more realistic insights into the system's long-term performance are required.

3.7.3 Conclusions

This study aims to understand how the behaviour of firms affects the implementation and robustness of symbiotic collaborations. It presents the first agent-based model that combines all ISN implementation stages of Tao et al. (2019) with the planned behaviour of agents. The modelled network evolves through local by-product transactions after a series of individual decisions, communication between agents and bilateral negotiations. Adding the theory of planned behaviour as our behavioural model allows for modelling agent negotiation and self-evaluation. The model shows that adding such behavioural theory provides significantly different and more detailed insights regarding network robustness and cash flow outcomes. If the behaviour were not modelled using TPB, important behavioural mechanisms would be lacking in the model, although this behaviour is measurably present in the real world.

Participatory modelling of behaviour does not merely increase the external validity of industrial symbiosis network models. It also provides stakeholders insights on how ISNs can be implemented and what factors are important to consider. The process of modelling has thus become part of the implementation of industrial symbiosis since it facilitated social learning among participants, affecting their behavioural intention.

For practitioners, this study shows that human behaviour variables, such as attitude, control beliefs and norms, are important to include in preparing, implementing and evaluating closed-loops in ISNs. Behavioural scientists can facilitate project leaders by measuring these variables. If the combination of behaviour values is unfavourable for the ISN robustness, the project leader can either rethink the system design to encourage stakeholders or engage new ISN participants.

3.7.4 Future research

The limitations of this study provide us with directions for future research.
More evidence from other cases should be collected to develop generic design rules for policies, business models and technology implementations. In future research, we will therefore integrate more case evidence. In addition, other organisational designs, such as waste-as-by-product or policy interventions, will be studied to support practitioners in ISN initiatives. Future research may also include questionnaires to determine TPB values, e.g., Ajzen (2002), to test interventions significantly affected by agent behaviour. To explore the long-term performance and resilience of the modelled system, it is required to study the effects of external disruptions, including the behaviour of actors. Finally, we suggest comparing and integrating the proposed model with other models to increase its contribution to understanding the complexity of real-world industrial symbiosis.

“I've done the math enough to know the dangers of our second guessing”

Tool – Schism[*]

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[*] Keenan, M., Jones, A, Carey, D., & Chancellor, J. (2001). Text fragment from *Schism* [Song]. On: Lateralus performed by Tool. BMG Rights Management. This text fragment was used with permission from the authors.

4

Study 3

Agent-based modelling and simulation for circular business model experimentation

Business models describe a firm's technical, organisational, and economic design. 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, opinions, and 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 has not yet been done systematically for CBMs. This chapter[3] *presents a systematic, iterative method (Figure 4-1) to explore and improve CBMs prior to actual implementation utilizing agent-based modelling and simulation to address this knowledge gap.*

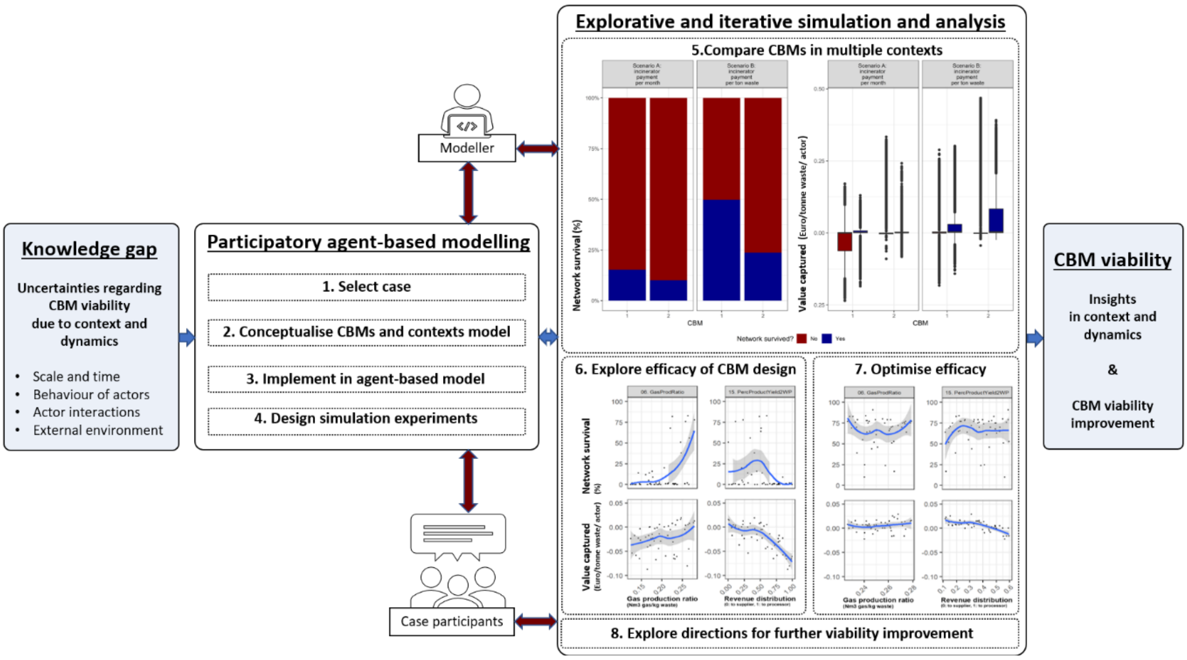

Figure 4-1 Ex-ante circular business model experimentation method.

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 combined 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 improve the CBM design from the company to the 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. The work thus provides knowledge on ex-ante testing and improving ISN robustness through collaborative modelling and simulation methods (RQ3).

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[3] This chapter was published as: Lange, K.P.H., Korevaar, G., Oskam, I.F., Nikolic, I., Herder, P.M., 2021. Agent-based Modelling and Simulation for Circular Business Model Experimentation. Resour. Conserv. Recycl. Adv. 200055. https://doi.org/10.1016/j.rcradv.2021.200055.

The first author conceptualised and performed the research. The other authors had an advisory role. Minor textual edits have been made to ensure alignment of the published paper into this dissertation.

4.1 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 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 policymakers, businesses and scholars (Geissdoerfer et al., 2018). CE requires bottom-up efforts from companies, for example, by 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 merely 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 insights into the viability of CBMs (Bocken et al., 2019; Bocken & Antikainen, 2018; Weissbrod & Bocken, 2017). Computer simulation models offer opportunities for CBM experimentation. If a simulation model is co-created with the stakeholders, it helps them increase their knowledge about the system they operate in (Bas, 2017; Batten, 2009; Smetschka & Gaube, 2020). Co-creation with stakeholders has three main advantages: it improves the design of the models, structures communication between the modellers and practitioners, and helps identify impact potentials (Epstein, 2008; Smetschka & 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 environmental risks. This study contributes to the development of CBM experimentation methods. It proposes a novel systematic method to explore CBM designs before implementation using agent-based modelling (ABM) and simulation.

4.2 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.

4.2.1 Circular business models

There are many definitions of business models, but business models generally describe a firm’s organisational and economic design, providing insights into how companies create, deliver and capture value (Teece, 2010). Today’s societal and environmental sustainability challenges undermine the viability of traditional business models, 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 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 & Wagner, 2011;

Stubbs & Cocklin, 2008). Traditional business models are generally built up of the following dimensions: value proposition, value creation and delivery, and value capture (Osterwalder et al., 2010; Richardson, 2008). Sustainable business models aim to create, deliver, and capture economic value for the company involved and contribute to environmental and social value creation among a broader span of stakeholders (e.g., Breuer et al., 2018; Stubbs & Cocklin, 2008). In line with this, business model innovation is regarded as crucial to implementing CE principles (De Angelis, 2016; Schenkel et al., 2015). Hence, circular business models (CBMs) are a specific class of sustainable business models (Bocken et al., 2014; Geissdoerfer et al., 2018). CBMs (sometimes called Circular Economy Business Models or CEBMs) are business models that create value according to the principles of CE by reducing waste and consumption and closing, slowing and narrowing resource loops (e.g., Bocken et al., 2016; Lüdeke-Freund et al., 2019). Companies can do so by constructing a novel business model, combining various 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 offer 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.

4.2.2 Gaps in the literature that hamper CBM implementation

Firms operate in a complex and evolving environment caused by factors that are not manageable (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 implementing 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; G Herczeg, 2016). We focus on the following gaps in the literature that have been identified as obstacles to 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) depend 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, the literature barely addresses scale and time in CBM viability (Lüdeke-Freund et al., 2019).
- **Effects of individual actor behaviour and social interactions among partners are hardly accounted for**. The 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, explicating actor behaviour and incentivising collaborative interaction are important (Geissdoerfer, Savaget, Bocken, 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).

- **Effects of the external environment on business model viability are 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 concerning 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 into dynamic relationships between technical artefacts, social actors and the environment. Understanding the complexity and dynamics of CBMs on both the firm level and the network level is crucial (Lewandowski, 2016; Ünal et al., 2019). Academic literature providing 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.

4.2.3 Agent-based modelling and simulation

Agent-based models (ABMs) are exceptionally suitable for modelling and simulating complex adaptive socio-technical systems (Van 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 that 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 specific processes to occur (Van Dam et al., 2013). Through the interaction among these agents with differing properties, patterns emerge that provide insights into the system's overall functioning (Janssen, 2005). Thus, agent-based modelling and simulation offer opportunities for CBM experimentation to explore interactions between environment, actors and technologies on the micro-and meso-level that result in practices in line with the principles of the circular economy.

4.2.4 Existing agent-based modelling studies related to circular business models

In 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 & 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 & 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 & Jia, 2017). Zhu & 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 from 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 *test business model viability from the CBM perspective systematically*. This chapter 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.

4.3 Proposed iterative CBM experimentation method and application to an illustrative case

This section illustrates 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) using 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 (A. R. Hevner, 2007). Design science research is considered a suitable research approach when working closely with practitioners; to test new designs in a realistic context while solving a domain problem by constructing an artefact (Dresch et al., 2015). In this study, our ABM is exactly that artefact: allowing us to iteratively find new knowledge and solutions by researchers and practitioners, aimed at collaboratively and incrementally improving the CBM viability. Therefore, our ABM is not intended to find the best or optimal settings for high CBM viability 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 affects 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 chapter 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 4.3.1);
2. participatory and iterative model conceptualisation (section 4.3.2);
3. software implementation (section 4.3.3);
4. experimental design (sections 4.3.4);
5. explorative and iterative CBM experimentation and analysis (section 4.4).

We conducted 11 semi-structured interviews, five roundtable discussions, and 17 individual feedback sessions with case practitioners and experts during the modelling and simulation steps. 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, appendix D (Lange, Korevaar, Nikolic, et al., 2021b): https://doi.org/10.25937/3ewr-yt59. It 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.

4.3.1 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 model a realistic narrative of real-world industrial symbiosis networks (ISNs), as Mulder et al. (2018, 2020) described. 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 & Davies, 2010). Although it is not the only archetype of business models within CE practice, scholars consider ISNs 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 & Ehrenfeld, 2012; Chopra & 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 chapter ISNs are considered a fair representation of the CBM viability challenges.

Only the case used for this study's simulation is described here for conciseness. It 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 & 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. (2018, 2020).

One of those initiatives emerged at a former shipyard area called NDSM wharf, 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 must be collected and processed separately (Circle Economic. 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 assure that the network would survive concerning waste supply and product demand (i.e., gas and digestate). The case participants required insights into the effect of reshaping the business model, offering an opportunity to use this case for business model experimentation.

4.3.2 Model conceptualization

We iteratively conceptualised and calibrated a model in collaboration with our case participants (Figure 4-2).

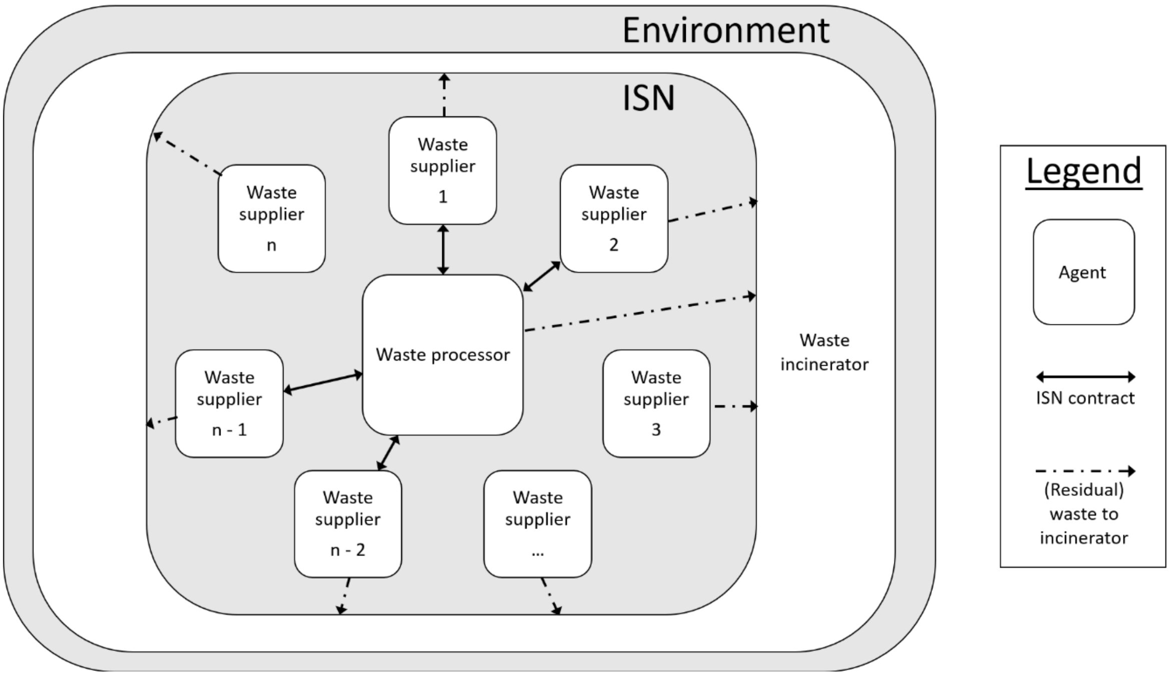


Figure 4-2 The modelled ISN. Waste suppliers and the processor exchange waste and money if a contract is established. Residual waste is brought to the incinerator.

Furthermore, the model builds upon the model presented in chapter 3 (Lange, Korevaar, Nikolic, et al., 2021c). Within the modelled ISN, firms act either from the role of waste supplier or from the role of the 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 (Figure 4-2), 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, the processor and the incinerator, depend upon the CBM design.

In consultation with our case participants, we test two CBMs: Circular waste management (CBM 1) and Waste as a by-product (CBM 2). Using the CBM morphology by Lüdeke-Freund et al. (2019), Table 4-1 shows how CBM design options come about in our case study, forming 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, cascading or repurposing.

Table 4-1 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 the 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): they are aware of environmental sustainability and using biogas as an 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 energy production.
		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 a sunk cost. In this CBM, it is seen as an input for energy production
	Value capture	Revenues	Additional product revenues	Selling biogas
		Costs	Waste handling, processing	Saving on disposal costs by not paying traditional waste management firms (waste processing)
		Costs	Resource inputs	Saving on energy costs by not paying 'traditional' external energy suppliers
		Costs	Transportation, logistics	Saving on disposal costs by not paying traditional waste management firms (waste collection)

Table 4-1 (continued).

CBM2	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 the 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 removal from firms and energy delivery to firms.
		Target customers	'Green' customers	Customers with a 'green interest' (Bocken et al., 2016): they are aware of environmental sustainability and using biogas as an energy source instead of fossil resources fits with these interests.
		Value delivery processes	Taking back waste	By-product removal
		Value delivery processes	Sharing waste	Sharing waste as a by-product to gather a stable amount of input for energy production.
		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 a sunk cost. In this CBM, it is seen as an input for energy production
	Value capture	Revenues	Additional product revenues	Selling biogas
		Costs	Waste handling, processing	Saving on disposal costs by not paying traditional waste management firms (waste processing)
		Costs	Resource inputs	Saving on energy costs by not paying traditional external energy suppliers
		Costs	Transportation, logistics	Saving on disposal costs by not paying traditional waste management firms (waste collection)

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 are 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 biogas production 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 and the waste suppliers, who now put more effort into increasing the quality of their valuable by-products.

4.3.3 Software implementation

This section provides a generic model description, 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, appendix D (Lange, Korevaar, Nikolic, et al., 2021b).

General model

We modelled three types of agents: the waste processor, waste supplier and waste incinerator. Each simulation step represents one month to model waste quantity and quality changes over the year. The processor and supplier go through all process stages concerning local exchange and treatment of organic waste, turning it into a product, as shown in Figure 4-3.

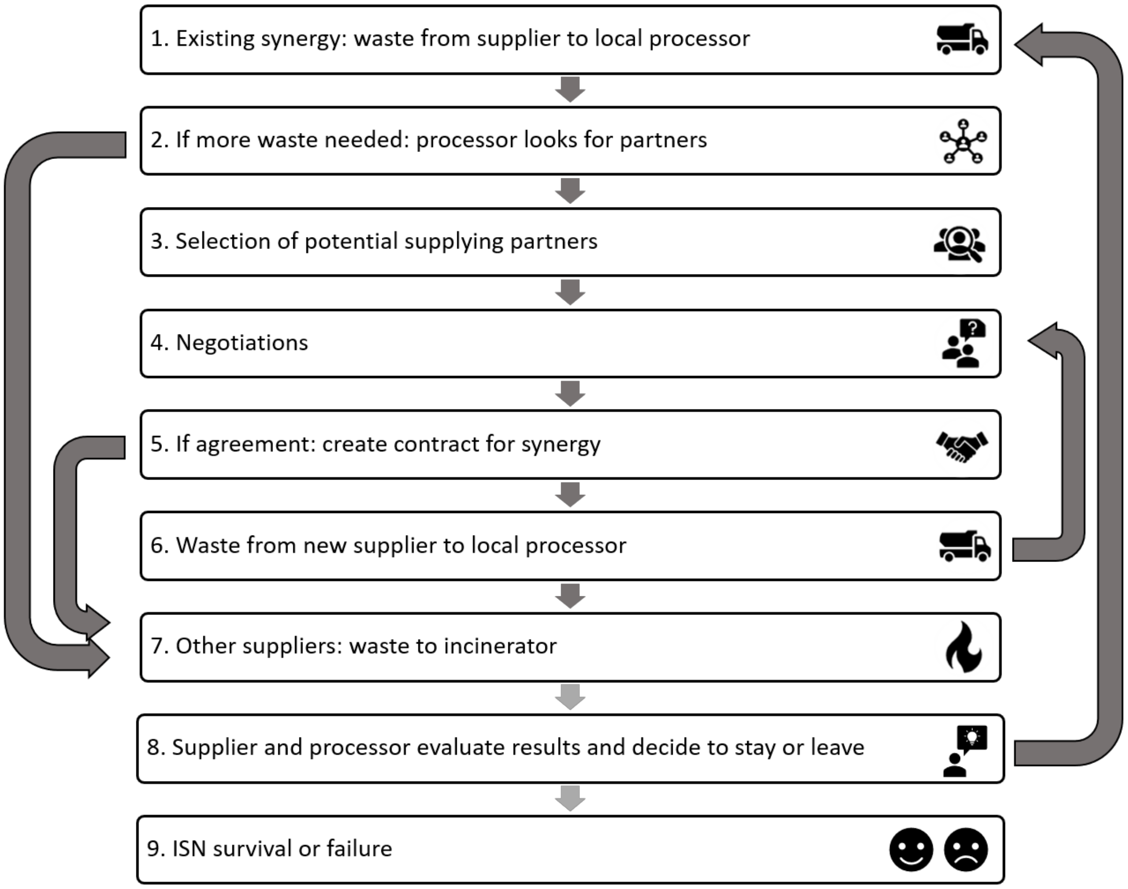


Figure 4-3 Schematic of the process of exchange and treatment from waste to product. Adapted from (Lange, Korevaar, Nikolic, et al., 2021c).

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 suppliers, 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 its most preferred supplier. For this, both agents determine the 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 create a synergy. The behavioural intention model 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 leaves the network.
9. If the processor leaves the network, for example, because of insufficient waste input or cash flow results below a threshold, the whole network fails. The simulation either ends after the network fails or after running a set time span.

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 described in Table 4-1, we modelled these as exogenous variables, i.e., as input parameters set to our model. Using a switch, the course of events during model start-up is determined, which sets the agents' roles, aims and actions, see Table 4-2.

Table 4-2 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. It implies that the supplier pays the processor to remove the waste. In the model, the supplier acts as a buyer during the negotiation stage 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 a by-product	Waste-as-by-product?	TRUE	This CBM is focused on producing energy (biogas) and 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 compensates for the processor's production losses.

Design options are the instantiations of the set of *design variables* within our model that affect the course of events within the CBM narratives. We quantitatively modelled 20 CBM design variables related to the CBM dimensions, see Table 4-3.

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

Table 4-3 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	An acceptable amount of waste (kg/month) for the processor.	Value creation and delivery.
5	I/Oratio	Mass digestate out: mass waste in (kg/kg).	Value creation and delivery.
6	GasProdRatio	Volume biogas out: mass 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 using a minimum quality threshold, which can be increased or decreased. All waste below that quality is discarded by the waste processor and sent to the incinerator.	Value proposition, value creation and delivery, value capture.
8	WSWQualControl	Increase of waste quality by the supplier through active separation at the source.	Value proposition, value creation and delivery, value capture.
9	WSWQualRNorm	Decrease of waste quality variance through active separation at the source.	Value proposition, value creation and delivery, value capture.

Table 4-3 (continued).

Design variables in the model			**Relation to CBM**
Nr.	**Design variables**	**Explanation**	**Dimension**
CBM Revenue and costs			
10	CPrice	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	GasPrice	Different market values for digestate. Approximately 0,07 to 0,01 euro per produced kWh, based on Mulder et al. (2020).	Value capture.
12	BPPrice	By-product price (used when Waste-as-by-product? = TRUE).	Value capture.
13	WPrice	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	PercAvoidedWaste-Costs2WS	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.

4.3.4 Experimental design

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 period of 5 years. Therefore, our main performance indicators for the viability of CBMs are [1] the ISN survival rate (percentage of runs with surviving ISNs) and [2] the value captured, 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 the 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 (Figure 4-4).

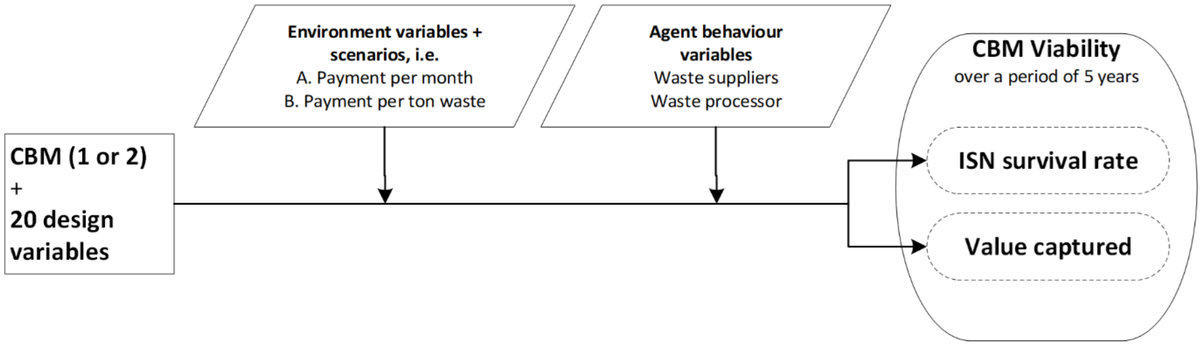


Figure 4-4 Application of the conceptual framework to the case study.

The environment and agent behaviour moderate the mechanisms and outcomes during the simulations. Billing by the incinerator occurs outside the ISN. Two incinerator billing scenarios were included in our experiments based on the cases. In scenario A, waste suppliers pay the incinerator per month. In scenario B, waste suppliers pay the incinerator per mass unit of waste. Scenario B may occur when a collection system is equipped with sensors to measure the amount of waste. It implies that the waste supplier avoids costs in scenario B by bringing the waste to the ISN (see design variable 16, Table 4-3).

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 utilizing 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 through 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, Korevaar, Nikolic, et al., 2021b).

We used a Latin-hypercube sampling (LHS) algorithm to decrease simulation runtime while exploring the full simulation space. We simulated both CBMs over five years, a maximum of 60 simulation steps based on the case study requirements. Each simulation was repeated 100 times 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. The next sections describe the results, contributions, and limitations concerning this CBM experimentation method.

4.4 Explorative and iterative CBM experimentation and analysis

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

- Step 1: we compared the two CBMs as described in Table 4-1 and Table 4-2 (section 4.4.1);
- Step 2: we explored the efficacy of CBM design variables in Table 4-3 with the highest survival rate (section 4.4.2);
- Step 3: we improved the CBM viability by optimising design variable ranges based on the results of step 2 (section 4.4.3);
- Step 4: we explored directions for further viability improvement by studying the role of context and behaviour variables (section 4.4.4).

4.4.1 Comparing the efficacy of the two CBMs

The simulation results for comparing the CBMs are shown in Figure 4-5. 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.

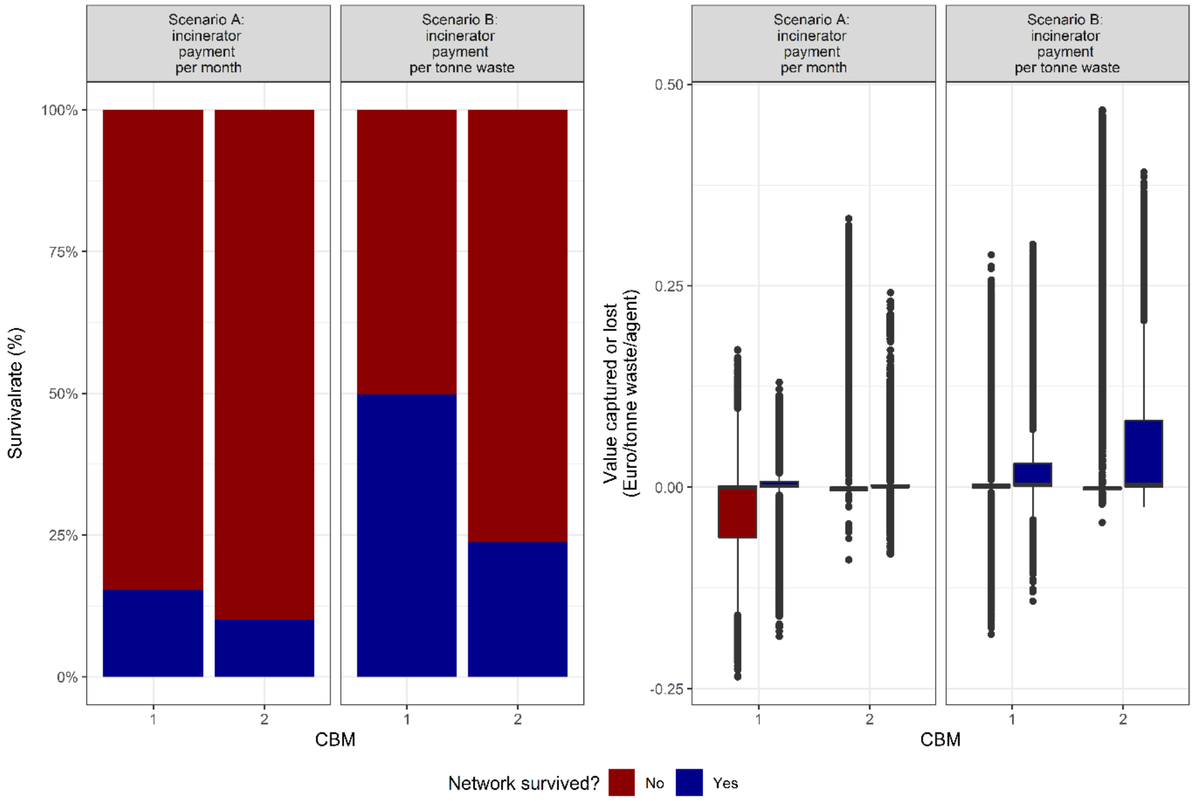


*Figure 4-5 Survival rate (left) and economic benefits or losses (right) of both CBMs for two scenarios. The box plots follow standard Tukey representations, showing the mean value (line), the interquartile range (IQR, box), the values no further or lower than 1.5*IQR (whiskers) and outliers (dots).*

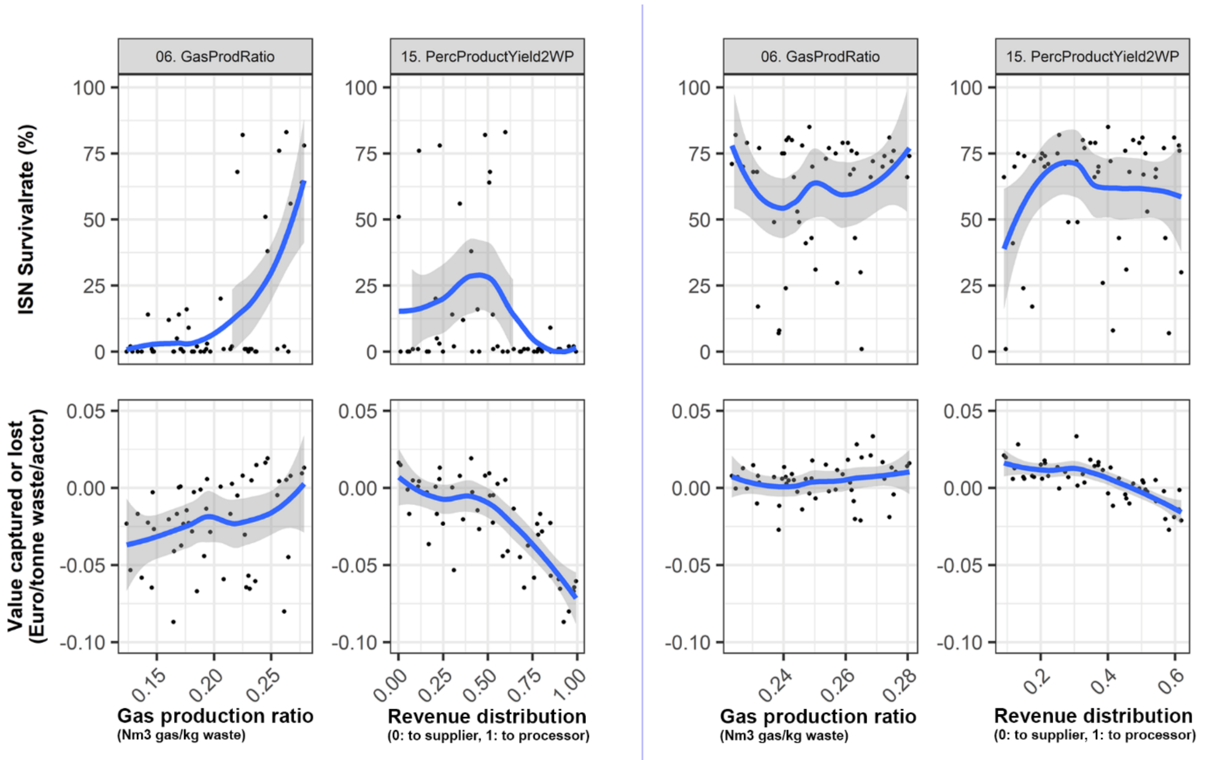
CBM 1 clearly shows higher survival rates than CBM 2 in both scenarios. In addition, it shows that scenario B - in which waste suppliers pay the incinerator per mass unit of waste - is clearly more in favour of local biodigestion initiatives, regardless of the chosen CBM. When actors collaborate, and 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. Therefore, we decided to explore the CBM with the highest survival rate - CBM 1 - in the following steps. However, it is still desirable to find ways for companies to increase their viability. Therefore, the next step describes how to explore the effect of the design variables.

4.4.2 Exploring the efficacy of CBM design variables

The results of the two variables are shown in Figure 4-6a. There are two types of outcomes, which we call Type I and Type II variables[4]:

1. Type I variables show either a clear positive or negative correlation with 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*).



a. Before optimisation **b. After optimisation**

Figure 4-6 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.

Increasing or decreasing Type I variables is correlated to a higher CBM viability. However, improvement of CBM viability through Type II variables is less obvious: stakeholders have to

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

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, shown in the next step.

4.4.3 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 positive value captured (no loss). 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 increased to approximately 65%, as shown from the examples in Figure 4-6b. One-third of the simulation runs lead to ISN failure even within a favourable design variable range. The average cash flow per actor is slightly positive, with negative outliers.

4.4.4 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 new ideas since context and behaviour variables were included. As shown in Figure 4-7, the context and actor behaviour parameters may also affect the CBM viability outcomes.

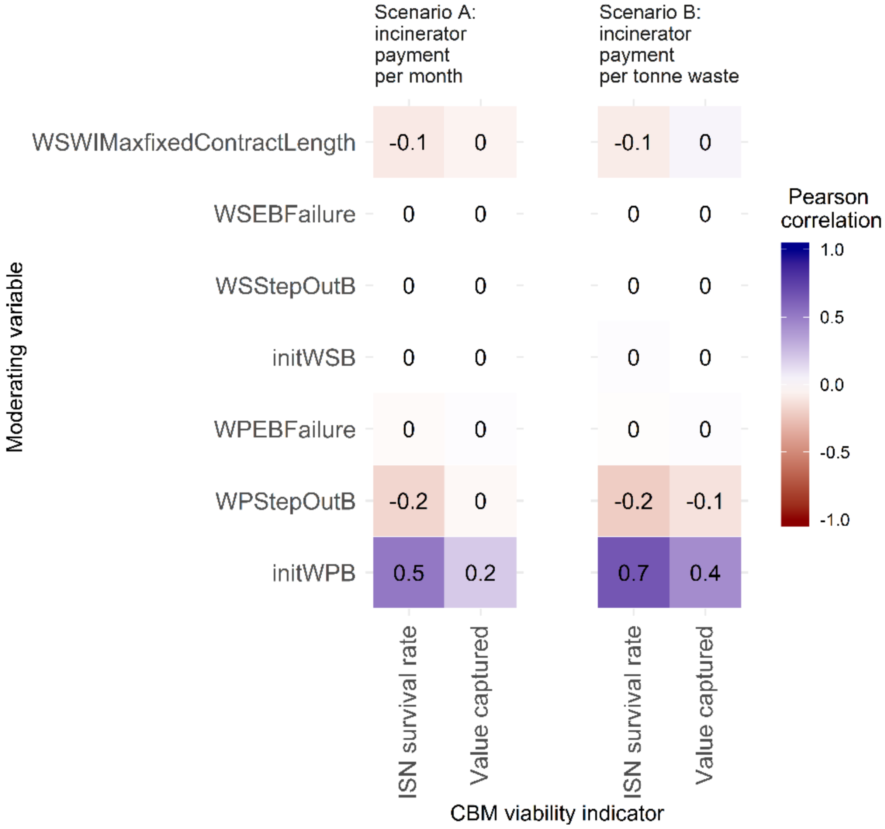

Figure 4-7 Correlation between moderating context and behaviour variables and CBM viability in both scenarios.

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 to improve CBM viability.

4.5 Discussion

This section discusses the simulation results, reflects on the proposed CBM experimentation method, and discusses the study limitations and implications for practitioners.

4.5.1 Validation

Since the purpose of the model is to explore multiple possible futures, traditional validation by real-world comparison is not feasible. Echoing Van Dam et al. (2013), we 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 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 could not create new synergies after the first was established, which corresponds to observations by Chertow & Ehrenfeld (2012). Cash flow ranges were confirmed by experts and compared to data from a Life Cycle Costing study by Mulder et al. (2020).

4.5.2 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 values 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 a by-product*' (CBM 2) was based on the highest survival rate. The two incinerator billing scenarios showed that paying per tonne increases the network robustness. Thus, the CBM viability improves if the incinerator is convinced to switch to a payment-per-tonne scenario. This scenario may be achieved by involving the incinerator as a network partner. Alternatively, by convincing public policymakers to redesign policies that encourage payment per mass unit.

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

The third perspective was to explore a range of inputs for each design variable 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 income from visitors who are willing to pay for education on the process of biodigestion. Another way to improve CBM viability could be to capitalize on environmental and social benefits 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, Korevaar, Nikolic, et al., 2021c).

4.5.3 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 gain insights into complexity and dynamics on both the firm and network levels, which is required for CBM innovation (Ünal et al., 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. Agent-based modelling and simulation are powerful methods to experiment with CBMs and various design options. Where ISNs are rooted in Industrial Ecology and focused on resource efficiency, other types of CBM archetypes have different purposes that also foster the principles of CE. Based on the socio-technical 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 testing generic business model dimensions, we expect the proposed experimentation method to 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).

4.5.4 Limitations and avenues for future research

This section discusses several study limitations and opportunities for future research regarding the model, the modelling process, and the modelling and simulation strategy.

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, such as 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 extending our model with other business model designs. Using 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., 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 concerning 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 the 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.

Modelling and simulation approach

The participatory modelling and simulation approach is part of a complex socio-technical system: the provided insights affect the ongoing business model innovation process. Therefore, the model contributes to exploring possible mechanisms and outcomes rather than predicting the future. It allows companies to examine potential risks in the future before these 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 and the benefits for the network as a whole, which is an important condition for network-level business models (Lindgren et al., 2010).

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 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 robust decision-making under deep uncertainty (Kwakkel, 2018). It could identify combinations of parameters and variable settings for improving CBM resilience. It helps uncover factors that dampen the negative effect of extreme externalities or find ways to deal with extreme events by changing the configuration of the CBM design according to the environment.

As this work also provides 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. It may provide opportunities to integrate business model experimentation literature and studies on the dynamics of supply chain management, e.g., Costas et al., 2015; Trkman et al., 2015; Zarandi et al., 2008; Zimon et al., 2019).

4.5.5 Implications for practitioners

Agent-based approaches help stakeholders understand the system in which they operate and what role they play. They provide 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 and 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). However, 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.

4.6 Conclusion

This study contributes to developing ex-ante circular business model experimentation methods by proposing a quantitative approach 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 knowledge and design solutions related to obstacles that currently hamper CBM implementation. Participatory agent-based modelling allows us to simulate actors and technologies' day-to-day activities and interactions due to the 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 benefit the collaborative initiative and 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 CBMs involving stakeholder collaborations. This study shows that participatory agent-based modelling and simulation are powerful methods for circular business model experimentation. Hence, we invite the research community to adopt it as a standard approach for studying and improving circular business models.

5

Study 4

Re-Organise: game-based learning of circular business model innovation

This chapter[5] demonstrates how collaborative modelling and simulation methods support (future) professionals improve ISN designs through circular business model innovation. This is demonstrated using an experimental study with students in higher education. The study explores in detail how and to what extent game-based learning activities contribute to teaching circular business model innovation (CBMI). CBMI is the complex and dynamic process of redesigning business models for the circular economy. (Future) professionals would benefit from content-related, personal, interpersonal and iterative design thinking competencies to deal with the intricacies of CBMI.

The study uses a business game called 'Re-Organise', which originates from practice-oriented research into local community waste reuse. To conduct the experiment, the business game was redeveloped into an education game and provided with digital teaching and assessment materials, thus creating an educational package. To demonstrate the effect of gameplay, we experimented with 89 students in an MSc. Industrial Ecology programme. We worked with an experiment and a control group. All students filled out EMF's circular business model canvas and a learning reflection using Dee Fink's taxonomy after studying the reader and a personally assigned game role but before actual gameplay. The experiment group updated both the canvas and the reflection in a discussion after gameplay. The control group discussed and updated their work only before gameplay. The results were analysed using text-mining and qualitative methods, e.g., word-by-word comparison of pre- and post-test results, co-occurrence with words from the teaching materials, and sentiment polarity of the submitted reflections. Findings show that the students in the game group created richer business models using a larger variety of waste processing technologies. Moreover, the education game invoked a larger variance of positive and negative sentiments towards the learning experience. Findings indicate that gameplay thus supported the students in redeveloping their business model and increasing reflective competencies during learning. The detailed results (i.e., per business model element and learning category) enhance understanding of game-based learning for circular business model innovation. Recommendations for improvement of the education game, the education package, and the analysis methods were identified and will be implemented.

This study demonstrates how participatory simulation methods, such as serious gaming, can support developing knowledge, skills and attitudes that current and future industrial symbiosis stakeholders need to implement circular business models.

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The first author conceptualised and performed the research. The other authors had facilitating and advisory roles. Minor textual edits have been made to ensure alignment of the published paper into this dissertation.

5.1 Introduction

The transition to a circular economy (CE) has increasingly gained attention among scholars and practitioners over the past fifteen years (European Commission, 2019). CE is an alternative to the dominant linear economic model (Geissdoerfer, Savaget, Bocken, et al., 2017; Ghisellini et al., 2015; Ness, 2008). CE aims to close, slow and narrow resource loops, e.g., products, materials, and energy (Bocken et al., 2016), and create economic, environmental and social benefits (EMF & McKinsey, 2014). Therefore, CE provides a promising way to decrease resource demands and environmental footprints while maintaining (or even increasing) social welfare and well-being.

Businesses developing and implementing novel circular business models (CBMs) play a crucial role in the circular economy transition (Bocken et al., 2016; De Angelis, 2016, p. 38; Geissdoerfer, Savaget, & Evans, 2017). Business model innovation is the process of devising or improving value creation, delivery and capture by designing new business models or reshaping existing business models (Osterwalder et al., 2010; Zott & Amit, 2010). In line with the work of Guldmann (2018), our definition of Circular Business Model Innovation (CBMI) is the process of redesigning linear business models into circular business models to create, deliver and capture value through slowing down, closing and narrowing cycles.

Students in higher education are increasingly drawn to CE knowledge and practices. Many of them will become future CBM innovators or - at least - stakeholders affected by novel CBMs. This paper aims to contribute to teaching business model innovation towards circularity by evaluating an education package around a serious board game called '*Re-Organise – The Game*', abbreviated as *Re-Organise*, developed in earlier work (Lange, 2019b). We hypothesise that explorative and design-driven serious gaming is a powerful method to simulate and teach the intricate dynamics of shaping and implementing CBMs. In addition, we study the extent to which students learn and perceive their learning experience in detail. The findings of this study contribute to the further development of circular economy business modelling in higher education.

In the following sections, we first elaborate on the challenges regarding circular business model innovation in higher education and explore using game-based learning in circular business model education. Then, we introduce the game and the education package. Next, we explain how we studied the learning effects of the *Re-Organise* education package. The last sections discuss the learning effects and what this means for future research and education concerning circular business model innovation.

5.2 Literature review

5.2.1 Learning and teaching in higher education

Literature on game-based learning in higher education lacks shared definitions of learning (Vlachopoulos & Makri, 2017). However, there is abundant general literature on learning taxonomies. Scholars generally accept three learning taxonomies (Dee Fink, 2013): [1] cognitive, involving understanding, thinking and solving problems; [2] affective, comprising interaction with others and self-reflection; and [3] psychomotor, entailing experiential learning, reflection and action. The most influential cognitive taxonomy is the one created by Bloom (1956) and revised by Krathwohl et al. (2002). The taxonomy describes six types of learning, from remembering knowledge to creating solutions. Teachers have widely used it to design teaching activities. However, this taxonomy has been criticised for lacking affective and psychomotor aspects of learning. Several scholars have created taxonomies to structure those learning perspectives (e.g., Cooper & Harrow, 1973; D. Krathwohl, 1964). Dee Fink's taxonomy (2013) is a widely used and practical framework that integrates cognitive, affective and psychomotor learning into six learning categories: foundational knowledge, application, integration, human dimension, caring, and learning how to learn. This study uses Dee Fink’s taxonomy to provide structure in analysing the learning impact.

5.2.2 Circular business model innovation

Circular business models are rooted in multiple business and sustainability-related fields (Geissdoerfer et al., 2018). Some of these fields are Industrial Ecology (Graedel & Allenby, 2010), Cradle-to-Cradle (Braungart et al., 2007) and the Performance Economy (Stahel, 2008). Based on the work of Richardson (2008), Geissdoerfer *et al.* (2018) state that CBMs articulate the logic of how organisations create, deliver, capture and offer economic, environmental and social value to multiple stakeholders by closing materials cycles. Circular business model innovation – more than regular business model innovation - involves developing a comprehensive set of novel collaborations among previously unacquainted stakeholders (Geissdoerfer et al., 2018). While traditional business model innovation is already challenging and time-consuming (Chesbrough, 2010), sustainable business modelling - such as CBMI - is even more complex (Roome & Louche, 2016). Understanding how business model designs affect key activities, processes, and economic, environmental and social impact across multiple stakeholders is crucial to achieving circularity. To do so, students need to understand, apply and integrate all dimensions of circular business models, including value proposition, value creation and delivery and value capture for creating and maintaining successful circular practices. EMF & IDEO (2016) provided a business model canvas to support this broad integration of CBM dimensions. It is built upon the traditional canvas elements by Osterwalder et al. (2010), addressing circularity and multiple sustainability values.

5.2.3 Challenges in teaching circular business model innovation

Innovating circular business models requires a variety of competencies because of the broad set of stakeholders involved, each with different economic, environmental and social values. Professionals designing new circular business models are expected to have combinations of applied knowledge and skills regarding operations and organisation and develop attitudes that enhance coordination and collaboration (Gábor Herczeg et al., 2018). We now elaborate on the different types of learning required for circular business model innovation.

Content-related competencies

Circular practices involve connecting output flows to production inputs, often first converting the waste streams into usable resources, requiring technological and organisational knowledge and skills. Furthermore, students must consider multiple CE strategies (PBL Netherlands Environmental Assessment Agency, 2019) for economic, environmental and social value creation and capture (EMF & McKinsey, 2014). Thus, students need to understand, create and apply business models that describe the implementation of new technologies and organisational arrangements (Guldmann & Huulgaard, 2020). They also need to understand and apply foundational concepts of the circular economy and sustainable impact (Centobelli et al., 2020). In this study, we refer to these as content-related competencies.

Personal and interpersonal competencies
CBMI requires more than connecting residual materials to production processes.
It entails the creation of shared and sustainable value among partners and customers, spanning across organisational boundaries (Geissdoerfer et al., 2018). Creating collaborations across stakeholders requires personal and interpersonal skills, behaviours and attitudes. The viewpoints regarding normative sustainability goals and affective competencies to reach collaborations are crucial to creating and maintaining a circular business (Breuer et al., 2018). Thus, students need to reflect upon their learning experiences and develop values, interests, and feelings related to the topic, their peers and the learning process.

Iterative design thinking competencies
CBMI is characterised by highly uncertain and changing conditions (Guldmann, 2018, p. 78). Companies may hesitate because alternative options are automatically discarded by cooperating and investing in certain resource conversion technologies. A competition among technical, organisational and network solutions may thus emerge (Korhonen et al., 2018). As circumstances change and stakeholders learn and adapt, CBMs support conversations among stakeholders to improve the CBM design. Thus, learning outcomes in CBMI education must include the corrective iterative nature of CBMI (Wynn & Eckert, 2017). Improving and learning are basic elements of CBMI (Baldassarre et al., 2019) since iterative design thinking processes support integrating theory with practice. Therefore, design thinking must be included in teaching CBMI (Geissdoerfer et al., 2016).

To summarise, teaching CBMI should include technical and social aspects, facilitate stakeholder integration, follow collaborative and inclusive processes (Breuer et al., 2018), and incorporate iterative design thinking to develop new collaborations and organisational arrangements in a dynamic environment. It needs personal and interpersonal reciprocity and integration of technical and social perspectives. Iterative thinking is a key element in CBMI (Geissdoerfer et al., 2016), requiring reflective action, adaptation or even rethinking the CBM design. The students learning about CBMI need to be engaged in all learning domains. Teaching students about these complex issues and processes strictly theoretically is therefore insufficient.

5.2.4 Game-based learning for circular business model innovation

Higher education institutes increasingly use serious games as rich, safe and interactive learning tools (Caponetto et al., 2014)). Serious games enable players to experience situations in a virtual world, aiming to have a positive and meaningful impact on skills development (Susi & Johannesson, 2007). Fraccascia, Sabato and Yazan (2021) show that digital games are suitable for teaching business dynamics of circular practices but are limited in direct communication. Board games have not yet been studied as extensively as digital games, but they are considered suitable for collaborative games due to their transparency and immediate interactive nature (William et al., 2018). Serious games are explicitly suitable for solving complex problems in collaborative settings (Geurts et al., 2007). They provide a safe virtual learning environment, allowing students to make mistakes without risk. Game-based learning - learning during and from playing serious games - fosters learning engagement through role-playing (Tobias et al., 2014).

Numerous studies have shown that teaching sustainability through game-based learning is effective (e.g., Katsaliaki and Mustafee, 2012; Bevilacqua *et al.*, 2015; Chappin, Bijvoet and Oei, 2017). Serious games have already been developed to teach sustainable design decisions (e.g., Clarke, 2020), circular economy design and business opportunities (e.g., Inchainge, 2019), finance-focused circular economy (K. Whalen, 2017) and circular product design (K. A. Whalen et al., 2018; K. Whalen & Peck, 2014). Multiple games have been developed to teach business modelling (e.g., Innovative Dutch, 2021) and business model innovation (e.g., Davidovici-Nora, 2013). Fraccascia, Sabato and Yazan (2021) conclude that game-based learning is necessary to teach innovations in circular business modelling. Manshoven & Gillabel (2021) recently published an article presenting a game for educating business model innovation. They tested the learning effects using game observations and post-test surveys.

Literature suggests increasing rigour, detail and structure to enhance understanding of game-based learning for CBMI. Rigour is obtained through utilising pre- and post-test data from randomised experiment and control groups (Connolly et al., 2012). Boyle et al. (2016) suggest studying the interplay between game design and mechanics, other educational activities and learning on a detailed level. By connecting game mechanics to learning taxonomies, a structured foundation for understanding and communicating the effects of game-based learning is provided (Arnab et al., 2015).

5.2.5 Study objectives

CBMI is already challenging for practitioners, let alone for students without working experience. Therefore, teaching must take place in a safe but realistic learning environment to facilitate students becoming the circular professionals of the future. Most existing studies on game-based learning of CBMI use data from game observations and post-test surveys. By experimenting using our education package *Re-Organise*, this study furthers understanding of game-based learning for CBMI. We collected data from a pre- and post-test experimental and control randomised group study. We analysed this data on a detailed level: per business model element (EMF & IDEO, 2016) and learning category (Dee Fink, 2013). By doing so, this study aims to provide rigorous, detailed and structured recommendations for enhancing research on game-based learning for circular business model innovation while improving the game and accompanying educational package.

5.3 Methods

We start this section by presenting the origin of the game, the game characteristics, and the game education package, including student assignments. Then, we explain how we conducted the experiment and collected data from the submitted student assignments. Last, we explain how we analysed the data to explore any learning effect.

5.3.1 Re-Organise - a game originating from case study research

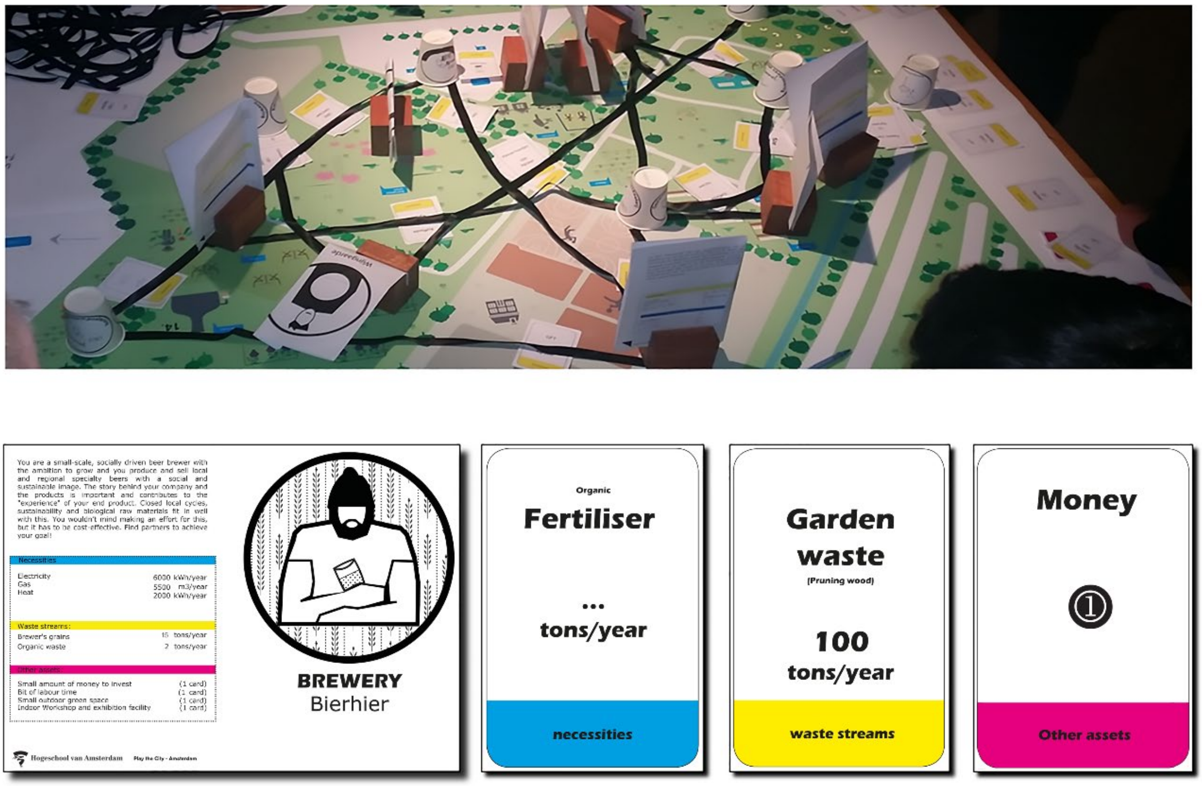
Re-Organise is an explorative and design-oriented serious game. It was based on practice-oriented research in two case studies of agro-industrial symbiosis networks in Amsterdam, the Netherlands (Lange et al., 2017; Mulder et al., 2018). These networks consist of industrial and commercial actors that exchange (mainly biotic) materials, energy and information to increase resource efficiency (D. R. Lombardi & Laybourn, 2012). The game has been developed in two versions: version 1 for the *research project* and version 2 for the *education package*.

In the *research project*, practitioners in the two cases aimed to find ways to exchange, process and re-use their waste streams locally. They intended to increase the creation – and avoid the loss - of economic, environmental and social value (Mulder et al., 2018). The board game was developed by a consortium of project researchers, circular economy consultants and a game developer. *Re-Organise* is a typical simulation game creating a scenario-based environment. It consists of various real-life activities, phenomena or mechanisms and has rules to simulate reality for training and learning (Vlachopoulos & Makri, 2017). We used the game for two purposes. Firstly, it was used to validate collected data regarding waste streams and necessities with the stakeholders. Secondly, it was used for the ideation of new closed-loop value networks. The game resulted in the co-creation of several collaborative and circular business model concepts. After ending the research project, one of the concepts created during gameplay, was implemented in the form of a composting cooperative (Tuinen van West, 2019).

We anonymised the game and added an *education package* to teach circular business model innovation to bachelor's and master's degree students. The game and education package were iteratively redesigned to improve the learning experience during two pilot studies with undergraduate engineering students and lecturers at the Amsterdam University of Applied Sciences.

5.3.2 Game characteristics

Re-Organise is a collaborative multiplayer board game consisting of 8 to 16 roles (figure 5-1).



You are a small-scale, socially driven beer brewer with the ambition to grow and you produce and sell local and regional specialty beers with a social and sustainable image. The story behind your company and the products is important and contributes to the "experience" of your end product. Closed local cycles, sustainability and biological raw materials fit in well with this. You wouldn't mind making an effort for this, but it has to be cost-effective. Find partners to achieve your goal!

Necessities	
Electricity	6000 kWh/year
Gas	5500 m3/year
Heat	2000 kWh/year
Waste streams:	
Brewer's grains	15 tons/year
Organic waste	2 tons/year
Other assets	
Small amount of money to invest	(1 card)
Bit of labour time	(1 card)
Small outdoor green space	(1 card)
Indoor Workshop and exhibition facility	(1 card)

Figure 5-1 An impression of Re-Organise. The game consists of a board, technology and role pawns, connection ribbons and play cards (representing necessities, waste streams and other assets).

In the game, each player (or duo) takes on the role of an organisation within an agro-industrial park. A role description is given on a card placed as a pawn on the board. Examples of game roles are a *cattle farmer*, *restaurant owner* and *recreational area manager* (public institution). The players' goal is to find as much local use for their waste streams (represented by '*Waste*' cards) as possible while maximising the fulfilment of their own needs ('*Necessities*' cards). To achieve this, they can use several assets ('*Other assets*' cards) to invest in processing technologies. The optimal outcome for a player is to play all waste and necessities cards on the board without using other assets. The players are free to do whatever it takes to close their loops, provided that the game is played in a respectful, safe manner and the rules as described on the cards are being followed. Despite the freedom given to the players, the gameplay unfolds more or less according to the process in figure 5-2. The game ends after a given playing time of 1 hour.

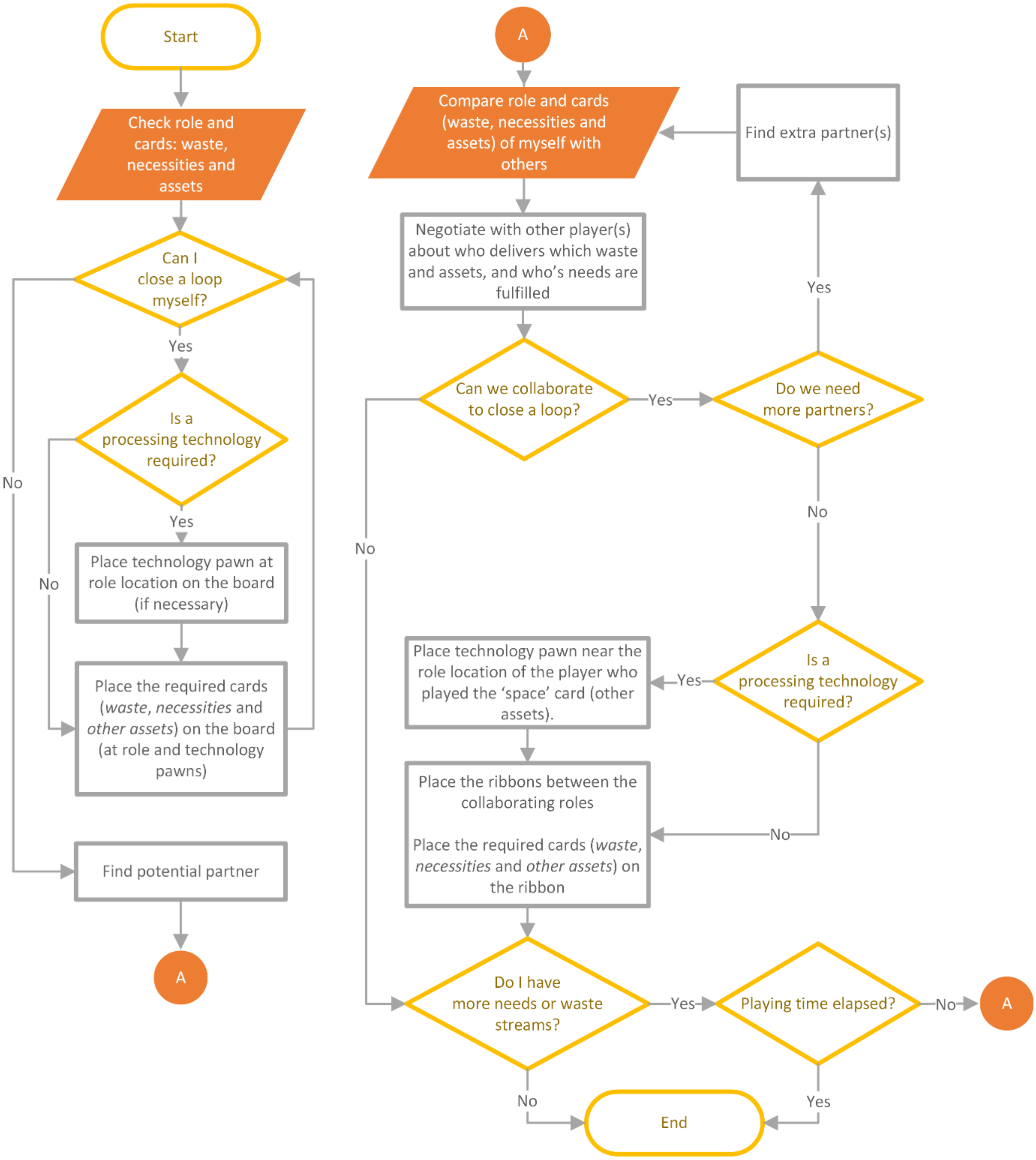


Figure 5-2 Re-Organise game process.

Table 5-1 shows how real-life elements were reflected in the first version (business game) and the last version (education game).

Table 5-1 Real life game elements versus the elements of both game versions.

Research project		**Education package**
Real-life elements	Game elements	Game elements
Case area	Board	Board
Case participants	Role pawn (with real names)	Role pawn (anonymised)
Waste streams	Waste streams cards with quantities	Waste streams cards (simplified by rounding off quantities)
Needs	Necessities cards with quantities	Necessities card without quantities
Other assets	Not included in the game	‘Other assets’ cards without quantities
Potential processing technologies to turn waste into products	Technology pawns (with input and output quantity ranges)	Technology pawns (with input and output quantity ranges)
Closed-loops	Ribbons	Ribbons

We aimed to explore solutions in the original game for the research project. However, in education, we aimed to teach the broader concept of CBMI. Therefore, we iteratively redesigned the game during the pilot to address this change of purpose. Compared to the original game, some complexities were simplified or added to improve the game experience for our teaching purposes.

One of the improvements entailed reducing the variety of waste cards by rounding off quantities to multiple units of 1, 2, 5, 10, etcetera. To avoid players losing interest or wasting time making exact input-output calculations, we deleted the quantities from the necessities cards and allowed gameplayers to estimate the quantities roughly. The third difference with the original game was the addition of the ‘other assets’ cards. We intentionally left out any obstacles to creating novel business concepts during the research project to increase creativity among case study participants. However, for educational purposes, we decided it was necessary to enrich the game experience with the notion that assets such as money, time, space, network connections, and knowledge are required to close the loop. The ‘*other assets*’ cards created this extra dimension. For example, the players had to collect money, time, and space cards to invest in technology. The instructions were provided on the technology pawn.

5.3.3 Game education package

According to the principles of constructive alignment (Biggs & Tang, 2010), the education package was created to align learning objectives (study and gameplay), activities and assessment. Based on the literature study, the following learning objectives were determined:

Content-related competencies, i.e.:

1. applying biotic waste streams, resource needs, processing technologies and other assets to close loops in an agro-industrial symbiosis network;
2. applying the Circular Business Model Canvas by EMF & IDEO (2016).

Personal and interpersonal competencies, i.e.:

3. understanding different perspectives and goals of the various actors, including their own;
4. reflective skills on the learning experience.

A design thinking competency, i.e.:

5. understanding and experiencing that CBMI is a dynamic, iterative design process.

To achieve the learning goals, we provided the student with the education package consisting of the following items:

- the game, and a flip-over to summarise the game outcomes.
- digital supplementary teaching materials:
  - an introductory presentation (presented during a lecture)
  - a digital reader with a brief explanation of the assignment, a case description, and descriptions of the roles and technologies;
  - an assigned role (ticket).
- digital assessment materials:
  - a circular business model canvas (CBMC) questionnaire; and
  - a reflection questionnaire.

We assessed the learning experience utilising two existing methods. Students filled out a Circular Business Model Canvas (CBMC) to prove that they achieved the required learning goals. In addition, a reflection assignment based upon Dee Fink's learning taxonomy was used to demonstrate the students' perception of learning. The CBMC assignment consisted of the canvas provided by EMF & IDEO (2016); see Appendix E. The CBMC was assumed to be easy to comprehend by our students because the traditional canvas is widely known by many students that obtained a bachelor's degree in business and technology innovation. The canvas has widely been in use since 2017. Furthermore, we assumed the questions in the CBMC to be quite straightforward. The reflection assignment (Appendix E) consisted of a questionnaire based on the taxonomy by Dee Fink (2013) to address knowledge construction, problem-solving skills and affective attitudes and behaviour.

The following sections show how we conducted an experiment using the submitted CBMs and personal reflections to measure the actual and perceived learning experience. Furthermore, we show how a mix of qualitative and quantitative data analysis methods was used to provide insights concerning the required competencies.

5.3.4 Experimental design to measure learning effects of gameplay

We conducted an experiment with 85 first-year students at the Master of Science Programme Industrial Ecology (joint degree of Delft University of Technology and Leiden University, the Netherlands) and 11 undergraduate students and PhD students from the Faculty of Technology, Policy, and Management (Delft University of Technology, The Netherlands), see Table 5-2.

Many Industrial Ecology students were new to the field, as the experiment was performed during their introduction week. About half of the participants were international, and the other half were Dutch. English was the language used, but this was not the primary language for most students. The students attended a lecture two days before gameplay in which they were introduced to the game. During the lecture, they received the reader and the assignments. They were randomly given a role ticket. The students filled out and submitted the CBMC and reflection assignment in the following days. Then, we split the group into a game group and a control group, ensuring that the roles were equally distributed. The game group first played the game, then discussed the outcomes during an interactive tutorial in the classroom and updated both CBMC and reflection assignments. The control group students first discussed their CBMCs and reflections during the interactive tutorial. They updated their work and then played the game afterwards. Three weeks after playing the game, the students were asked to reflect and discuss their opinions on their learning experience during a lecture. Furthermore, they provided written feedback during the course evaluation.

Table 5-2 Experimental design.

Group	**Experiment step**			
	Step 1	**Step 2**	**Step 3**	**Step 4**
Game group 1 (n=46)	1A Pre-test: • Lecture • CBMC + reflection assignment	Gameplay	1B Post-test • Discussion in an interactive tutorial • CBMC iteration + new reflection assignments	1C Student feedback session • Qualitative feedback (from discussion and evaluation)
Control group 2 (n=43)	2A Pre-test: • Lecture • CBMC + reflection assignments	2B Post-test • Discussion in an interactive tutorial • CBMC iteration + new reflection assignments	Gameplay	2C Student feedback session • Qualitative feedback (from discussion and evaluation)

5.3.5 Data analysis methods

Table 5-3 provides an overview of how various data collection and analysis methods contribute to multiple perspectives on this study's learning objectives. Text mining is a quantitative manner of automatically extracting and processing written information by computer. It supports gaining new insights into that information (Hearst, 2003). We generally followed the generic text mining steps from Kwartler (2017). Table 5-3 shows that three simple text mining methods were used for the comparative analysis. These are [1] a comparison of pre-test and post-test CBMC and reflection answers per student, [2] a comparison of the use of technology and role card terms in the CBMCs, and [3] a sentiment analysis of the answers in the submitted reflection. After text organisation and data clean-up, the work of 79 students (44 in the game group, 35 in the control group) remained suitable for data analysis.

Table 5-3 Data collection and analysis methods to evaluate competencies.

Competencies			**Data collection and analysis**		
			CBMC assignment (pre- and post-test, quantitative comparative analysis)	**Reflection assignment** (pre- and post-test, quantitative comparative analysis)	**Classroom feedback and course evaluation** (post-test, qualitative analysis)
Content-related	1	Applying waste streams, resource needs, processing technologies and other assets.	• Use of card words during the learning experience (sum of both CBMCs).		General Feedback.
	2	Applying the CBMC.	• Presence of unanswered questions; • Difference between pre-test and post-test CBMC answers. • Use of card words during the learning experience (sum of both CBMCs).		
Personal and interpersonal	3	Understanding different roles, including their own.	• Use of card words during the learning experience (sum of both CBMCs).	• Sentiment analysis of the reflection answers (Human Dimension and Caring).	
	4	Reflective skills on the learning experience.		• Difference between pre-test and post-test reflection answers. • Sentiment analysis of the reflection answers (Learning How To Learn and Caring).	
Design thinking	5	Experiencing that CBM innovation is a dynamic and iterative design process.	• Difference between pre-test and post-test CBMC answers.	• Difference between pre-test and post-test reflection answers. • Sentiment analysis of the reflection answers (Foundational Knowledge, Application, Integration).	

Difference between pre-test and post-test CBMC answers

We compared the word-by-word difference between pre-test and post-test CBMCs of each student. The results show us whether the CBMCs were filled out multiple times. Since scholars widely consider repetition as an important premise for the improvement of knowledge and skills (Brabeck & Jeffrey, 2014), this measurement tells us which group experienced a better application of the CBMC (learning objective 2) and a more thorough learning reflection (learning objective 4). Furthermore, the change of answers shows which of the groups experienced the dynamic and iterative nature of the design process (learning objective 5).

We performed multiple text organisation, data cleaning and feature extraction steps. First, the pre- and post-test answers were extracted from the submitted work, anonymised and ordered per student, group, and question. The data was cleaned, and unanswered questions were tagged as such. In addition, the complete answers to the pre-test and post-test were ordered per question. Then, the absence of answers in both pre-test and post-test and the presence of similar patterns were detected.

For visualisation and analysis purposes, the results were ordered in four categories of answers, see section 5.4:

1. “Both no answers”, in which no answer was given in both the pre-test and the post-test
2. “Same answer”, in which the pre-test and post-test consisted of precisely the same answer
3. “Addition to the first answer”, containing a similar pattern between pre-test and post-test, and an addition, and
4. “New answer”, in which the pre-test answer was completely removed and exchanged for a new answer.

To gain insights into the words most used, we also created word clouds of the control and game groups (see Appendix E)

Use of information from the technology and role cards in the CBMCs

We measured the extent to which words used in each student’s complete work (pre-test + post-test) related to the game cards (i.e., technologies, waste streams, needs and other assets). By doing so, we compared the effect of gameplay on students’ learning objectives 1 to 3.

This measurement's text organisation and feature extraction steps were conducted as follows. First, a document-term matrix was constructed from the anonymised data by extracting the answers from the CBMC questions. Another document-term matrix was constructed from the technology cards and the role cards of the game. The data was ordered into four categories. The categories included words related to [1] technology names on the technology cards and terms related to the [2] waste streams, [3] needs and [4] other assets on the player’s role cards. Then, both document-term matrices were cleaned by:

1. correcting misspellings;
2. removing punctuation, numbers, capitals and whitespace;
3. removing stop words and irrelevant words, e.g., words related to the university name or game material;
4. replacing synonyms through lemmatisation;

5. word stemming (reducing inflected words) to avoid a mismatch between words with the same meaning but a different suffix.

The card words used at least once in both pre-test and post-test CBMCs were then identified by comparing the cleaned document-term matrices. We visualised the percentage of words used in the CBMCs compared to the total number of relevant words in the game cards (see Results). The word clouds in Appendix E show the words most used.

Difference between pre-test and post-test reflection answers

The answers to the two measurements of the submitted reflections were examined. These questions are about the perception of learning, according to the learning categories of Dee Fink (2013). In the same way as the CBMCs, we compared the differences between the answers per learning category.

Sentiment analysis of the answers to the reflection assignments

Sentiment analysis is intended to measure the emotional intent of persons based on the text these persons produced (Kwartler, 2017). In this study, we used the sentiment dictionary by Hu & Liu (2004) to tag polarised words (RDocumentation, 2019) and measure the emotional intent of students towards their learning experience. The polarity of the student’s answers indicates how positive or negative the students think about each of these categories. A polarity of 0 represents a neutral sentiment; 1 is positive; -1 is negative. A change in polarity score between the pre-test and post-test shows whether the students felt positive or negative sentiments towards the game-based learning experience. We set the number of words considered valence shifters at 6 before and 3 after the polarised word to optimise the polarity differences. The sentiment clouds in Appendix E provide insights into the relationship between words and sentiment.

Qualitative data from student feedback and observations

Through observations during the game, classroom feedback, and course evaluation, we gained more insights into students' learning experiences and perceptions.

5.4 Results

Students from the minor Data Science largely prepared data extraction from the submitted work and visualisation code at AUAS (Mooij et al., 2020; Zweep et al., 2020). The anonymised data is available in a public data repository (Lange, 2019a). In addition to the quantitative results presented in this section, Appendix E provides several word clouds to get a feel for the data.

5.4.1 Difference between pre-test and post-test CBMC answers

The measured differences between CBMC answers are shown in figure 5-3.

These results show that the game group made more changes in all questions of the post-test CBMC assignment. Questions related to the value propositions, key partners and key resources changed more than 50% after gameplay. However, the game group also contained more unanswered questions, particularly about *channels* and *revenues*. The game group participants were more actively involved in applying the CBMC for the second time, indicating a positive learning objective 2. Furthermore, the game group students have experienced a more dynamic and iterative design process, positively affecting learning objective 5.

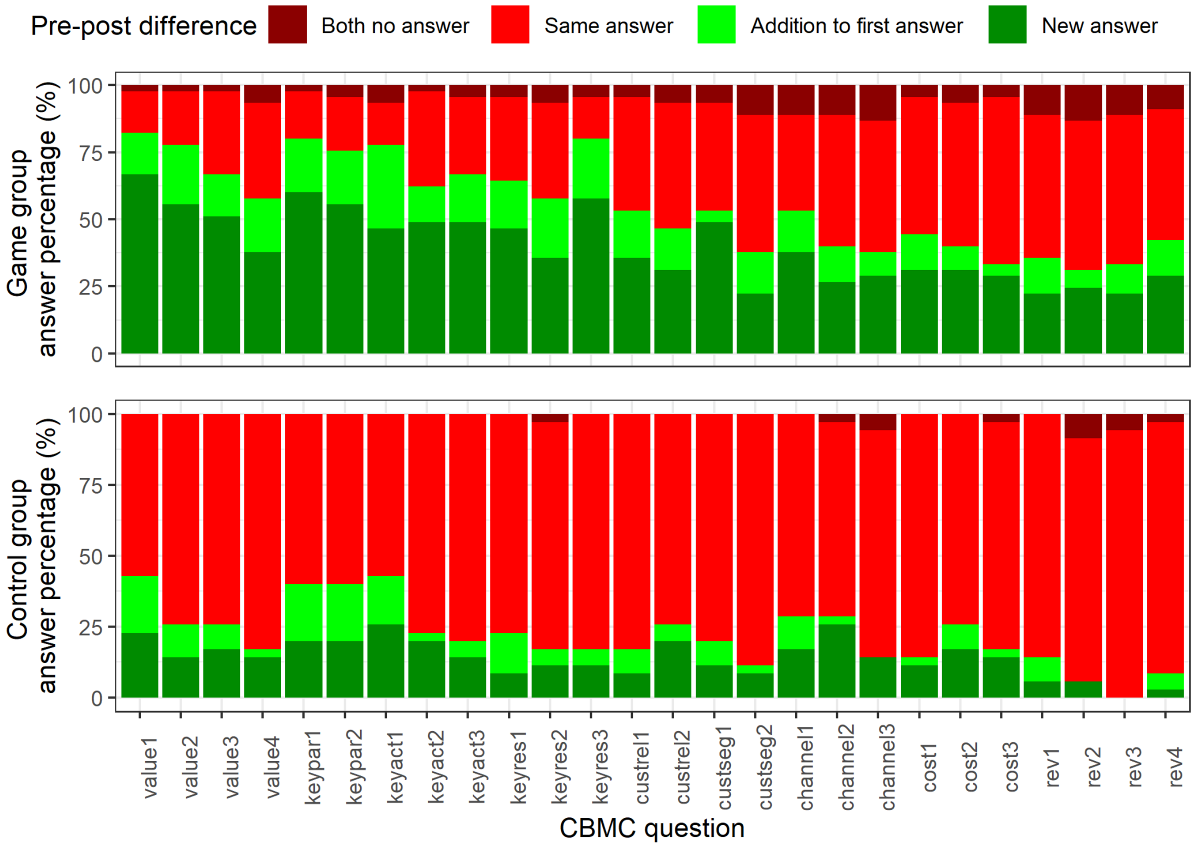


Figure 5-3 Difference between pre-test and post-test CBMC answers. The questions used in the CBMC assignments can be found in appendix E. Visualisation prepared by our students (Mooij et al., 2020).

5.4.2 Use of information from the technology and role cards in the CBMCs

The use of information from the cards in the submitted CBMCs is shown in figure 5-4.

The small sample size weakens the results, and therefore, we found no statistically significant differences between the groups. Nevertheless, these boxplots indicate that the game group used more terms related to technologies and needs and other assets to a lesser extent. These results suggest that there is a positive impact of the game on learning objectives 1 (application of technologies) and 3 (understanding the roles) and more thorough use of the CBMC (learning objective 2).

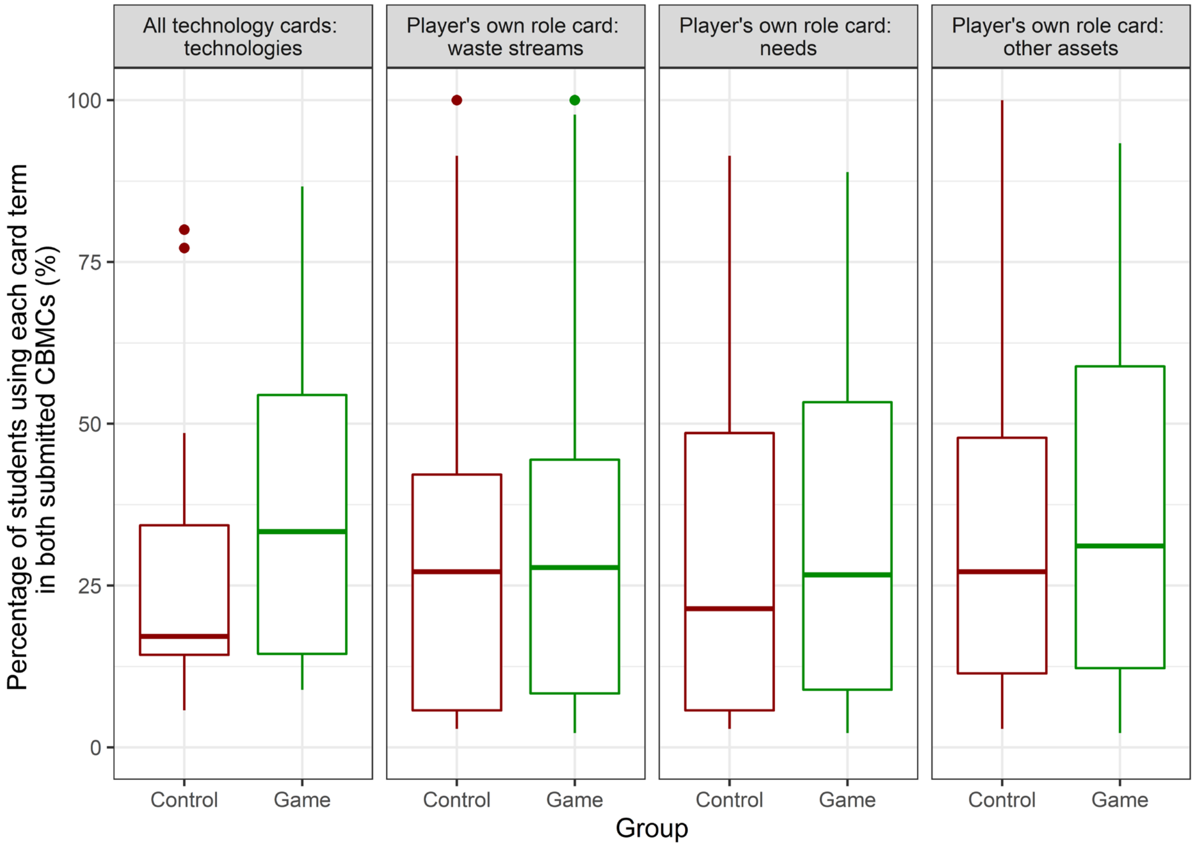


Figure 5-4 Percentage of students using each card term in both submitted CBMCs. Standard Tukey boxplot representation.

5.4.3 Difference between pre-test and post-test reflection answers

In the same way as the CBMCs, the answers between the pre- and post-test reflections were examined. This time, each of the answers to questions regarding the learning categories of Dee Fink (2013) were compared, see figure 5-5.

The results provide insights into the extent to which the perceived learning experience of students evolved. The game group participants made much more changes to the reflection than the control group. In line with Dee Fink (2013, p. 7), changes in thinking affect learning positively. Game group students have thus practised more reflecting on the learning experience (learning objective 4). Since the game group reflections show more answer differences, we can conclude that the game positively affects learning about iterative design thinking (objective 5).

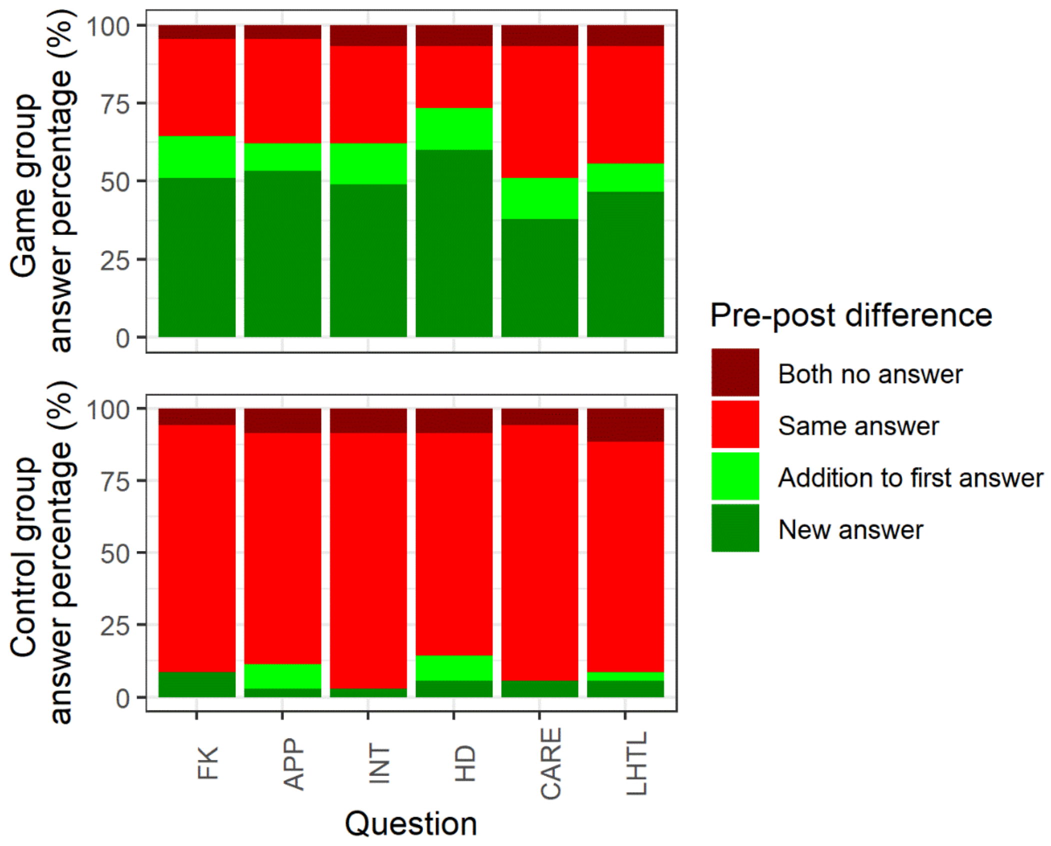


Figure 5-5 Difference between pre-test and post-test reflection answers. The questions can be found in Appendix E; each involves one question per learning category (Dee Fink, 2013). Students prepared this visualisation (Mooij et al., 2020).

5.4.4 Sentiment analysis of the answers to the reflection assignments

Figure 5-6 shows that the average polarity did not change. However, the boxplots' variance (i.e., interquartile range) reveals that many answers from the game group resulted in a more significant polarity change than the control group students. These results indicate that gameplay leads to practising a more thorough and outspoken reflection in the post-test (learning objective 4). The game group experienced more positive or negative feelings about applying and integrating knowledge, such as excitement or disappointment by (not) realising their plan. Moreover, we observed a broader sentiment variance concerning learning how to learn (LHTL). This variance suggests that the game invokes a stronger sense of contextual dynamics and the need for iterative design (learning objective 5). The question regarding the category Human Dimension (HD) reflects that game group students were clearly either more positive or negative about learning from themselves and other participants, referring to perspectives and goals of the various participants (learning objective 3). The sentiment cloud in Figure 5-7 gives an impression of the words used by the game group in this learning category.

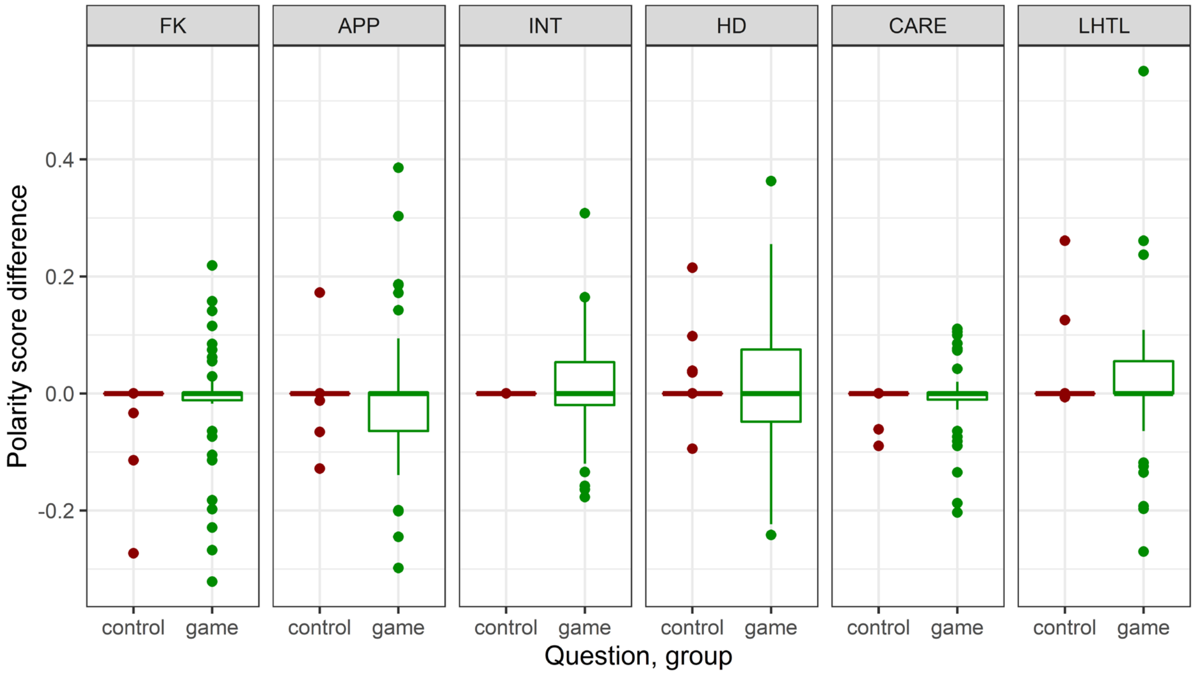


Figure 5-6 Polarity score difference of student answers to the reflection questions. Standard Tukey boxplot representation. The questions can be found in appendix E.

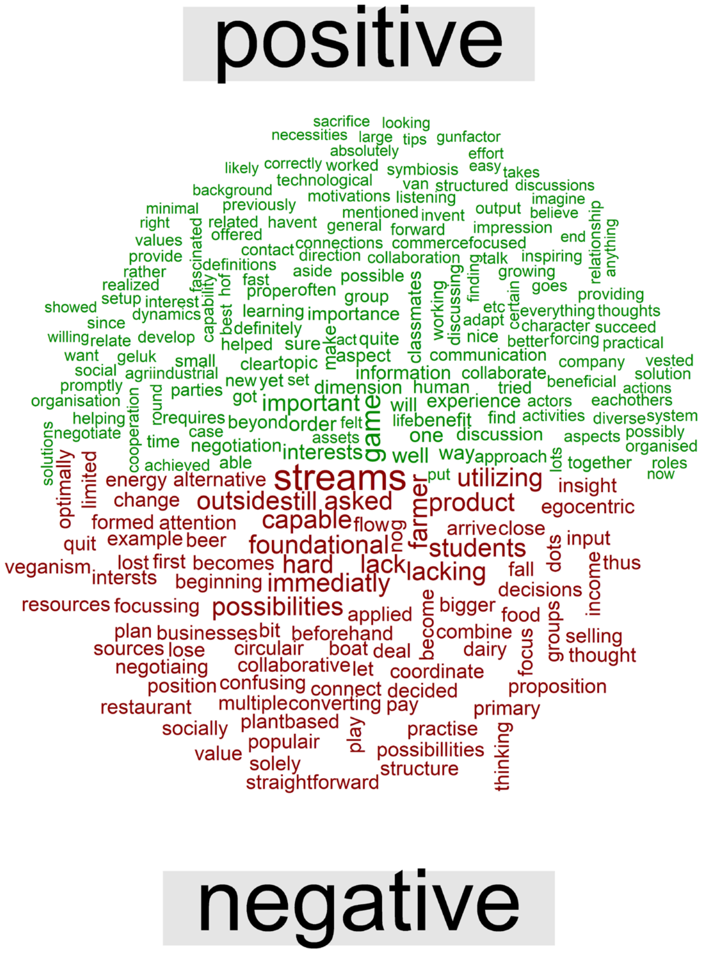


Figure 5-7 Sentiment cloud of the terms used in the learning category "Human Dimension". Source: submitted reflections of the game group (Lange, 2019a).

5.4.5 Student feedback and other observations

A qualitative analysis of the participant's feedback was performed to give more meaning to the results.

In the course evaluation, students from the Industrial Ecology programme generally found it *"a nice game to get the feeling of complexity and how processes can go unstructured."* However, few students did not quite understand why the game was not structured: they felt it would be *"more professional and better prepared"* if it were more bound by rules. Some students came up with ideas to improve the game in that direction. We explained to these students that coincidence and the unstructured nature of the game were deliberate elements to simulate real-world complexity and dynamics. Some students would have liked to have more background to apply the knowledge better, especially on applying the business model canvas. The business model canvas was more thoroughly explained in the discussion sessions (control group step 2 and game group step 3). The students declared that this made them feel more familiar with the canvas and comfortable using it. Their comments implied that more time and effort should be invested in explaining the CBMC and building up experience with its various elements. A few students declared that they disliked playing board games and did not like the assignment. Furthermore, a student suggested combining the game with other games to extend the learning scope on CBMI, industrial symbiosis and network development.

Discussions with participants of the mixed group of undergraduate and PhD students showed that they enjoyed the gameplay and found it instructive. However, these students were volunteering in their own time, so we can assume that they already had an intrinsic motivation to play a game about the topic. In addition, these students all have some degree of knowledge about the business model canvas and the circular economy.

5.5 Discussion

5.5.1 Reflection on the experiment results

The experiment results show that gameplay invoked the students to put more effort into adapting their work. It supported creating richer business models. Game participants used a richer palette of technologies, fulfilled needs and used other assets. However, the game did not result in more waste streams being re-used. The game imposes some boundaries on the maximum amount of waste to be recovered. It thereby simulates competition between the various solutions due to limited resources. However, we also conjecture that students' limited game time may have resulted in unoptimised resource recovery.

The results show the extent to which business model elements were affected by gameplay. For example, in *"customer segments"* and *"revenues"*, the questions related to who else might benefit from the business model were the least adapted by both groups (although still more than the control group, which almost left these topics unchanged). Since these questions require more background knowledge of the case, the limited modifications may be caused by the limitations of the case description and the simplified world the game represents. Thus, educators must be aware that the learning goals in mind are properly addressed by the game and accompanying educational materials. Another option is to iteratively adapt the game when certain questions are not addressed satisfactorily.

Furthermore, sentiment analysis results offer detailed insights into the students' perceived progress per learning category. The game resulted in stronger sentiments regarding the learning experience. The change of sentiment was the highest in learning categories application, integration, human dimension and learning how to learn. In the application and integration categories, negative sentiments were related to some students' frustrations when their pre-test CBM was not implemented during gameplay. These negative sentiments imply that students learned about competition in CBMI. Positive sentiments were more related to a sense of victory when loops were closed. Students in the game group had stronger opinions on integrating knowledge, whereas the control group students remained neutral on this topic. Thus, the game engaged students to integrate and connect ideas, technologies or people/organisations. The game also invoked stronger feelings on learning from themselves and others and the learning effectivity of the gameplay, implying that the perception of affective learning varies more as a result of the game.

The sentiment analysis and the qualitative evaluation strongly suggest that the game invokes a stronger sense of contextual dynamics. Some students only discovered during the evaluation lecture afterwards that the unstructured nature of the game was a deliberate element in teaching complexity and dynamics. Thus, the game often makes students experience a rollercoaster of frustrations, passion and emotions, which provides a (perhaps even critical) positive influence on learning (Tyng et al., 2017).

5.5.2 Key findings and implications

Effect of gameplay on learning and implications for research and education

The effect of gameplay for each learning objective (section 5.3.3) is discussed below.

Content-related competencies:

1. The game encourages the application of a more diverse set of resource needs, processing technologies and other assets to close loops in an agro-industrial symbiosis network.
2. The game motivates students to rethink their business model designs. Although students in both groups found the discussions on business model canvasses enlightening, the control group did not change their canvasses based on these discussions. These findings imply that the game positively impacts learning to apply the canvas. This evidence supports the conclusion of Fraccascia et al. (2021) that games are suitable learning tools for teaching circular business model innovation.

Personal and interpersonal competencies:

3. The game helps students understand the different perspectives and goals of the various actors, including their own. Evidence can be found in modifications made in the canvas elements *value proposition*, *key partnerships* and *customer relationships*. In the reflection assignment, the *human dimension* learning category was mostly affected by gameplay. In this category, a change of sentiment was strongly present.
4. Gameplay motivates students to reflect on their learning experience, as seen in the differences in modifications of the game and control group reflections.

Design thinking:

5. The answers to the CBMC and reflection assignments and the student feedback show that the game increases an understanding of the dynamic, unstructured and iterative process of CBMI. It also shows the need for an evaluative discussion after finishing the assignment to help some students understand the unstructured and competitive nature of the game. The richness of the submitted game group CBMCs shows that these students got to fulfil more needs and use more technologies and other assets.

To summarise, the results show that the aimed content-related, personal and interpersonal and iterative design thinking competencies are better developed after gameplay. Furthermore, the students' perceptions of their learning were also demonstrably higher after gameplay.

Experiment and analysis methods and implications for research

Using pre-test and post-test experiments with control and game groups provides strong evidence of how the circular business model canvas by EMF & IDEO (2016) and students' reflections evolved from game-play. We have shown that this can be done on a detailed level, i.e., results are visible per business model canvas element and learning category.

To our knowledge, measuring and analysing the student's perception of learning using Dee Fink's taxonomy is new in both the context of game-based learning and text mining. The taxonomy assumes that learning goes beyond the cognitive domain and that change is one of the most important learning indicators (Dee Fink, 2013, p. 7). Applying the sentiment polarity method to Dee Fink's six learning categories enabled us to measure each student's change of perception per learning category. This study thus demonstrated that change is measurable and can be analysed by employing digital text collection and mining methods.

The use of text mining for analysing written information from submitted student assignments is gaining attention among game researchers and educators but is still in full development (Ferreira-Mello et al., 2019). Some text mining methods, such as sentiment analysis, have been used to measure learning in serious board games e.g., William et al. (2018). The novelty of this study lies in proposing a method to match data from an existing CBMI tool and learning taxonomy with learning objectives (Table 5-3). By using mixed quantitative and qualitative data analysis methods, this study contributes to a broad and deep understanding of game-based learning.

To conclude, the amount of detail our experimental method provides can guide researchers and educators in shaping games so that the desired business model elements and learning competencies are addressed according to the needs of the course programme.

Game and education package design and implications for education

Although the original purpose of the game was to help practitioners explore solutions for closing the loop, its purpose could be extended to the broader scope of circular business model innovation after modifying the game. During redevelopment, the game was used with various players from different backgrounds. Undergraduate, graduate and PhD students from different programmes, part-time students with professional backgrounds, and research participants played the game for different purposes. The students in our pilots merely learned about the concept of closing loops; students participating in our experiment learned about CBMI.

The business model canvas' format provides formulated open questions, making the assignment comprehensible to students. The used business model canvas is only one of many (circular) business modelling tools. The game can thus be combined with other tools if it has a certain common ground with the game elements (i.e., technologies, roles, waste streams). The game is versatile, and it can be tailored for different learning objectives. Still, it must not be used standalone: it always needs additional materials and activities to help the participants understand and interpret the meaning of gameplay.

5.5.3 Limitations and avenues for future research

Some limitations concern our sample group. The groups of students consisted of a diverse mixture of Dutch and international students with different educational backgrounds. As a result, we observed a dichotomy between experienced and inexperienced students regarding the circular economy, business model innovation, and reflective skills or customs. English was not the native language for most students in our experiment, and specific circular business modelling jargon was even more challenging for many students. We have attempted to deal with these differences by randomising the division of students into groups, using pre- and post-test results to measure the development of each student, and using text mining methods to support the software in finding the right co-occurrences with the reader. Still, it would be of value to experiment with other types of students and groups, e.g., native English-speaking students or professionals in further education and compare the differences in outcomes. Furthermore, we expect that the game facilitator may also affect the results. Therefore, we recommend providing both lecturers and students with a minimum level of knowledge regarding the business model canvas and the taxonomy of Dee Fink.

The board game was intended to be played in a setting of multiple interacting participants to encourage free communication as if it were happening in real-world conversations. However, negotiations are increasingly being held through digital communication (Harvard Law School, 2020), especially during the COVID-19 pandemic. Therefore, we recommend converting this game into a digital variant, in which participants can communicate through chats or other social media services. It could provide interesting insights into the similarities and differences between physical and digital negotiation and its effect on CBMI. This game is created in the small context of agro-industrial symbiosis networks. It thus only simulates local and small-scale exchange and processing of organic materials, which may not appeal to all target groups. Future work may therefore encompass the simulation of technical material loops on multiple scales of collection and re-use. It would also be interesting to develop a less unstructured game version that includes the role of a facilitator to demonstrate how this will affect the course of events and the outcomes.

Although the circular business model canvas proved suitable for our educational purposes, it is certainly not the only relevant circular business modelling tool, especially since the circular economy is developing rapidly. It would be of value to experiment with other tools, for example, the value mapping tool by Nancy Bocken et al. (2015). The same applies to the used taxonomy in the reflection assignment. Since CBMI processes touch upon affective behaviour, skills and attitudes, the traditional taxonomy of Bloom (D. R. Krathwohl, 2002) would not have been sufficient, whilst Dee Fink's taxonomy does include these 'softer' sides of learning. Nevertheless, studying the effect of gameplay using other taxonomies that incorporate cognitive, affective and psychomotor learning is still warranted to enhance our understanding of teaching CBMI.

Quantitative text analysis methods are still most suitable for English texts. Therefore, we recommend conducting experiments with games in English until the next generation of text mining tools has been developed to an equal level. Another caveat is that the measurement groups were not large enough to make statements about statistical significance. Repetition of the experiment with more groups of students is needed to provide a conclusive answer to this.

This study provides opportunities to develop new ideas for both education and research. The education package could be tailored in detail. It can also be combined with other games and simulations of industrial symbiosis networks and circular business modelling contexts, which may provide students with other perspectives on the circular transition, such as material criticality or financial, environmental and social impact. In line with suggestions made by Tseng et al. (2021), the game could be used to create a digital twin, e.g., an agent-based model, to study the different decision-making processes and other activities during the development and implementation of circular business models. Doing so may eventually provide more insights into the role of business model innovation in the transition towards the circular economy.

5.6 Concluding remarks

Our study findings provide detailed information per business model element and learning category. It furthers understanding of game-based learning for circular business model innovation while improving serious games and accompanying educational packages. Therefore, this section presents this study's conclusions and contributions from three perspectives: the game, the education package, and the experiment.

This study demonstrates how *Re-organise* evolved from a product of practice-oriented research – a business game - into an educational tool for game-based learning – an educational game. During this process, the game objectives changed from exploring solutions for closing loops to teaching about circular business model innovation. It was necessary to enhance the gameplay experience by simplifying the game cards. Adding the assets cards to the game was necessary to ensure that the students understood that innovation also involves making investments. The game is versatile, and it would be interesting to extend or redevelop it for other contexts and sectors. However, additional materials need to be developed to ensure an optimal learning experience if this is done. In general, this study thus shows how originally explorative business games for practitioners can be redesigned for higher education purposes by aligning the game narrative with course learning objectives and assignments.

The *Re-Organise game - education package* teaches the iterative process of circular business model innovation. The game is a realistic simulation, as it was based on real-world case evidence. It encourages the application of technologies to fulfil needs, which helps in a better understanding of the role of technologies in the real world. Important dynamics and path dependencies that affect circular business model innovation are revealed during gameplay; the players' decisions can undercut planned solutions in earlier game stages. The gameplay also increases the student's reflective competencies on the learning experience. It gives insights into the importance of social interactions and learning from oneself and others. Furthermore, it motivates students to develop interests and feelings about circular business model innovation, entrepreneurship and the concept of industrial symbiosis. Based on these findings, we argue that game-based learning is important in helping students understand, synthesise, and iteratively improve circular business models. We recommend including this education package and other game-based learning tools in curricula that teach circular business model innovation and industrial symbiosis.

In the context of game-based learning for circular business model innovation, this article is the first to combine mixed quantitative and qualitative analysis methods on data from pre- and post-test experimental and control groups. Echoing Dee Fink (2013, p. 34), learning is a process of change: *"No change, no learning"*. The methods used offer insights into this change process on a highly detailed level: per business model element and Dee Fink's learning category. Text mining is an exceptionally powerful method to study the changes in large text corpora of many sources. We applied it to CBMCs and reflections of large student groups in this study. Since emotional change is a strong indicator of learning, this study's sentiment analysis of Dee Fink's learning categories demonstrates the broadness of the game-based learning experience. Text mining methods thus provide opportunities to gain insights into learning about circular business model innovation and the student's perception of their learning experiences. The current developments in text mining uncover a world of new insights for game-based learning and sustainability in higher education. This study advances a deeper understanding of game-based learning by utilising these methods. Moreover, it provides detailed directions for shaping serious games and accompanying educational packages to meet educational and professional requirements.

6

Conclusions, reflections, recommendations

This chapter holds a review of our research goals, a set of conclusions, a reflection upon the contributions and limitations of our work, and recommendations for future research, practice, and education.

6.1 Conclusions

In this thesis, we developed methods and tools for researchers, practitioners, and students to understand and shape industrial symbiosis networks.

Using the methodological framework from chapter 2, we have co-developed a business game and an education game, including an education package (chapter 5) for the ideation of circular business models. Furthermore, we have collaboratively created two agent-based models to study the roles and effects of actor behaviour (chapter 3) and business model innovation (chapter 4) on the robustness of industrial symbiosis networks. In addition, we have developed and used an ex-ante business model experimentation method (chapter 4).

Our research questions guided our studies and the associated development of research artefacts. This section is organised into four discussion topics, each guided by the research questions from chapter 1. We use our analytical framework to integrate the lessons learned and draw general conclusions from the perspective of theory, practice and education.

RQ1: What collaborative modelling and simulation method can facilitate designing business models for viable and robust industrial symbiosis networks?

Study 1 (chapter 2) answered research question (RQ) 1 from both theoretical and practical perspectives; see Figure 6-1.

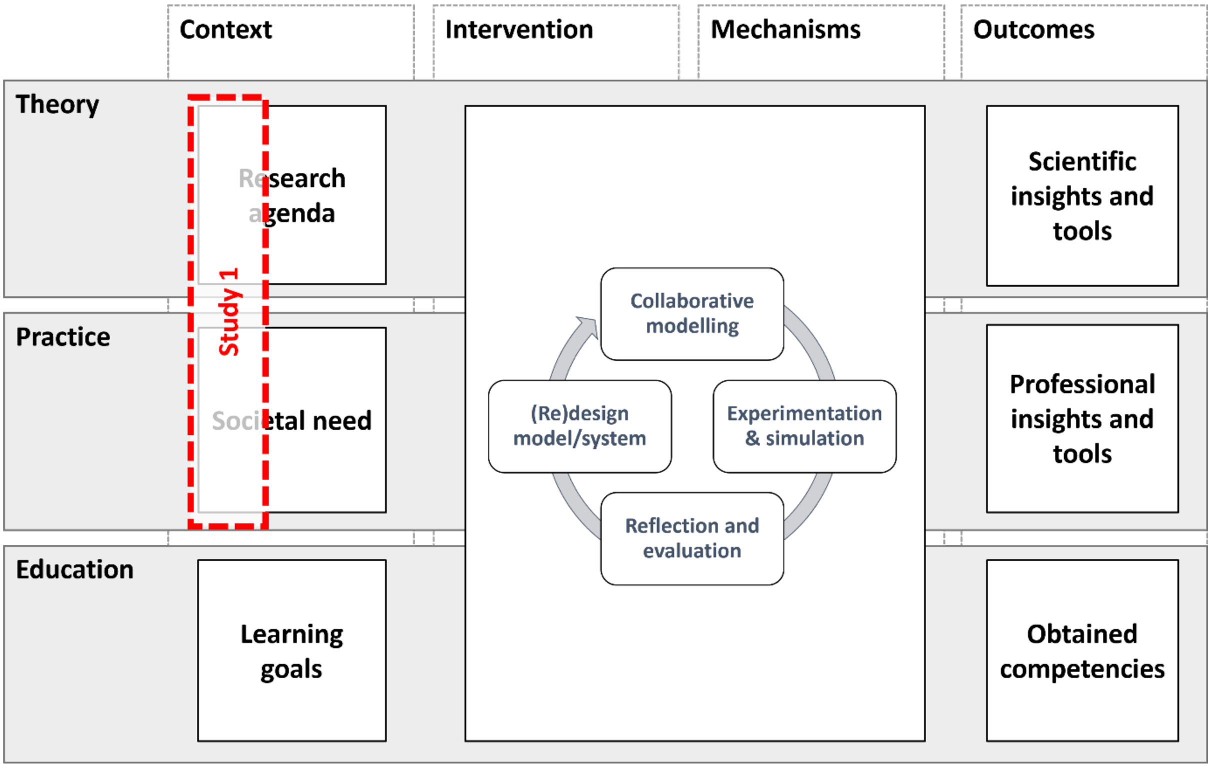


Figure 6-1 Contribution of study 1 to answering research question RQ1.

The diagram visualises that the collaborative research and design method proposed in study 1 (chapter 2) drew on empirical observations and a literature study. The study set the stage for the first iteration steps in design science research.

Theoretical perspective. The methodological framework was built upon the design science research paradigm and collaborative modelling methods. It aimed to elicit discussions among stakeholders to explore the dynamics of industrial symbiosis, such as network environment, stakeholder behaviour, and business model designs' effects. Combined with our initial research agenda (appendix B), the framework was used as a guideline during shaping the problem definition in this dissertation (chapter 1). In addition, it supported the collaborative development of our artefacts, such as the two agent-based models as presented in chapters 3 and 4 (Lange, Korevaar, Nikolic, et al., 2021a, 2021b), the games and the education package described in chapter 5 (Lange, 2019b).

Practical perspective. The design science research method allowed us to integrate practical questions from real-world cases with generic research objectives. It guided collaborative modelling and simulation activities in the research project 'Re-Organise' and contributed to shaping approved grant proposals to perpetuate our empirical research. The method supported setting up a practically relevant and scientifically rigorous research context that enabled us to perform the studies in chapters 3 to 5 and ultimately meet our research objectives.

<u>RQ2: How do network and actor behaviour affect the robustness of ISNs during implementation?</u>

This thesis answers research question 2 from the perspectives of theory, practice, and education, see Figure 6-2.

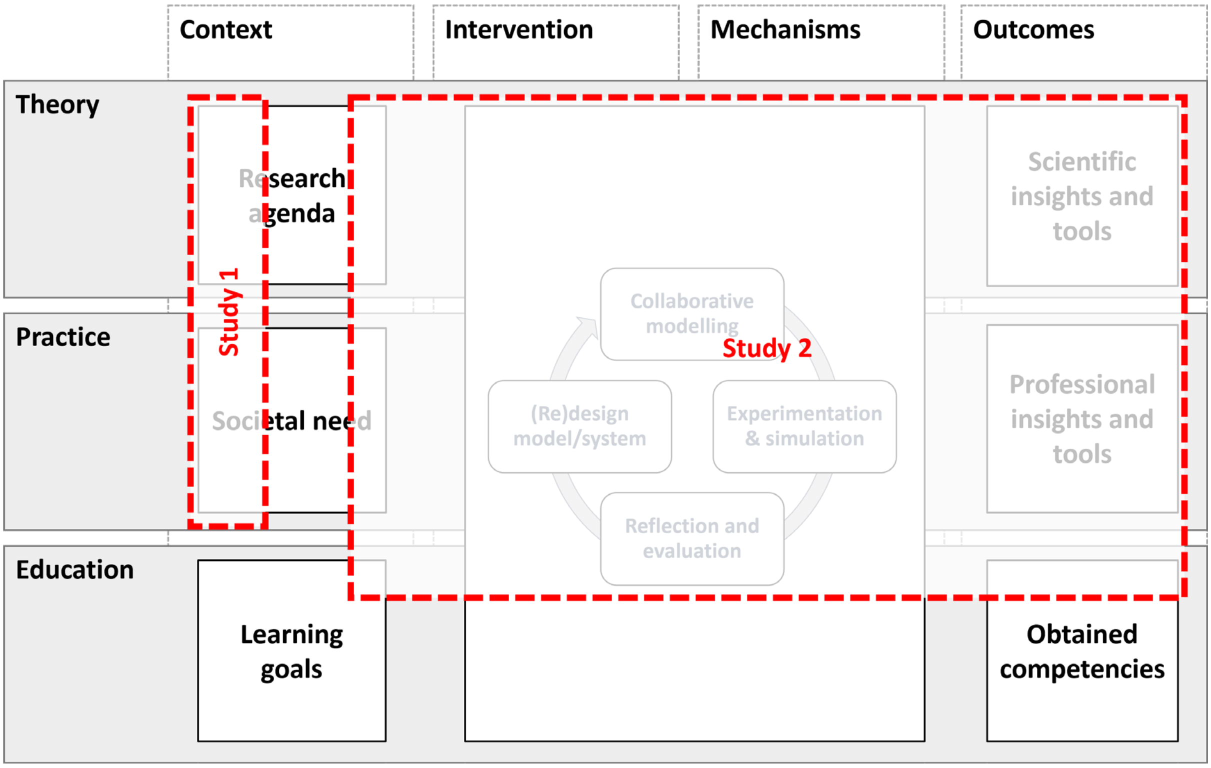


Figure 6-2 Contribution of studies 1 and 2 to answering research question RQ2.

This diagram visualises the following:

1. Study 2 mainly contributed to understanding industrial symbiosis dynamics due to network and actor behaviour, covering all four key elements: context, intervention, mechanisms, and outcomes (CIMO).
2. The context description is partly covered to visualise that a refinement step was made in an iterative context description, building upon the results of study 1.
3. The education flow is merely partly covered to show that the students worked on existing learning goals within their graduation project. Although this gave the students opportunities to answer their own research questions, their contributions to our specific study goal were limited. However, their work inspired our modelling study by expanding networking activities, supplying literature reviews on ISN dynamics and actor behaviour, and creating code examples for ABM.

We now answer the question from the three different perspectives.

Theoretical perspective. This thesis advances knowledge on actor behaviour and industrial symbiosis robustness by bringing forth the first generic and comprehensive simulation model that integrates human beliefs, behavioural intention and planned behaviour with context and design factors in five symbiosis implementation stages. Generic insights from the model are that in a free waste market - in which waste suppliers negotiate with processors to create contracts:

- Planned behaviour of individual waste processors can affect the robustness and economic outcomes of themselves, their collaborative partners, and the whole network. On one side, the unwilling behaviour of the processor leads to overcharging the waste suppliers. This type of behaviour may cause suppliers to leave the network, eventually leading to network collapse. On the other side, too much eagerness from the processor leads to unacceptable economic losses, resulting in network failure.
- Planned behaviour of waste suppliers only affects economic benefits and losses on both the individual and network levels.
- Research on motivating and supporting the processor to improve industrial symbiosis network robustness and economic outcomes is warranted.

Practical perspective. Practical insights are:

- The use of the business game helped the stakeholders in face-to-face communication for understanding and conceptualising industrial symbiosis. It supported data validation, finding business solutions, and raising questions. It also provided stakeholders with insights on the importance of human behaviour in business model innovation.
- The co-creation of the game forced the game developers to structure the available data. It provided a structure to create actor and object cards. It thus supported system analysis and narrative development of our agent-based model.
- The agent-based models help practitioners demonstrate how individual human behaviour factors, such as attitude, control beliefs and norms, are essential to the viability and robustness of the network. The models are helpful during shaping behaviour change for robust industrial symbiosis.

Educational perspective. During this process, two Master thesis students worked on parallel agent-based modelling assignments. These studies expanded the knowledge on modelling industrial symbiosis networks and actor behaviour, thus providing valuable input for creating our ABM.

The main findings for education are about the involvement of these students in research workshops of our case studies. Within the context of their thesis works (e.g., Kerssens et al., 2019), we observed that these workshop activities provided the students:

- access to the research participants and case study information, which helped the students identify and model behaviour;
- practical insights into the behavioural challenges of industrial symbiosis;
- examples of how collaborative research using models and simulations can be conducted to explore human behaviour.

RQ3: How can circular business models for viable and robust industrial symbiosis networks be tested and improved before implementation through collaborative modelling and simulation methods?

Iteratively building on the research approach from study 1 and the composting ABM from study 2, we collaboratively developed a new agent-based model (Lange, Korevaar, Nikolic, et al., 2021b). The model was validated, improved and used with practitioners and experts around biodigestion. We simultaneously developed the circular business model experimentation method (study 3), thus extending theoretical and practical knowledge, see Figure 6-3.

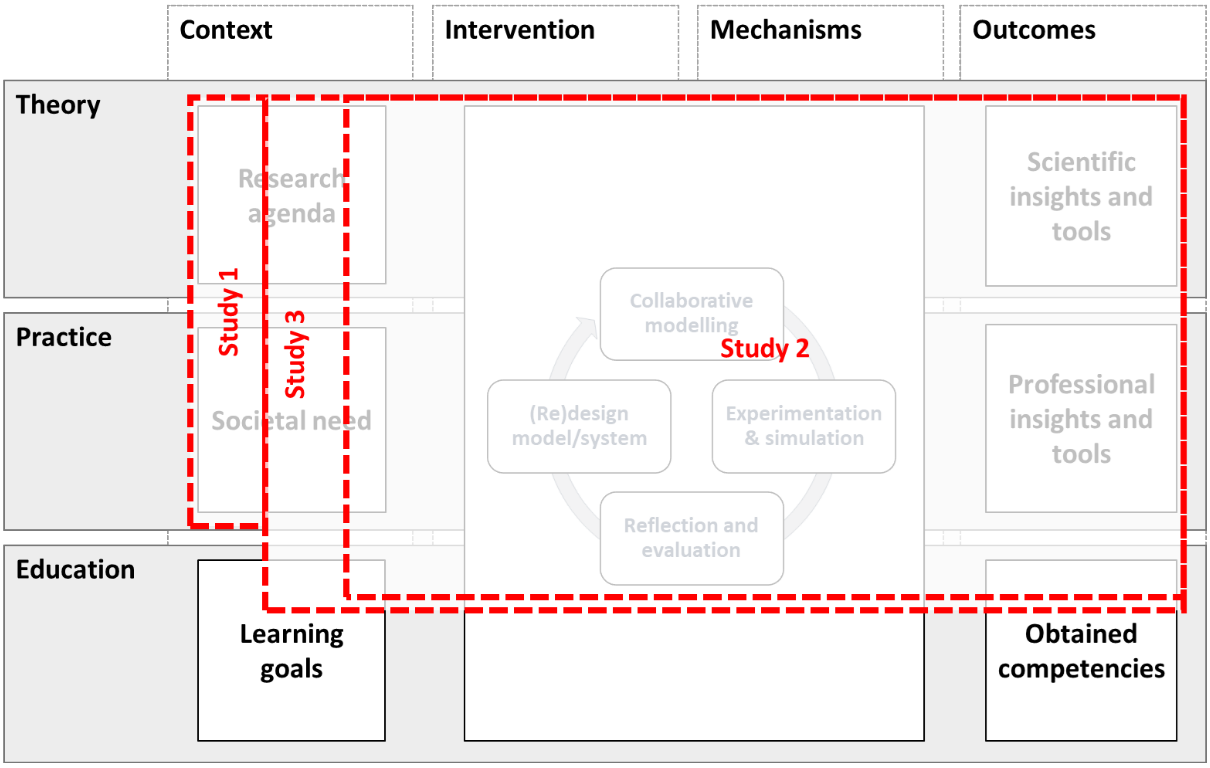


Figure 6-3 Contributions of studies 1 to 3 to answering research question RQ3.

The diagram shows that:

- Answering this research question built upon studies 1 to 3.
- Whereas study 2 mainly focused on exploring network and actor behaviour, study 3 also included a method for testing and shaping circular business models. Hence, the area of study 3 covers the complete theoretical and practical knowledge flows
- The design science research approach of study 1 was used to develop and inspire the iterative business model experimentation method.
- Since this study built upon the modelling and simulation study of research question 2, the student activities contributed similarly to the development of this model.

Thus, the thesis addresses our research question from the three perspectives of theory, practice and education.

Theoretical perspective. That study contributed to the domains of circular business modelling and supply chains by providing an ex-ante business model experimentation method. The proposed method is the first to enable systematic exploration and simultaneous improvement of all business model dimensions with agent-based modelling and simulation. It thereby includes the dynamic behaviour of external factors and individual actors. Since the experimentation method connects agent-based modelling with key elements of business models, we infer that it is suitable to assess all kinds of sustainable business models which involve multistakeholder collaboration.

Practical perspective. The method supports stakeholders by concretizing their reticence, exploring uncertainties in the system, and uncovering directions to improve the business model design. Since the model connects agent and network dynamics, stakeholders can use the study insights for their individual and collective benefits.

Educational perspective. Like in study 2, study 3 provided the students access to the case participants, empirically based insights and examples of how to research and shape industrial symbiosis using models and simulations collaboratively.

RQ4: How can collaborative modelling and simulation methods support the learning of (future) professionals for improving industrial symbiosis network designs?

Figure 6-4 shows how all studies answered this question, spanning the complete CIMO logic over all three knowledge flows.

Study 4 involved game-based learning of circular business model innovation. It was an experiment for and with education. It directly contributed to educating students about circular business model innovation. The accompanying education package is proven to be effective to this end and is ready for reuse. Furthermore, students provided valuable data analysis results, which stood at the heart of our study.

The game development and gameplay (study 4) served as input for agent-based modelling (studies 2 and 3). It resulted in a system description, validated case study data and process narratives for these agent-based models.

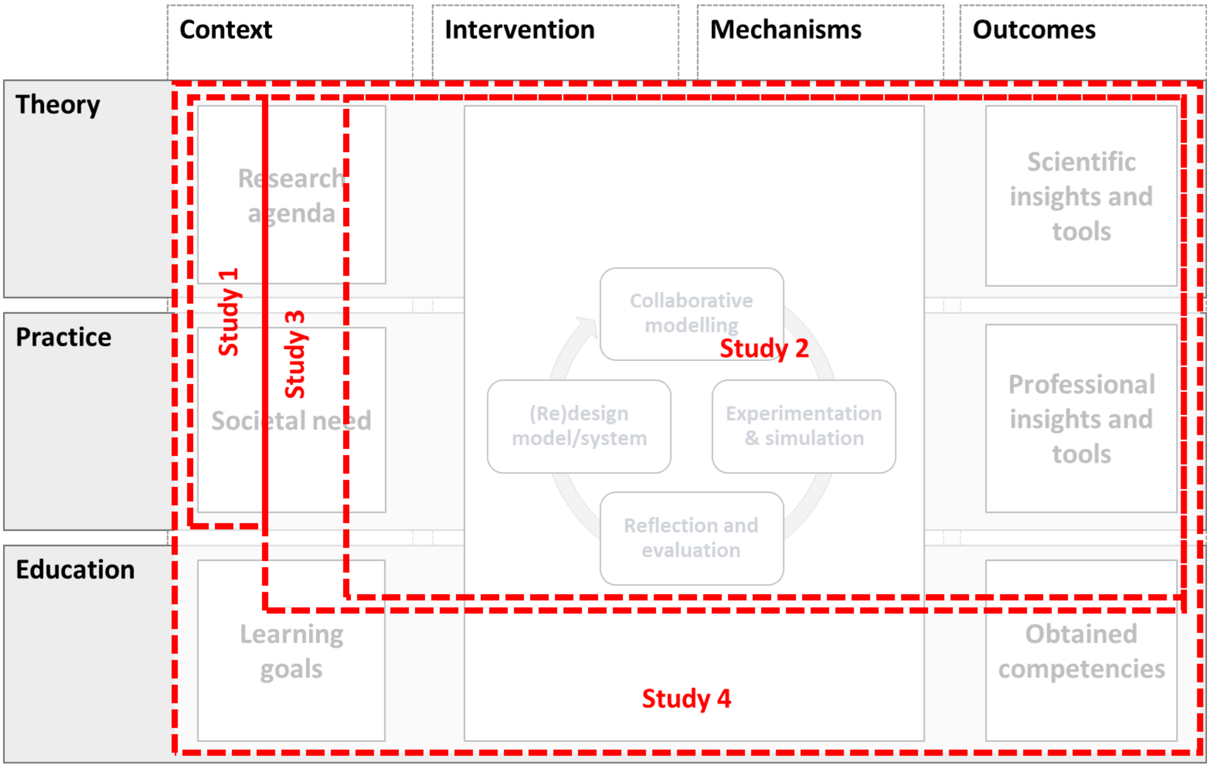


Figure 6-4 Contribution of the four studies to answering research question RQ4.

Theoretical perspective. Study 4 provided grounded evidence on:

- how game-based learning can be used to teach content, personal, interpersonal and design thinking competencies for circular business model innovation;
- how students can be guided in reflecting on their learning process through the taxonomy of Dee Fink;
- how qualitative and quantitative analytical methods can be used to assess the effects of learning through games and simulations in the context of the circular transition. For example, it provides directions for future development of education packages that use other simulation tools, such as our agent-based models.

Practical perspective. The game supported the creation of an accessible and safe environment for stakeholders to discuss potential solutions for symbiosis. For stakeholders, the game proved to help explore:

- waste streams, needs and assets of potential partners for symbiosis;
- the behaviour of potential partners. This knowledge supported stakeholders in exploring whether they had a personal connection with each other to encourage them to continue exploring solutions after gameplay;
- concepts of mutual interest for closing local waste cycles to create economic, societal and environmental benefits.

Educational perspective. The game study (study 4) demonstrated how simulation artefacts from practice-oriented research could be applied to construct and test a game-based educational package.

In the board game experiment, we taught students content-related, personal and interpersonal, and design-thinking competencies concerning circular business model innovation. We use the CIMO logic to explain how. The context is the set of learning goals addressed by the curriculum, course or teaching material (in this case, the game education package). In general, the task of educators is to impose (preparatory and in-class) learning interventions that help the student meet the learning goals. The interventions – the game, education package, and in-class activities – consisted of an assignment and interactive sessions with peers and lecturers. Students iteratively performed learning activities based on the learning interventions, activating learning mechanisms such as developing the skills or understanding prescribed in the learning goals. In the game experiment, the students experienced mental changes in thinking, acting and reflecting. Finally, playing the game proved to improve the learning outcomes.

6.2 Contributions

In addition to the contributions described in each study, we here describe how this dissertation advances theory, practice and education in a more generic sense.

6.2.1 Contributions to theory

This dissertation draws from circular business model innovation, design science research and complex adaptive socio-technical systems to develop methods and tools supporting understanding and shaping industrial symbiosis. The theoretical contributions of this research to the domains of circular economy and industrial symbiosis are in advancing industrial symbiosis simulation, circular business model design and experimentation, and circular economy education (see Figure 6-5).

Contributions to industrial symbiosis simulation

Our research and complementary artefacts advance simulating industrial symbiosis. The simulation results contribute to understanding complex socio-technical dynamics, such as the behaviour of the system and its constituent human actors in industrial symbiosis networks. For example, it demonstrated the importance of understanding the behaviour of waste processors to balance incomes among stakeholders and improve the network's survival rate. The simulation studies offer directions for business and policy interventions supporting nascent and evolving industrial symbiosis networks.

The studies bridge the gap between the social and technical sides of industrial symbiosis and show that more circular economy and industrial symbiosis research using collaborative modelling and simulation methods is warranted. The games and agent-based models developed in this work are exemplary tools addressing the need for combined social and technological approaches in circular economy research (Baumann & Lindkvist, 2021). Furthermore, the studies show how various quantitative and qualitative data from scholarly and practical resources can support creating and validating games and dynamic models.

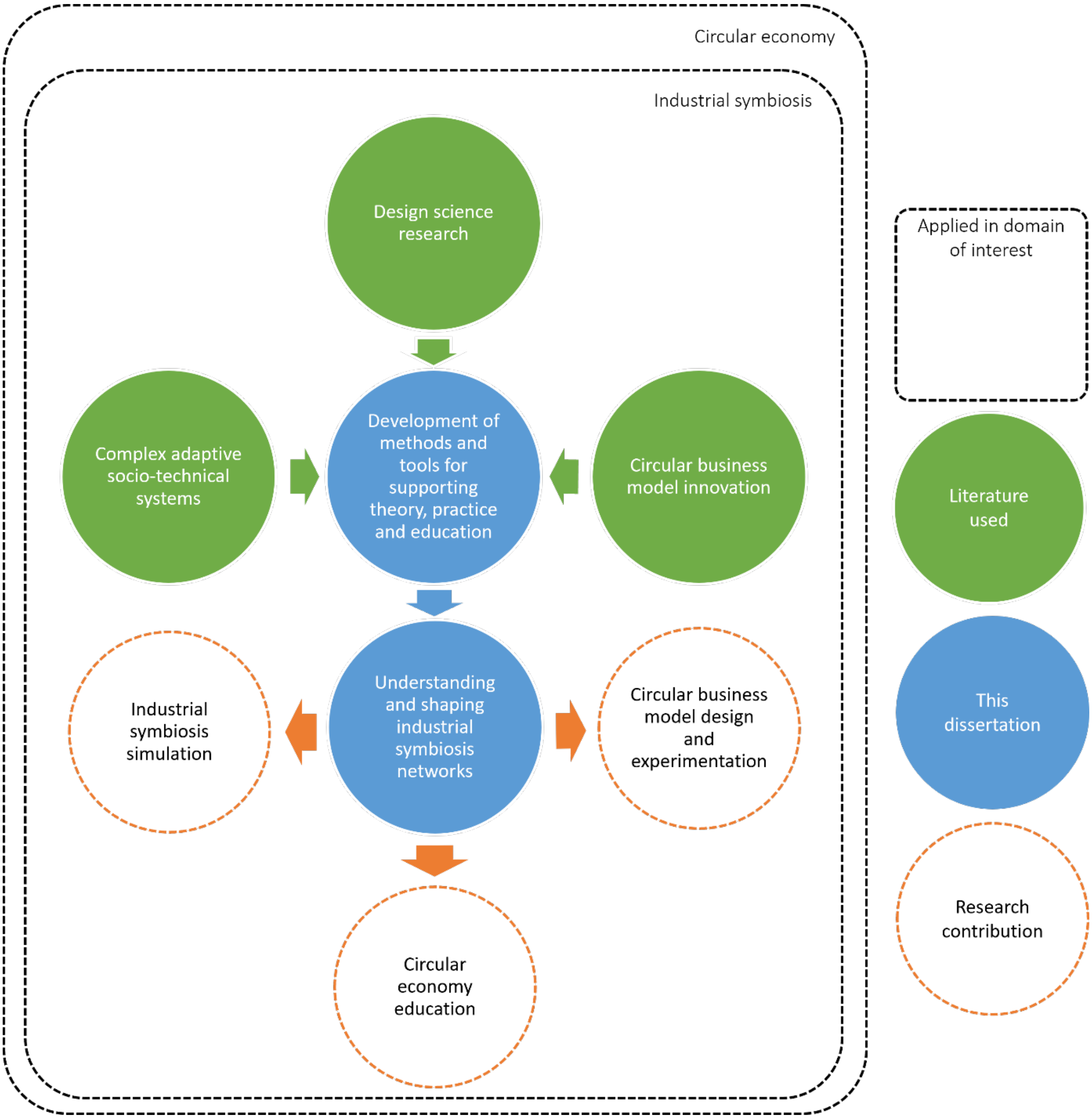


Figure 6-5 Theoretical contributions of the research.

Contributions to research on circular business model design and experimentation

The academic literature on circular business models is predominantly based on case-specific and qualitative insights. Therefore, the interactions between context, network and individual actors are often underexamined (Yap & Devlin, 2016). Approaches to systematically assess business models under uncertainty are currently limited. This research addresses this gap by supporting circular business model innovation using games and digital simulation models with stakeholders. It helps scholars and collaborating partners to design network-level circular business models. The work also demonstrates how to explore the dynamics and complexities involved in circular value chains: it shows how to assess potential future impacts of the novel business models, from actor-level to system level, under various circumstances. In addition, the work sets an example of how other circular business model archetypes can be explored and shaped to support transformations towards circularity. This dissertation thus paves the way for more research on ex-ante circular business model design and experimentation using digital simulation methods.

Contributions to research on circular economy education

The studies in this dissertation show how simulations can facilitate learning processes that involve designing circular business models and industrial symbiosis. The simulations uncover the complexities and dynamics of interdependent technologies, actors, and environments. Study 4 showed how combining mixed qualitative and quantitative analysis methods can ground evidence of learning, designing and reflection processes using simulation.

This work also offers diverse examples of the role of student work and sustainable education in design science research. The novel analytical framework contributes to sustainability education by supporting the analysis of interconnected evolving learning processes among students, practitioners and researchers.

6.2.2 Contributions to practice

This research's generic practical contributions are to be found in the synthesis of methods and tools that help collaborating partners in networks set up circular businesses. As the studies showed, the game supports a safe simulation environment for the ideation and conceptualisation of industrial symbiosis and its accompanying business model. The agent-based modelling studies uncovered the dynamics of specific industrial symbiosis networks, including system and process descriptions. In addition, it guides stakeholders towards the improvement of industrial symbiosis robustness. Chapter 3 gives directions for stakeholders to improve network robustness by encouraging a mutual understanding of attitudes, beliefs, and norms among partners. Furthermore, it may support policymakers that aim to govern behaviour change in favour of industrial symbiosis. For companies that aim to achieve circularity by collaboration, the systematic business model experimentation method can remove uncertainties related to implementation risks, such as investing in innovative technologies or establishing contracts with potential partners.

6.2.3 Contributions to education

Scientists and educators are expected to contribute to developing knowledge and skills for the circular transition. Alumni from higher education will become the leaders, decision-makers and business owners of tomorrow. Hence, they should be capable of shaping the circular economy.

The contributions of this research to education are twofold. First, during the conception of this work, this research directly contributed to the teaching of students. Multiple pre- and postgraduate students and students with diverse backgrounds (such as Engineering, Data Science, Engineering Policy Analysis, Industrial Ecology, and Biological Sciences) carried out study assignments related to serious game development, gameplay, modelling, simulation and analysis. During the process, these students inspired this research with literature studies, data collection in case studies, and data analysis (e.g., text mining the results of the gameplay experiment). Along the research process, the created open-access data sets, scientific articles and contributions to book chapters for practitioners were used to enrich these students' resources. The second direct contribution to education was the game experiment study in chapter 5. It proved that the game was of value to teaching future Industrial Ecology experts and engineers about the circular transition. Pilot studies have shown that gameplay is not limited to young and engineering(-related) students. We have played the game with various full-time and part-time students, new and experienced, from education programmes varying from Engineering to Public Administration to Applied Psychology.

To conclude, students from diverse educational programmes and levels engaged in various roles, from researcher to research participant, from analyst to designer. Therefore, the students' learning activities involved in this research were an integral part of the research.

6.3 Reflections and limitations

6.3.1 Theory

Research design

The analytical framework proposed in chapter 1 guided us through the different knowledge perspectives and the key elements (CIMO) of design science research. The frameworks show that our research design facilitated interactive knowledge development across three knowledge flows and the four CIMO elements. However, some aspects of the research design uncovered some tensions between the generic research objectives and the various interests of our stakeholders. For example, we developed extensive agent-based models to contribute to a general theoretical understanding of industrial symbiosis. The advantage of this is that it enables a broad and systematic exploration of actor behaviour profiles and business model designs, covering all implementation stages of industrial symbiosis. The downside is that the modelling process was time-consuming: the model development took four years in two successive two-year projects (see appendix A). Some key partners in the first project also participated in the second project. Still, we also experienced a decrease in the involvement of some original partners after finishing the first project. In the second project, new participants entered the modelling process, and it took a while to get them acquainted with the approach. During model development, the models became quite complex, making validating the model increasingly challenging. The use of triangulation methods to validate the model using several methods, researchers and cases (section 1.3.1) was crucial to increase rigour. The development and use of the board game, flow charts of the ABMs and simulation outcomes provided clarity for participants and domain experts. They resulted in feedback to improve our agent-based models.

Since we were collaborating with stakeholders, the execution of the research was highly affected by local and temporary circumstances. Exemplary is the end of the second project, which coincided with the COVID pandemic outbreak. The accompanying lockdown forced us to finish the project without physical gatherings to evaluate the project. In addition, participating companies were often forced to focus on urgent matters that threatened their immediate business continuity, which affected the extent of stakeholder involvement at the end of the project. Even though these kinds of daily worries affected some of our case participants, the design science research approach allowed for enough flexibility to gain generic theoretical and practical insights.

Scope

This dissertation focuses on closing and narrowing loops among industries and companies in The Netherlands. Since we used case studies to build our models, these models can only be used to study composting and biodigestion networks in similar contexts. Parts of the model, such as the different implementation stages and planned behaviour, can still be applied to other types of symbiosis. We also expect that the method for circular business model experimentation applies to a broader context.

In our study, the robustness of industrial symbiosis depends on the availability and value of waste streams acting as resources for lower-level resource energy and nutrient recovery. Therefore, the study focused on implementing lower-level cycles of biodegradable materials, mainly energy and nutrient recovery (M. Lombardi & Costantino, 2021; Moerman, 2009). Nevertheless, we expect similar models and CBM experimentation to apply to higher levels of circularity, such as re-use for animal feeding, human care, or food prevention strategies. The method is not limited to cases of biodegradable material cycles only. We also conjecture that the approach can be applied to study the behaviour of other actors involved in the value network, for example, consumers (e.g., Wastling et al., 2018) or customers in closed-loop supply chains (e.g., Inderfurth, 2004) in both the biological and technical cycles.

6.3.2 Practice

The companies involved in our case studies gained practical insights into the interdependencies and dynamics of industrial symbiosis. We consider the simulations convenient tools for both researchers and educators in terms of usability. The game supported clear and direct communication among our case study participants to explore each other’s needs and wishes and design the symbiosis network. The various types of students in our game-based learning experiment could communicate with peers and play with circular business model innovation, which indicates that the game is easily accessible. Concerning the agent-based models, the developed ABMs and business model experimentation methods are suitable for practitioners with knowledge of modelling and simulation, for example, consultancy firms with digital simulation skills. Hence, the practical relevance lies in providing methods and tools for socio-technical systems modelling and simulation experts to facilitate circular business model innovation.

6.3.3 Education

The research project described in this thesis was conducted in a collaboration between two knowledge and higher education institutes: Amsterdam University of Applied Sciences (AUAS) and Delft University of Technology (TUD, faculty of Technology, Policy and Management). Most alumni work in professional fields, which means that higher education institutes must deliver high-quality professionalism (Griffioen, 2019). Knowledge and education institutes thus have the duty to teach competencies from theory-driven and solution-driven perspectives. Theoretical competencies include discovery, theorization, and systemization. Practical knowledge, skills and attitudes are related to creation, integration and implementation (Griffioen, 2019, p. 19). The studies in this dissertation followed a design science research approach, which took place in a multi-actor learning environment, enabling students to learn from practice and researchers, and vice versa. We trust that our study approach helps inspire other scholars that aim to combine their research with practice and education.

6.4 Recommendations

6.4.1 Directions for future research

Recommendations for future research can be found in the study topics: design science research, socio-technical modelling and simulation of industrial symbiosis, circular business model experimentation and circular economy education.

Design science research approach

To increase the scientific and societal impact of the circular economy, industrial ecology, and industrial symbiosis research communities, we recommend expanding design science research approaches such as provided in this work. We need multidisciplinary teams of researchers and practitioners with diverse backgrounds, from engineering, business, and economy to governance, humanities, and ethics, to develop robust symbiotic networks collectively. The design science approach developed in this thesis proved to be of value to this end. Based on the literature, we also conjecture that it can support studying other policy or business model interventions that follow the principles of the circular economy.

Socio-technical modelling and simulation of industrial symbiosis

Given the societal urgency, we suggest developing generic design rules to foster industrial symbiosis. To do so, the modelling approach and models from this dissertation can be of use to assess behaviour change policies and their effects.

To increase validity, this study's models, or parts of it, can be used and compared with different models of (environmental or entrepreneurial) behaviour and negotiation theories than the theory of planned behaviour, for example, the practice theory for entrepreneurs (Johannisson, 2011), protection motivation theory (e.g., Steg & Nordlund, 2018) or game theory (e.g., Yazan et al., 2020).

We also recommend exploring roles, actions and behaviour outside our study scope, however relevant for a broad understanding of industrial symbiosis dynamics. For example, we suggest researching various kinds of anchoring and facilitation roles (Sun et al., 2017), logistics agents, and product buyers. Lastly, we recommend model expansion by integrating interconnected economic, environmental, and social impacts on actor behaviour and network dynamics.

Circular business model experimentation

Aiming for maximal social and environmental impact, the business model experimentation method developed in this dissertation may be used as a source of inspiration to test business models for high circularity strategies, such as those that encourage resource or product refusal or re-mining landfilled materials (Reike et al., 2018).

To increase an understanding of the interplay between business models and policy designs, we suggest using our study as a starting point to develop a broader experimentation method that unifies business models and policy designs in industrial symbiosis networks and other circular supply chains.

In the real world, entrepreneurs are flexible, and they continuously adapt their business model when they are unsatisfied with the results of their business model. We therefore also recommend conducting further research on network resilience under adaptive business model designs and changing circumstances.

Circular economy education

Studies on agent-based models and the accompanying learning effects in sustainability education are currently limited. Specifically, the extent to which agent-based models and simulation tools of divergent complexity can contribute to various educational levels is understudied. We recommend studying how to fit agent-based models to teach complexities of industrial symbiosis using a similar approach as in the game-based learning study of chapter 5. It may add to the existing literature on the role of agent-based simulation in education, for example, from Koster et al. (2016). Based on companion modelling literature (e.g., Voinov & Bousquet, 2010) and our experiences with communicating complex agent-based models to practitioners, we conjecture that teaching through gameplay and visualisations improved the usability and accessibility of agent-based model narratives. Therefore, we recommend that scholars from the gamification and interaction design communities shed light on existing collaborative modelling methods and approaches and contribute to increasing the accessibility of agent-based models.

6.4.2 Recommendations for practice

The shift towards a circular economy entails a tremendous changeover of companies, affecting nearly all materials, energy, and information flows in the economy. As a result, the circular transition touches upon diverse sustainability impacts. Companies need to understand these impacts and act upon them to enhance positive change. Sectors, industries and single companies need to shape their businesses in accordance with interconnected environmental and social needs while addressing other transitions (e.g., digitalisation, energy transition) at the same time. Examples related to the ecological impact include but are not limited to material criticality, nitrogen and phosphorus cycles, water pollution and extraction, chemical pollution, biodiversity loss and land conversion. The social impacts of the circular transition bring about different and often unique consequences and meanings for the variety of actors involved. For example, circular economy practices may largely avoid raw material extraction activities that usually involve child labour and hazardous working conditions. However, designing circular solutions in the western world is not automatically a driver for better living conditions in other parts of the world. A broader systems approach is needed to improve social well-being and equity by arranging improved educational systems and labour conditions. A close collaboration between industries that engage in the circular transition and affected public institutions, citizens and non-governmental organizations is highly recommended.

Modelling and simulating complexity offer opportunities to support this. It enables exploring commonalities and conflicts between the vast palette of materials, energy sources, information flows, and human values, interests and needs. (Policies to shape) actor behaviour and business model innovations related to different circularity strategies - to rethink, reuse, refurbish, or recycle - will determine the focus and emphasis on sustainability impact. Vice versa, the circularity strategies that address the most well-known sustainability issues may become the most influential. We recommend using our work as a source of inspiration to explore other circularity strategies. Eventually, this may contribute to the public debate on the role of business in sustainability.

6.4.3 Recommendations for education

Civilians and policymakers increasingly expect companies to be aware of their position within society. Policymakers progressively ask companies to be held accountable for their business activities' societal and environmental impacts, as demonstrated by recent EU legislation efforts to address due diligence across the supply chain (CBI, 2021). To comply with these societal needs, professionals need to obtain enabling competencies to understand and shape systemic changes towards circularity. In our view, this starts with teaching sustainability and circularity concepts to young students at primary school. It needs embedding in secondary, vocational, and scientific education. Refresher training and masterclasses are also required to speed up the transition. Although we suggest trying out the educational game in secondary schools and vocational education, we give recommendations that apply to BSc. and MSc. level education.

Future work entails integrating the artefacts and written content from this dissertation in new curriculum designs to encourage the use and further development of the methods and tools developed in this thesis. Study 4 presented linking gameplay to teaching and assessing network and business model design processes using text mining. The ABMs from studies 2 and 3 can be utilized likewise. Students can play with the models and explore how various interventions and externalities affect circularity. The advantage of using digital models such as ABMs is that the simulation outputs come in standard digital formats, making automated grading and feedback easy. Depending on the education level, the ABMs may need amendments for improved usability or (online) access. We recommend using the principles of online gamification to redesign ABM interfaces and improve connectivity and usability.

Lastly, we encourage future PhD students who aim to combine practice-oriented design science research with educational activities to use the design science approach and accompanying analytical framework as a source of inspiration.

6.5 Epilogue

This thesis addressed some of the challenges and uncertainties businesses face in the transition towards a circular economy, specifically those aiming to implement industrial symbiosis. We have connected these challenges with opportunities that design science research and collaborative modelling and simulation methods offer to gather knowledge while finding solutions. During this PhD research project, multiple policy directives on the circular economy have been implemented in the EU and the Netherlands. This trend signals the importance and urgency sensed by policymakers and citizens to change our economy from a profit-driven system into a system that supports a liveable and sustainable society. Companies often struggle to unify business continuity and economic viability with social and environmental sustainability. These conflicting interests sometimes lead to heated societal debates. We aimed to equip researchers, practitioners, and students (as our future leaders and practitioners) with knowledge, tools, and methods to shape industrial symbiosis. In a broader perspective, with this dissertation, we trust in having created a source of inspiration for learning, collaborating, and discussing the future role of businesses in shaping a circular society.

7 References

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Lange, K. P. H., & De Rijke, S. J. (2019). Project Re-Store: Simulatiemodellen van lokale ketens voor organisch bedrijfsafval. Hogeschool van Amsterdam. https://research.hva.nl/en/publications/project-re-store-simulatiemodellen-van-lokale-ketens-voor-organis

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9 Curriculum vitae

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Summary

After graduating from the Faculty of Industrial Design Engineering at TU Delft, Kasper Lange (MSc.) started working as a Research and Development Engineer in the manufacturing industry. After nine years, he decided to dedicate his career to sustainable engineering research and education at the Amsterdam University of Applied Sciences (AUAS). In 2014, he obtained a basic teaching qualification for university lecturers. By the end of 2015, Kasper received a scholarship from AUAS to start a PhD research project on understanding and shaping industrial symbiosis networks at Delft University of Technology. He was the main researcher in two related practice-oriented RAAK-mkb projects (NWO SIA project numbers 2015-03-03M and RAAK.MKB07.010). From March 2017, the project was also financed with a personal PhD grant for teachers by The Netherlands Organisation for Scientific Research (NWO, project number 023.009.037).

Overview of work experience

2015 – Present	PhD researcher and lecturer at Centre of Expertise Urban Technology, Faculty of Technology, Amsterdam University of Applied Sciences, and Faculty of Technology, Policy and Management, Delft University of Technology.
2012 – 2015	Researcher and Project Manager in CleanTech and Urban Technology Research Programmes at AUAS.
2012 – 2015	Developer, coordinator and lecturer CleanTech Honours Programme (AUAS).
2005 – 2011	(Senior) Research & Development Engineer at machine manufacturing companies in The Netherlands.

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Appendices

The appendices can be found on: http://repository.tudelft.nl/.

The European Commission aims for a full circular economy (CE), an economy that aims to reuse all resources in 2050. CE is a promising way to increase welfare and wellbeing while decreasing environmental footprints. Industrial symbiosis, in which companies exchange residuals for resource efficiency, is essential to the circular transition. However, many companies are hesitant to implement business models for industrial symbiosis because of the various roles, stakes, opinions, and resulting uncertainties for business continuity.

This dissertation supports researchers, professionals, and students in understanding and shaping circular business models for industrial symbiosis networks through collaborative modelling and simulation methods. Three theoretical perspectives, design science research, complex adaptive socio-technical systems, and circular business model innovation, shed light on designing business models for industrial symbiosis. A serious game and agent-based models were developed in multiple case studies with researchers, practitioners, and students. These were then used to design circular business models and explore their efficacy under uncertain conditions, such as various behavioural intentions of potential partners in diverse natural and societal contexts.

This dissertation advances business model design and experimentation by integrated simulation of social and technical aspects of industrial symbiosis. Furthermore, the research shows how simulations facilitate learning processes in designing circular business models. Ultimately, the thesis equips researchers, practitioners, and students with knowledge, tools, and methods to shape a circular economy.