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Developing and Understanding Design Interventions in Relation to Industrial Symbiosis Dynamics

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Abstract: Symbiotic Urban Agriculture Networks (SUANs) are a specific class of symbiotic networks that intend to close material and energy loops from cities and urban agriculture. Private and public stakeholders in SUANs face difficulties in the implementation of technological and organisational design interventions due to the complex nature of the agricultural and urban environment. Current research on the dynamics of symbiotic networks, especially Industrial Symbiosis (IS), is based on historical data from practice, and provides only partly for an understanding of symbiotic networks as a sociotechnical complex adaptive system. By adding theory and methodology from Design Science, participatory methods, and by using agent-based modelling as a tool, prescriptive knowledge is developed in the form of grounded and tested design rules for SUANs. In this paper, we propose a conceptual Design Science method with the aim to develop an empirically validated participatory agent-based modelling strategy that guides sociotechnical design interventions in SUANs. In addition, we present a research agenda for further strategy, design intervention, and model development through case studies regarding SUANs. The research agenda complements the existing analytical work by adding a necessary Design Science approach, which contributes to bridging the gap between IS dynamics theory and practical complex design issues.

Keywords: industrial symbiosis dynamics; participatory agent-based modelling; network evolution; Symbiotic Urban Agriculture Networks; design research

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 [1–6]. 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 [7,8]. 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 [9]. Based on the study of Mougeot, [10] (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 for developing closed loop systems in Urban Agriculture is stimulated by the idea that a multi-objective business model is crucial to make Urban Farming economically, environmentally, and socially sustainable [8,11,12]. In this paper, we focus 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 [1,2,4]. Urban Agriculture stakeholders are reluctant to change the technological and organisational design of the system, because they are lacking knowledge on 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 [11,13].

A field of literature that is relevant for this research topic is Industrial Symbiosis (IS). IS aims to understand how a collaboration between traditionally separate, but geographically proximate economic industrial agents may contribute to closing material, water, and energy cycles [14]. Chertow [14] (p. 313) states that "*The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity*". Gibbs and Deutz [15] (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, that 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) [16]. Hence, Industrial Symbiosis, with its focus 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 SUANs are dynamic networks that consist of actors that execute 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 can be considered to be sociotechnical Complex Adaptive Systems [17]. Complex Adaptive Systems are defined as systems that consist of heterogeneous components that adapt as they interact [18–21]. Bauer and Herder define socio-technical systems as systems where "*technology is central for their operations*" [22] (p. 602), and Dijkema and Basson [17] consider the sociotechnical system to be 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 process [18–20,23]. The recent comparative framework by Boons et al. [23], which provides a set of IS dynamics typologies, is based on historical data. According to Yap and Devlin [24], historical data from case studies provide an initial common explanation, but it gives no insights on 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 [25], and participatory methods in modelling are widely accepted by scholars as ways to encourage co-evolutionary learning among stakeholders during the process of designing context specific solutions [26,27]. 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 article, we do so by studying the literature from these three fields of literature, IS dynamics, Design Science methods, and participatory methods in modelling, and by proposing an iterative design research method.

With this research, we contribute to the field of IS dynamics by bridging the gap between history-based IS dynamics theory and design intervention issues in current and future case studies. The paper therefore provides a literature-based conceptual Design Science method, illustrated with a practical agricultural network example in the city of Amsterdam, The Netherlands. In addition, we propose a research agenda for further method development of this combination of dynamics and design in SUANs.

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 next sections, we elaborate on the concepts of Design Science and participatory methods in modelling. Finally, the state-of-the art in IS dynamics will be discussed on applicability from a design 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, etc.). Both quantity and quality of these flows are important aspects that influence the reuse potential in terms of business value.

By using the conceptual frameworks of Despeisse et al. [28] and Leigh and Li [29] as a source of inspiration, and by using literature by Bastein et al. [2] and Metaal et al. [11] on respectively urban organic material loops and Urban Agriculture, we created a simple model of flow exchanges between actors in SUANs, including their resources and waste flows (see Figure 1). Note that it is possible for actors to 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 stakeholders in Figure 1 do not represent the exhaustive set of stakeholders that is involved with influencing the SUAN's dynamics.

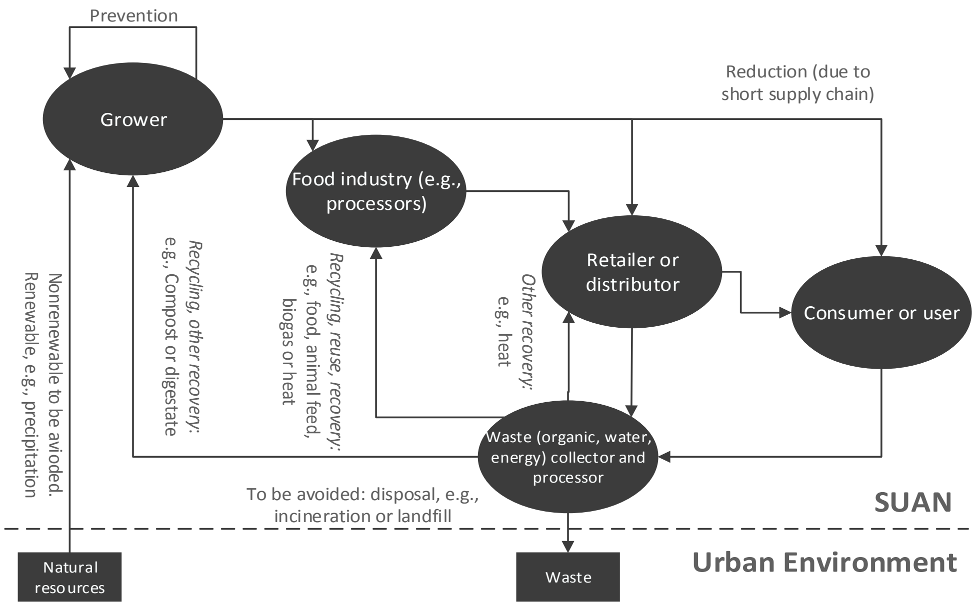

Figure 1. Simple generic model of day-to-day resource and waste flows in a Symbiotic Urban Agriculture Network. SUAN = Symbiotic Urban Agriculture Network.

In this article, the concept of Industrial Symbiosis as a sociotechnical Complex Adaptive System is studied from a design perspective, in addition to the traditional explanatory approach. It is quite evident that transforming analysis methods into design interventions regarding economical and sustainable development in practice are an important aspect of the field's right to exist [30]. In line with Pugh [31], 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 the fact 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 Desrocher states that it "*is unlikely to live up to the expectations of its proponents*" [32] (p. 1099).

3. Design Science, Modelling and Stakeholder Participation

Many studies on the concept of IS can be considered as analytical and description-driven, whereas explanatory sciences aim to describe, explain, and/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 in the generic comparative studies). Where the analytical sciences provide explanations through causal models through hindsight, Design Sciences provide a set of alternative solutions by means of grounded technological rules [33].

Dresch et al. [34] (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 as practice oriented, applied, evidence-based management research, or innovation action research [25,33,35,36]; these terms are all used for a type of research in which *prescriptive* knowledge on solving practical problems is obtained through artefacts, rather than providing for generic explanations of phenomena through causal models. Dresch et al. [34] emphasize that even though Design Science differs from traditional analytical sciences, they complement each other because of their different objectives. Design Science particularly aims for pragmatically developing 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 [34].

While in traditional science the researcher acts as an observer, in Design Science the researcher rather participates by facilitating a discourse in which stakeholders strive for pragmatic solutions for a particular class of problems through iterative analysis and synthesis steps [34]. Hence, the problem description and matching solutions are simultaneously and iteratively developed in Design Science [37]. Four key concepts play a key role within Design Science: Context, Interventions, Mechanisms, and Outcomes (CIMO). An explanation of these key concepts is given in Table 1.

Table 1. Context, Interventions, Mechanisms, and Outcomes (CIMO) explained, inspired by Denyer et al. [25], Boons et al. [23], and Holmström [36].

Concept	Explanation
Context	Internal and external technical, economic, geo-spatial, and institutional factors and the nature of human actors, which influence behavioural transformation of the sociotechnical system.
Interventions	Interventions that are available within the power of the design participants, which mean to influence behavioural change of the sociotechnical system.
Mechanisms	Mechanisms that are 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 methods [38]. 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*" [25] (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 [36]. According to Yap and Devlin [24], the analytical approach on IS dynamics provides a scientifically sound explanation of historical events, but it has no predictive power. Although the Design Science approach does not provide comprehensive predictions on IS dynamics, it does contribute to gaining context specific insights on how certain design interventions within the context influence the symbiotic network behaviour and vice versa [25,34,35]. It also provides insights on the behavioural changes in similar contexts, leading to empirical design rules for organisational changes and technological innovation [25,34,35]. 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 certain 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 [39].

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; and (3) subsystem (agent) interaction is characterized as flexible and agents are heterogeneous [39]. Design interventions in the case of SUANs evidently match these conditions, which is in line by a recent study on sociotechnical aspects of agro-industrial ecological systems by Fernandez-Mena [2]. 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. [40], Bichraoui [41], Ligtvoet [42], and Batten [43]. Batten [43] (p. 211) states that: "*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 certain design intervention scenarios, and whether these pathways are stable or not. Thus, agent-based modelling is a promising tool for the evaluation of technological and organisational design decisions in symbiotic networks.

To make a connection between the models and real-life situations, it is important to build models that are accurate enough to increase insights, and transparent enough to provide communication and social, co-evolutionary learning [43]. Participatory methods in modelling are particularly helpful in clarifying and identifying fundamental and latent assumptions and behaviour of real-life agents [26]. Other types of socio-technical Complex Adaptive Systems have successfully been developed and evaluated by using participatory modelling techniques for ABMs, e.g., in resource and water management [27,44,45]. However, only one paper by Batten [43] was found 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 for further development of generic knowledge to resolve the problem.

Considering the need for prescriptive knowledge on design interventions, and coherent with observations by Holtz et al. [26], Batten [43], and Hare [27], 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 the field of IS mostly intend to understand organisational phenomena through 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: by aiming for simultaneous development of pragmatic grounded solutions in running case studies, it is likely to provide generic design rules that can be applied in future design interventions in different contexts. An iterative design research method, using participatory methods in establishing ABMs, is very likely to contribute to scientific and practical knowledge development concerning technological and organisational design interventions in IS dynamics.

4. Conceptual Design 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 participatory methods by Hare [45] and agent-based modelling methods of Dam et al. [39], and placed these in the context of the Design Science methodology by Aken and Andriessen [33] and the CIMO-logic by Denyer et al. [25], resulting in Figure 2. The proposed conceptual methodology shows that generic knowledge development is reached by means of an iterative multiple case study analysis. Each tab represents a single case study, in which the design research methodology is applied. In the model, CIMO logic is represented throughout the phases.

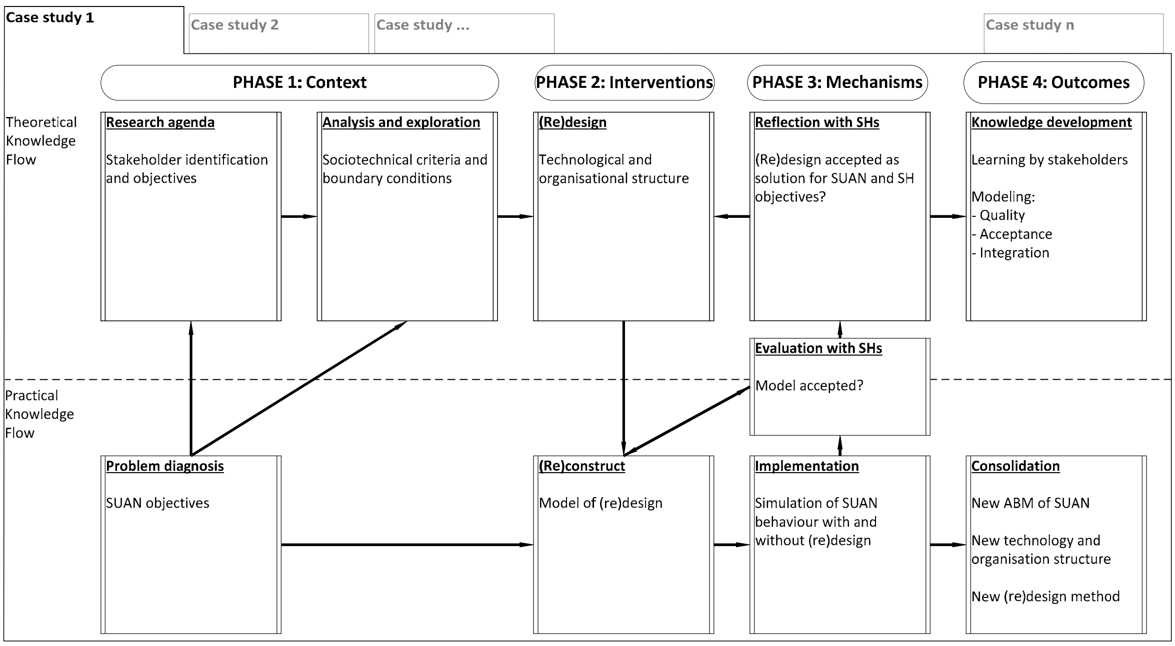

Figure 2. Conceptual design research method for facilitation of design interventions regarding technology and organisational structure in SUANs. SUAN = Symbiotic Urban Agriculture Network; SH = stakeholder; ABM = agent-based models.

Existing theory and methods from IS and IS dynamics are useful for communicating, modelling, and analysing simulation results. Zhu and Ruth [46] 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 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. [47] did an extensive review on the theory and methodology of industrial symbiosis research. They provide an overview of theoretical frameworks, analytical methods, indicators, and examples which may be useful during data collection and analysis of the network development. The researcher should actively select and present relevant information in an understandable manner to the participants in order to facilitate discussions on the simulated course of events. For example, Fichtner et al. [13] provide an interesting overview of personal, enterprise-level, and inter-organisational barriers that prevented stakeholders from closing loops in 25 historical case studies. These barriers may be useful to take into account 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 stakeholders in the real world have to be involved in an iterative validation of the agents that represent their role in the model and a reflection on the simulation results that come about. 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. [19] may be helpful to communicate the simulation results to the stakeholders. Along the process, the researcher or facilitator observes the process of participation during concept evaluation through development and use of an ABM. This will result in insights in 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 specifically include any exceptions on who is performing the design intervention activities. This 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.

5. Case Study

This section describes a case study to give illustrative insights in the application of the proposed methodology. In our project 'Re-Organise', a project that aims to stimulate the collaboration between local small and medium-sized enterprises (SMEs) and higher education institutions, the proposed methodology is going to be fully implemented at SUANs in Amsterdam, The Netherlands [48]. One particular consortium of companies consists of SMEs that are all located on the fringe of Amsterdam West. The goal for the stakeholders is 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 for local vegetable production, fruit gardens, and beekeepers), food service, and 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. For this, companies need energy products for cooking and heating, and material products, such as fertilizers and animal feed. The area has a rich development history and is therefore depending 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 mutual stakeholder dependency may be cooperative, for example, some parts of the area are owned by public stakeholders. These public institutions intend to give the farmers the right to maintain the area, while handing over local resources (grass, wood, etc.) to these farmers. This dependency may also be competitive: some internal and external parties, for example, want to expand at the expense of the current landowners. The design research of this case study will be following the phases of Figure 2: Context, Intervention, Mechanisms, and Outcome. We will now describe how the CIMO-logic looks like in this particular case study.

Phase 1: *Context* starts with gaining insight through a series of unstructured and semi-structured interviews with initial committed stakeholders [48]. For stakeholders that are interested in participation, the available technologies, business activities, input and output flows, geo-spatial information (e.g., location, size, and type of terrain) and institutional factors (e.g., relevant legislation, taxes, subsidies, and area development plans) are collected. The previous activities result in practical individual questions around stakeholder problems and opportunities regarding the sociotechnical aspects of the current technologies and organisational structures (see Table 2).

Table 2. Initial questions by stakeholders that are involved at the SUAN in Amsterdam West [48–50].

Stakeholder	Practical Question
Fruit garden owner	"What is the quantity and quality of the products (biogas, digestate) that are produced by my biodigestion system, and how can I use this technology to meet the market's demands in order 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, in order 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 economical value through recycling and upcycling, and particularly in the food sector?

An initial practical diagnosis of a research agenda is set up by combining the highlighted key words in Table 2 and formulating a case specific question that was shown to and approved by all stakeholders after several iterative steps [48]: "*Can we process and reuse local organic waste in a decentralized biodigestion system in order to increase economic and ecological value?*"

Then, materials, water energy, and information demands and supplies are to be mapped by means of material flow accounting methods. Data is 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 are translated in a case specific description of the SUAN's objectives through iterative brain writing and participatory meetings, resulting in a prescriptive design hypothesis: "*Use biodigestion systems for production and exchange of local biogas and fertilizers from public, private, and civil organic waste in order to realise 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 is used to develop a sociotechnical design through stakeholder participation. In addition, inspired by the work of Boons et al. [23] and Zhu and Ruth [46], IS dynamics typologies will be used to propose initial states and rules in model agent behaviour. This results 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 are put in a schematic model layout for further development of the ABM, using the methods of Van Dam et al. [39]. In Table 3, the steps for building an

ABM are shown, including the extent of stakeholder participation and the intended result. This ABM is used for experimentation with case specific design interventions: different plausible organisational structures around the implementation of decentralized biodigestion systems.

In phase 3: *Mechanisms*, first, the model is evaluated on quality, such as accuracy, acceptance by stakeholders, and system integration (completeness) based on theory by Hare [27]. This may lead to an additional model improvement step, for example, a more accurate description of the context and/or intervention. If the model is accepted, however, the stakeholders participate in an interactive reflection of the simulation results with the intention to improve the mutual understanding of the design intervention effects with respect to the intended SUAN scenarios. Depending on the results of the model or the lessons learned, either phase 1 or 2 is repeated, or phase 4 will start.

The emerging mechanisms will take the form of typologies, as described by Boons et al. [23] and can be evaluated in terms of series of events. During the participatory modelling of the system, the stakeholders can steer the intervention between facilitation and self-organisation or governmental planning. The model will help them to understand which dynamic is most appropriate in their case and the researcher can conclude in the end 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 [51] and Bauer and Herder [22]. This may contribute toward understanding which governance and management level events can be influenced directly through interventions within the abilities of the SUAN stakeholders. These iterative design optimization steps will take place in phase 4, but only after acceptance of the model.

Table 3. ABM modelling steps, inspired by Van Dam et al. [39].

Step	Methods	Intended Result
Concept formalization	Iterative model conceptualisation and show-and-tell participation methods	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, this 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 sociotechnical system

In phase 4: *Outcomes*, the lessons learned can be used as a learning tool for optimization experiments by practitioners in the specific case. Phase 4 allows for simulating contextual adjustments over time, to investigate whether the design intervention remains pragmatically valid in terms of intended outcome in spite of emerging contextual changes. For example, reasons for discontinuance, as mentioned by Shi et al. [52] (such as price volatility and bankruptcy), can be simulated. The ABM allows for studying the gradual effect of (interim changes in) both the context and design interventions on network collaboration and individual financial viability, as these indicators remain crucial to successfully implementing symbiosis [15]. If combined with other cases, the case specific outcomes lead to generic recommendations for improvement of participation and modelling methods, or even the methodology as a whole. In addition, the specific ABM can be used for setting up a generic ABM for SUANs, which may be useful for modelling and social learning in other cases as well.

This methodology may provide a different understanding of mechanisms and outcomes through ABMs that are based on literature as well as new empirical data. The methodology may therefore lead to improved insights in IS dynamics and its typology arrangement. In addition, it provides a way to take technological and organisational design interventions, as well as complex institutional behaviour into account

6. Research Agenda

In order to offer stakeholders grounded and tested insights into the mechanisms and outcomes that are imposed by technological and organisational design interventions on IS dynamics, a structured research agenda is proposed in this section. The research agenda is based on the previously presented conceptual methodology for participatory ABM development and analysis. The agenda distinguishes itself from the discussion on the industrial symbiosis dynamics by representing a prescriptive design approach, providing for theoretical as well as directly applicable knowledge on design solutions for SUANs in particular, and for industrial symbiotic networks in a broader sense.

The research agenda enables administering existing empirical knowledge from historical analyses, but allows for new insights on IS dynamics at the same time. Figure 3 shows how the research agenda, including research topics (light boxes: R1, R2, and R3), contributes to prescriptive knowledge development on design interventions through CIMO-logic in practice (dark boxes). The first research topic aims to provide a method to facilitate technological and organisational structure design in dynamic symbiotic networks. The second research topic is intended for development of insights among stakeholders in SUANs on the effect of technological and organisational design with respect to the symbiotic network as a whole. The third research topic provides the development of a generic ABM of SUANs. The arrows represent knowledge transfer. The next sections elaborate on the different research topics (R1, R2, and R3 in Figure 3).

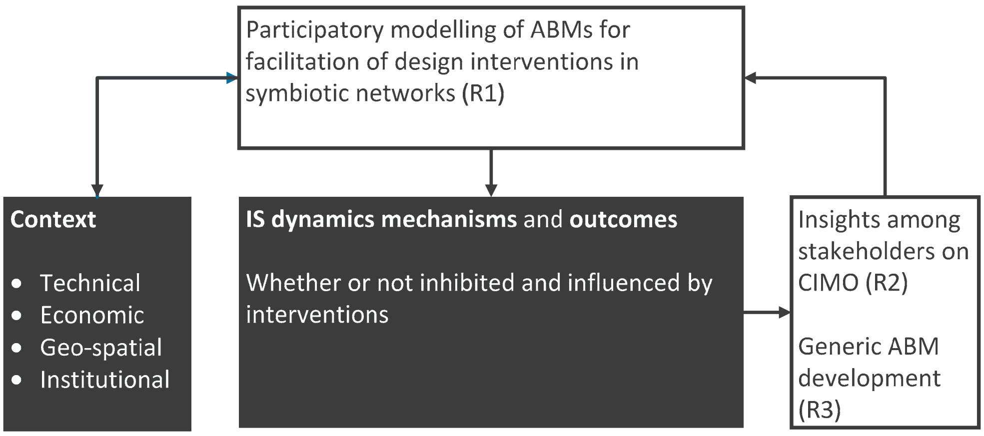

Figure 3. Diagram of the research agenda in relation with prescriptive knowledge development. R1, R2, and R3 refer to research topics. IS = Industrial Symbiosis; CIMO = Context, Interventions, Mechanisms, Outcomes; ABM = agent-based model.

6.1. Research Topic 1: New Design Intervention Facilitation Method for Symbiotic Networks

This design research addresses the next empirical step in further development of the literature-based prescriptive conceptual framework. The new method sheds light on the discussion regarding IS dynamics in SUANs and in other symbiotic networks. It provides a way to implement existing knowledge, by using contextual aspects and storylines in new cases. It also provides an a priori method for iteratively testing and evaluating mechanisms and resulting network evolution in these new cases. Monte Carlo simulations will be used to test the stability of the outcomes. Simulations also accelerate exploring new outcomes and possible occurrences. In addition, accompanying analyses on network functions such as business value and environmental impact will be connected to the scenarios.

6.2. Research Topic 2: Social Learning on Effects of Design Interventions on IS Dynamics

The proposed method aims to provide empirically grounded and tested socio-technical methods that enhance the implementation of the concept of IS through social co-evolutionary learning in practice. The activity of modelling is therefore regarded as a technique for encouraging stakeholder discussions, clarification of definitions, and uncovering mutual benefits or conflicts during the design process. These activities uncover the individual aims and reasons behind engaging in IS, and therefore add to the clarification of the desired network behaviour. The agent types, their behavioural mechanism and relation to the context, will be used for the development of ABMs through stakeholder participation.

6.3. Research Topic 3: Generic Agent-Based Model of Symbiotic Networks

While iteratively developing ABMs for multiple SUAN cases, patterns in corresponding contextual factors (e.g., actor and interaction behaviour) and intervention effects may come about. In the next few years, the models will be used to identify agent types, their corresponding behaviour, and the underlying IS dynamics. In addition, lessons learned on system boundary conditions and modelling aspects are likely to provide a higher accuracy and a larger embeddedness.

The research agenda aims to thoroughly analyse the development of a generic ABM of symbiotic networks. This accelerates model development in future cases. In order to develop a generic ABM, we will start with a conceptual framework, as presented in this article, and we will use the presented typologies (from Boons et al. [23]) as initial state. Based on the modelling and simulation outcomes, and the practical application of the generic tool to our SUAN case study and other case studies, we will come up with more precise insights on IS dynamics.

7. Concluding Remarks

In order to advance the facilitation of design interventions in dynamic symbiotic networks, a literature-based Design Science method and a research agenda for further method development was proposed in this article. The research agenda complements the 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 research agenda is a valuable contribution to the discussion around IS dynamics typologies. It is likely to provide tested and grounded evidence towards ex post IS dynamics typologies for usage in comparative analyses of new cases. Design Science methods are promising for uncovering prescriptive knowledge on design interventions for IS. It is important to note that the research agenda does not result in a single comprehensive set of rules that leads to successful development of IS networks. The agenda does, however, contribute 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 on 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 how to meet these societal demands. We are also convinced that participatory modelling methods are likely to encourage potential participants in practice to engage in IS, because of its power to elicit discussions among the participants. In addition, the research agenda 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 article sets an agenda on how Design Science methods in combination with participatory modelling can provide practical as well as theoretical knowledge on IS dynamics. A generic ABM that will be developed through the methods and agenda proposed in this article will provide more precise insights on how technological innovations and organisational structures influence IS dynamics.

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