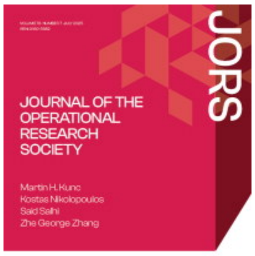

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A decision-making framework for the valorisation of the water cycle through industrial symbioses

Otto Chen[a,b], Navonil Mustafee[b], Barry Evans[a], Mehdi Khoury[a], Joep van den Broeke[c], Tavishi Guleria[c], Lydia Vamvakeridou-Lyroudia[a,c], Albert S. Chen[a], Slobodan Djordjević[a] and Dragan Savić[a,c]

[a]Centre for Water Systems (CWS), Civil Engineering, University of Exeter, Exeter, UK; [b]Centre for Simulation, Analytics and Modelling (CSAM), University of Exeter Business School, Exeter, UK[c]KWR Water Research Institute, Nieuwegein, The Netherlands

ABSTRACT

Industrial symbiosis (InSym) can further the goal of water sustainability by leveraging geographic proximity and developing solutions that allow the exchange of recycled water among businesses. However, InSym decision-making is complex as it involves multiple agents representing different stakeholder groups and displaying non-linear interacting behaviours. Operations Research (OR) techniques can capture such dynamic and emergent behaviour and help assess the feasibility of InSym formation. For example, multiple criteria decision analysis (MCDA) can evaluate conflicting criteria in decision-making problems, and computer simulation can model the operational processes, emergence and non-linear system feedback using approaches such as discrete-event simulation (DES), agent-based simulation (ABS) and system dynamics (SD). The paper proposes an OR framework that combines MCDA with a hybrid simulation (DES, ABS and SD) to support InSym decision-marking. The case study region in De Volt, The Netherlands, is poised to face stricter national regulations regarding discharges. It also experiences a water deficit during dry seasons, substantially worsened by climate change. Both challenges reveal the urgent demand for better water reuse and the deployment of OR tools to assess InSym formation. Our study contributes to the literature on deploying hybrid methods to maximise opportunities for shared value creation.

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1. Introduction

In water resource management, valorising resources within the water cycle is considered the holy grail for circular economy and environmental sustainability. Using a concept known as industrial symbiosis (InSym), a circular exchange of water, energy, and material between businesses can help realise synergies by leveraging their geographic proximity (Chertow, 2000). In this configuration, the waste and by-products of one industry become valuable resources/materials for another (Yazıcı et al., 2022; Frosch Ra, 1989). The potential of InSym in closing the water cycle is now widely recognised. However, as the formation of self-organising symbiosis involves different, and even conflicting, interests amongst the stakeholders (Bollinger et al., 2015; Guedes et al., 2019), its implementation is fraught with challenges. Further, InSym also implies a new business model. Although tacit knowledge and best practices exist, they mainly focus on individual businesses. This further complicates the stakeholders' assessment of new InSym business models to inform decision-making and whether to join the collective system.

The field of OR offers a plethora of tools and techniques, including hybrid approaches, to enable better and more informed decision-making (Mustafee & Katsaliaki, 2020). As InSym represents a complex adaptive system (CAS) involving multiple agents representing different stakeholder groups and displaying non-linear interacting/dynamic behaviours, OR could help with the quantitative assessment of such a system. However, modelling using a single OR approach, e.g., mathematical modelling or simulation techniques such as agent-based simulation (ABS), discrete-event simulation (DES) and system dynamics (SD), does not capture the intricacies of CAS. On the other hand, hybrid modelling draws on multiple such OR and simulation techniques and leverages the strengths of individual methods to provide the best possible representation of the system under scrutiny (Mustafee et al., 2020). This paper presents a hybrid modelling approach that combines ABS, DES, SD and multiple criteria

CONTACT Navonil Mustafee n.mustafee@exeter.ac.uk Centre for Simulation, Analytics and Modelling (CSAM), University of Exeter Business School, Exeter EX4 4ST, UK

decision analysis (MCDA) for modelling the water cycle in an InSym context.

InSym displays non-linear and interacting behaviours between various system components that change dynamically over time. For example, a business may join a collective system motivated by the efficiencies reported by existing adopters; however, over time, the benefits may become less favourable, and the business may decide to exit the joint venture. Any change in the composition of the cooperative will affect the return on investment, which will be a key decision point for entities already part of the InSym or considering joining it. Modelling InSym using a single simulation/OR approach does not adequately capture such complex decision-making. A hybrid approach provides an alternative by combining the modelling of operational flows in InSym (DES) with network emergence (ABS) with system feedback (SD). Further, MCDA evaluates conflicting criteria in decision-making problems involving several stakeholders; it is especially relevant for our analysis as it addresses the essential nature of InSym, which constantly involves stakeholders' decisions requiring balancing multiple factors (i.e., criteria), sometimes explicitly and sometimes without conscious thought, from both the perspective of individual adopters and the collective symbiosis.

The primary contribution of the paper is the application of a generic computational modelling framework that supports decision-making for industrial symbioses of the water cycle—the *Framework for the Symbiotic Water Cycle (F-SWC)* (Chen et al., 2025a). The framework has been used in three case studies for the EU Horizon 2020 ULTIMATE project (CORDIS 2024). The first case study is on the Dutch greenhouse InSym which is the subject of this paper. The second and third case studies are on a mobile rental wastewater treatment service in the Peloponnesian region of Greece (Chen et al., 2025a) and olive mill wastewater treatment in Karmiel, Israel (Chen et al., 2025b). To the best of the authors' knowledge, this is the first study that not only demonstrates the generic nature of a framework for InSym (implemented in three case studies) but also the only study related to the computational modelling of InSym formation with greenhouse owners as the potential adopters of a collective solution.

Section 2 reviews the literature on OR approaches to modelling InSym. Section 3 presents the F-SWC framework. Section 4 is on implementing the F-SWC for a Dutch greenhouse case study involving potential adopters (farmers with greenhouses) of an InSym solution related to collective wastewater treatment plants (WWTPs) and water reuse. Section 5 presents the results from experimentation and performs a rigorous analysis of the scenarios. Section 6 is the paper's concluding section and presents a short summary of the work, limitations and future research directions.

2. Literature review

Several challenges complicate the adoption of InSym solutions within a circular economy. The use of OR methods and approaches can help alleviate some of these challenges by applying both quantitative and qualitative models for InSym decision-making. In Section 2.1, we identify InSym adoption challenges concerning Circular Economy and stakeholder conflicts and provide examples of relevant work in OR. Section 2.2 is a review of InSym studies in the OR literature; here we identify the opportunities of employing multiple OR methods or hybrid modelling approaches. Section 2.3 includes a review of existing InSym frameworks. Here we identify the dearth of studies on generic frameworks for modelling InSym which has been applied in multiple case studies. In summary, whilst the motivation to use OR models for addressing InSym challenges in the context of Circular Economy is presented in Section 2.1, the gap in the literature with the use of OR models that combine multiple methods and the lack of generic frameworks to model InSym decision-making are identified in Section 2.2 and Section 2.3, respectively.

2.1. Challenges with InSym adoption within the circular economy with a focus on stakeholder conflict

Taqi et al. (2022) conducted an extensive literature review and identified technological, organisational, social and economic challenges for InSym adoption. Among these broad categories, a subset of stakeholders' challenges were covered under organisational context; these included the lack of organisational support and commitment, organisational culture that is not easily malleable, weak organisational policies and hesitations in transformation from the existing to the new collective system *(ibid.)*. Quantitative OR techniques like computer simulations could inform the stakeholders of the expected benefits of a collective approach (Chen et al., 2025a) and aid the transformation of the organisational mindset.

Taqi et al. (2022) and Cheruvallil (2025) identified social challenges that are particularly critical for the sustainability of InSym solutions; these include inter-firm coordination, networking and knowledge exchange. Trust among the stakeholders is considered "indispensable" for overcoming such challenges (Cheruvallil, 2025). A conceptual framework for developing trust exists in the InSym literature (Ramsheva et al., 2019); it includes a calculation-based trust (CBT) model of costs and benefits to estimate the likelihood of InSym actors to be (un)trustworthy. Similarly, in the OR literature, studies of trust include the work of Harper et al. (2021), which considers the various facets of trust between the stakeholder, the modeller and the OR model.

Yet another challenge in forming and sustaining InSym solutions is the conflicts among the stakeholders and the differences in power and influence exerted by individual actors. Hein et al. (2017) analyse the power aspect by adapting the *stakeholder value network approach* and applying it to a case study on incinerator symbiosis network in Europe. Conflicts can happen due to competitive interests among the actors as they are often in the same sector and engaged in similar activities (Henriques et al., 2021). Alosi et al. (2025) classify the *co-operation-competition paradox* within the InSym relationship into operations and strategic dimensions; the paradoxical tension between collaboration and internal efforts is classed as operational, whereas the paradoxical tensions between sharing and protecting information, and contradicting partner objectives are seen as strategic. An OR study that has considered stakeholders' conflicts of interest, values and motivation (among other dimensions) is the work of Morales and Diemer (2019), who developed an SD model to evaluate InSym in a port city in France (Dunkirk).

OR literature on the InSym *co-operation-competition paradox* (Alosi et al., 2025) and stakeholder conflict is arguably limited. One reason for this could be that case studies that employ real-world data from multiple actors make it difficult to realise such empirical studies (indeed, our case study was only possible as part of an EU Horizon 2020 project, which included the farmers' co-operative in the Netherlands as a project partner). Yet another reason could be that many of these studies focus on methodological aspects (rather than specific application areas), e.g., multi-stakeholder decision making and conflict resolution (Dowling et al., 2016), value conflicts (Wenstøp & Koppang, 2009), with several studies using qualitative (Soft) OR approaches, e.g., systems thinking (Maani, 2016) and cognitive mapping (Ferretti, 2016).

2.2. Review of or approaches for modelling of InSym and opportunities for hybrid modelling

Yazıcı et al. (2022) examined studies using OR techniques in InSym and categorised them into Exact Methods, MCDA, and Simulation. The study identified that almost half of the papers used simulation methods. In relation to MCDA, the study reported that the technique was widely used to determine the priority values of the criteria affecting the InSym network, for ranking alternatives, for network design and for the evaluation of the performance effects of InSym applications. In a similar study, Demartini et al. (2022) summarised the literature on InSym modelling into nine categories based on the most prevalent approaches: ABS, Input-Output model (IOM), Lifecycle Assessment (LCA), Material Flow Analysis (MFA), Network Analysis (NA), Mixed Integer Linear Programming (MILP), Decision-Making Trial and Evaluation Laboratory (DEMATEL, which is a form of MCDA), Ecological Network Analysis (ENA), and SD. The study identified ABS as the most widely used technique for modelling InSym. In terms of mixing methods, the study reports the use of ABS with IOM, LCA and MFA, and hybrid simulation using ABS and SD.

Lawal et al. (2021) reviewed InSym tools and categorised them into process integration (PI) and mathematical optimisation (MO). PI approaches have been applied to single or multiple plants to minimise resource utilisation and harmful emissions (Klemeš & Kravanja, 2013). Studies have applied MO approaches to assist in matching the inputs and outputs of participating companies. PI tools for InSym design and planning have mostly operated in isolation and thus concentrated on individual resources, e.g., heat, water, carbon, waste, and power; MO applications also demonstrated a similar pattern (Lawal et al., 2021). It is noticeable that both approaches focus on merely resource respect of InSym, i.e., reclaim, exchange, utilisation of resource in the process.

Yeo et al. (2019) provided a framework with several steps of the InSym creation process and reviewed tools for each step. More specifically, the study identified six steps: undertaking a preliminary assessment, engaging businesses, finding opportunities for synergy, determining feasibility, implementing transactions, and documentation. InSym tools were primarily used in the step related to finding synergistic opportunities (free-market mechanism-based matching, process input–output stream-based matching, and network design and optimisation) and to appraise performance in the implementation step. Thus, it is arguable that the tools are generally developed for a specific purpose to address a single aspect of the InSym creation process. With the use of a hybrid approach, there is potential to use qualitative OR (also referred to as Soft OR) tools and methods for problem conceptualisation, facilitated modelling and co-development of modelling scenarios, together with quantitative modelling techniques (Hard OR) such as computer simulations (Powell & Mustafee, 2017), and to apply them to various stages of the InSym development process.

We examined the characteristics of decision problems within InSym to identify the specific requirements of the modelling framework and which would inform the use of OR methods. InSym presents unique and complex challenges not typically encountered in traditional business models. These distinct features (InSym-F) can be summarised as follows:

- InSym-F1: Under a collective approach, businesses operate/behave differently due to their individual conditions and demands. Thus, the stakeholders view the system performance of symbiosis differently.
- InSym-F2: The higher the number of firms adopting InSym, the greater the profits and the reduction in waste disposal costs and the higher the chance to sustain InSym and attract new adopters (Demartini et al., 2020).
- InSym-F3: The exchange of resources plays a critical role in InSym, holding significant importance for all participating businesses rather than just one. Ensuring process efficiency is paramount since it directly affects all involved businesses. It is important to note that this process extends beyond manufacturing and encompasses various operational management aspects, such as logistics.
- InSym-F4: There are more relations amongst impact factors in InSym than in the normal business model. The relations are usually dynamic, non-linear, and variable.
- InSym-F5: An industrial symbiosis usually takes a long time to achieve its advantages. In a long-term decision problem, different priorities might exist at different stages.

The ABS approach can model the potential adopters of InSym as individual agents to account for the divergence of behavior due to individual conditions and demand (InSym-F1). ABS can also be used to model the interaction between the agents, for example, potential adopters and early adopters, and which can represent the evolution of the InSym through time. Using this technique, each agent can be modelled as a decision-making unit which may either join, continue or exit the collective InSym solution (InSym-F2). The DES approach can model InSym operational processes, including exchange of resources (InSym-F3); it can identify potential issues related to process efficiency and provide optimisation analysis. Further, the combined use of ABS and DES is an effective approach towards modelling InSym operational processes (using DES) that are related to individual businesses (represented as agents); the hybrid ABS-DES approach can also be used to model the overarching InSym operation which evolves through time (InSym-F1, InSym-F3). The SD approach has an advantage in dealing with interactive relations amongst impact factors of the symbiosis business model, particularly when relations themselves are dynamically variable due to the change of context (InSym-F4) and the passage of time (InSym-F5).

Based on our assessment of the inherent characteristics related to InSym decision-making (InSym-F1 through F5), and their mapping to specific simulation techniques from the modelling methodology perspective, it is arguable that a hybrid ABS-DES-SD simulation is an effective approach to modelling the formation of the industrial symbiosis. Further, the hybrid simulation model could also integrate MCDA to consider the different KPIs that are considered important for the potential adopters of the InSym solutions (InSym-F1), and also the change in priorities in the long run (InSym-F5).

2.3. Review of InSym frameworks and opportunities for developing a generic computational modelling framework for InSym decision-making

Several frameworks exist in the literature focussing on specific aspects of InSym. For example, Mirata et al. (2024) propose a business value framework that was developed through a synthesis of the literature and interviews from stakeholders with experience in InSym, and which captures business value propositions of InSym, including costs, benefits and sacrifices, and their enabling mechanisms. A mixed-level analytical framework comprising society, network, and enterprise has been proposed by Yap and Devlin (2017) to explain InSym emergence, development, and disruption. However, similar to the framework proposed by Mirata et al. (2024), it is a conceptual framework and therefore the application to case studies is not discussed. Yet another conceptual InSym framework is the work by Ramsheva et al. (2019), where the focus is on developing trust in the context of InSym strategies and progressing from "calculus-based trust to knowledge-based trust, and finally, identification-based trust" (*ibid.*). Henriques et al. (2022) developed an InSym framework composed of incentive identification that is derived from best practices of InSym and expert consultation, a risk assessment model based on risk factors identification and clustering, and finally, mitigation actions. However, framework validation through real-world implementation scenarios is discussed only as future research. Thus, in the literature on InSym frameworks, there is a dearth of studies that have developed a modelling framework specific to InSym decision-making. As part of our EU Horizon 2020 ULTIMATE project, our focus was on the development of such a computational modelling framework and its application to multiple studies, thus evidencing the translation of a proposed framework into a generic framework.

Existing frameworks on hybrid simulation focus on domains such as healthcare, construction, manufacturing and maintenance. For example, Chahal (2010) proposes a generic SD-DES framework for healthcare; Nguyen et al. (2024) proposes a hybrid SD-ABM framework and applies it to a case study on the transmission of COVID-19 in care homes. Examples of studies in construction include the work of Hwang et al. (2016) who developed a hybrid SD-DES framework for facility restoration planning after a disaster. In this study, DES enables the investigation of restoration operations based on the changes in the external conditions, which, in turn, are informed by a comprehensive understanding of restoration conditions through SD modelling. SD-DES framework specific to construction has also been proposed by Alvanchi et al. (2011), whereas Nasirzadeh et al. (2018) present a hybrid SD-ABS framework for modelling construction projects.

In manufacturing, Farsi et al. (2019) argue that the existing ABS-DES frameworks for complex manufacturing systems are limited to component and system levels of representation and introduce a new modular hybrid ABS-DES framework that enables the development of multi-agent DES. Yet another example from manufacturing is the work by Nagadi et al. (2018) who developed an ABS-DES-based assessment framework for smart manufacturing and applied it to a case study related to a manufacturing facility in North America that produces components for pumps and other mechanical devices. Hybrid simulation frameworks have also been studied concerning maintenance operations to enable more efficient production. For example, the work by Linnéusson et al. (2020) develops a hybrid SD-DES-based multi-objective optimization framework supporting strategic maintenance development to improve production performance. In a similar vein, Oleghe and Salonitis (2019) discuss an SD-DES hybrid modelling framework to study maintenance operations for total productive maintenance (TPM), which is a maintenance approach that optimises equipment effectiveness, eliminates breakdowns and promotes autonomous maintenance through routine activities of the workforce (Bhadury, 2000).

Only one study (Kobayashi et al., 2020) proposed an ABS-SD-DES hybrid simulation architecture for calculating dynamic material flow in connected lifecycle systems for InSym contexts. The study pointed out the advantage of ABS-SD-DES hybrid simulation approach for capturing the characteristics of industrial symbiosis. However, the methodology is based on the life cycle engineering (LCE) approach. It focused on analysing the input-output compatibility of material flows and value changes through the lifetime of responding products in industrial symbiosis. Unlike our F-SWC framework, it is not concerned with the dynamic evolution of InSym, and neither is it proposed as a tool for InSym decision-making.

In summary, the literature review has identified the dearth of studies that have applied OR approaches to analyse collective systems where geographical proximity is a key element. Moreover, decision-making problems may arise at any level, including operational, tactical, and strategic (Suzanne, 2021). InSym literature could thus benefit from hybrid modelling studies incorporating various techniques supporting different stakeholder groups. Towards this objective, we have developed a modelling framework to support InSym decision-making. The framework is designed around the need for continuous performance evaluation at both the individual and the symbiosis (system) levels, which dictate the system's dynamic evolution through time.

3. The framework for symbiotic water cycle (F-SWC)

F-SWC is an analytical framework that supports modelling InSym decision problems. It aims to help decision-making from the perspective of (a) potential adopters and current users of InSym, and (b) the operators of shared InSym facilities. The framework combines three modelling and simulation (M&S) techniques, namely, SD-DES-ABS—also called hybrid simulation (Brailsford et al., 2019)—with the MCDA approach. Thus, F-SWC extends a typical SD-DES-ABS hybrid simulation by integrating methods (MCDA) from the broader OR discipline; in the M&S literature, such extensions are referred to as a hybrid model (Tolk et al., 2021).

- The DES approach models the InSym operational processes. It can identify potential issues related to process efficiency and provide optimisation analysis.
- The ABS approach models the interaction of the InSym agents and the evolution of the cooperative network. The combined use of ABS and DES, both discrete techniques, enable effective modelling of InSym operational processes (using DES) related to individual businesses

(represented as agents) and also the overarching InSym operation.

- The SD approach has an advantage in dealing with interactive relations amongst impact factors of the symbiosis business model, particularly when relations themselves are dynamically variable due to the change of context.
- MCDA can offer insights for tackling InSym problems by evaluating alternative preferences of potential adopter enterprises and decision-making stakeholders both before and during the formation of InSym networks as well as during its operation (Yazıcı et al., 2022). For individual InSym participants, MCDA captures decision-making involving multiple criteria or objectives.

The use of the hybrid modelling approach thus enables us to simultaneously consider multiple aspects of InSym operation, including the simulation of participation dynamics and capturing both individual (business-level) performance and overall performance of the collective co-operative.

3.1. Components of the F-SWC framework

The framework consists of three parts: *Symbiosis Operation* (SO), *Symbiosis Performance Evaluation (SPE, regarding* system performance*)* and *Symbiosis Participation Dynamics (SPD)*. Figure 1 illustrates the components and their inter-relationship at a high level. Figure 2 depicts the interaction among the SO, SPD and SPE modelling components at a detailed level. SO uses event-based logic to simulate continuous processes. DES-based fluid flow modelling is the methodology of choice and it enables the analysis and optimisation of water resources. The SPE and SPD components use an MCDA-inspired approach to elicit the most important and representative motivation KPIs from symbiosis operators and potential participants (i.e., business entities), respectively. In the case of SPE, the performance KPIs derived from MCDA are used with SD. The SPD component is modelled using three interacting modelling approaches—MCDA, ABS and SD. MCDA identifies the main decision-making factors that determine whether a business entity wants to join the collective InSym system. ABS models the participating businesses and shared resources that are crucial factors for analysing the InSym business model (e.g., shared water treatment facilities); the resources are modelled as agents. SD calculates the motivation dynamics.

3.2. Interaction between F-SWC framework components

The interaction between the SO, SPE and SPD is illustrated through a swimlane diagram (Figure 2). It is structured based on the SO, SPE and SPD components and their respective modelling techniques. The 1st swimlane is associated with the SO DES technique, the 2nd and 3rd swimlanes relate to the MCDA and SD techniques employed by SPE, and the final three swimlanes are for the ABS, SD and MCDA techniques associated with SPD. As shown in Figure 2, the performance KPIs and motivation KPIs related to the MCDA elements for SPE and SPD must be selected first. Two sources of primary data for the MCDA are as follows: (I) ***A survey for potential adopters*** (2nd swimlane) elicits the representative motivation KPIs considered most important by the potential adopters, presenting the main factors of decision-making as to whether to join the collective system. (II) ***A survey for the InSym decision makers*** (6th swimlane) elicits performance KPIs considered most important for the evaluation of the performance of the symbiosis. Through a standard MCDA analysis conducted from primary data for (I) and (II), weights for KPIs are calculated; these are used as inputs to the SD models for SPE (3rd swimlane) and SPD (5th swimlane), respectively. In terms of data requirements, we note that the

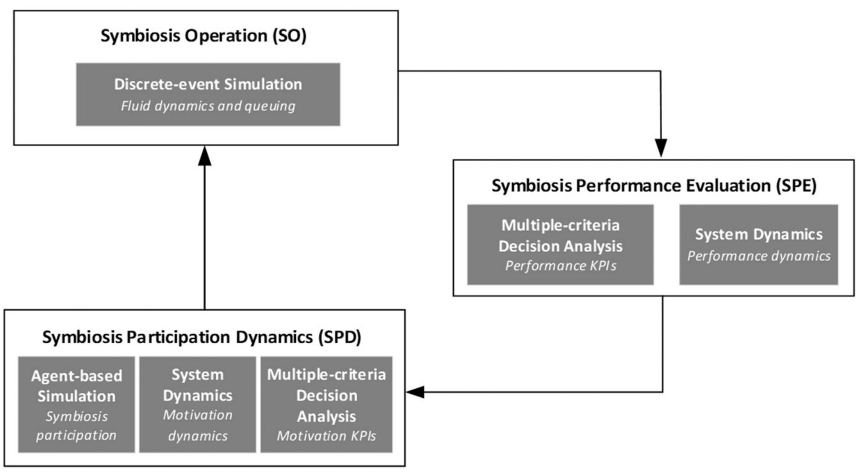


Figure 1. The relations between the components of the F-SWC modelling framework.

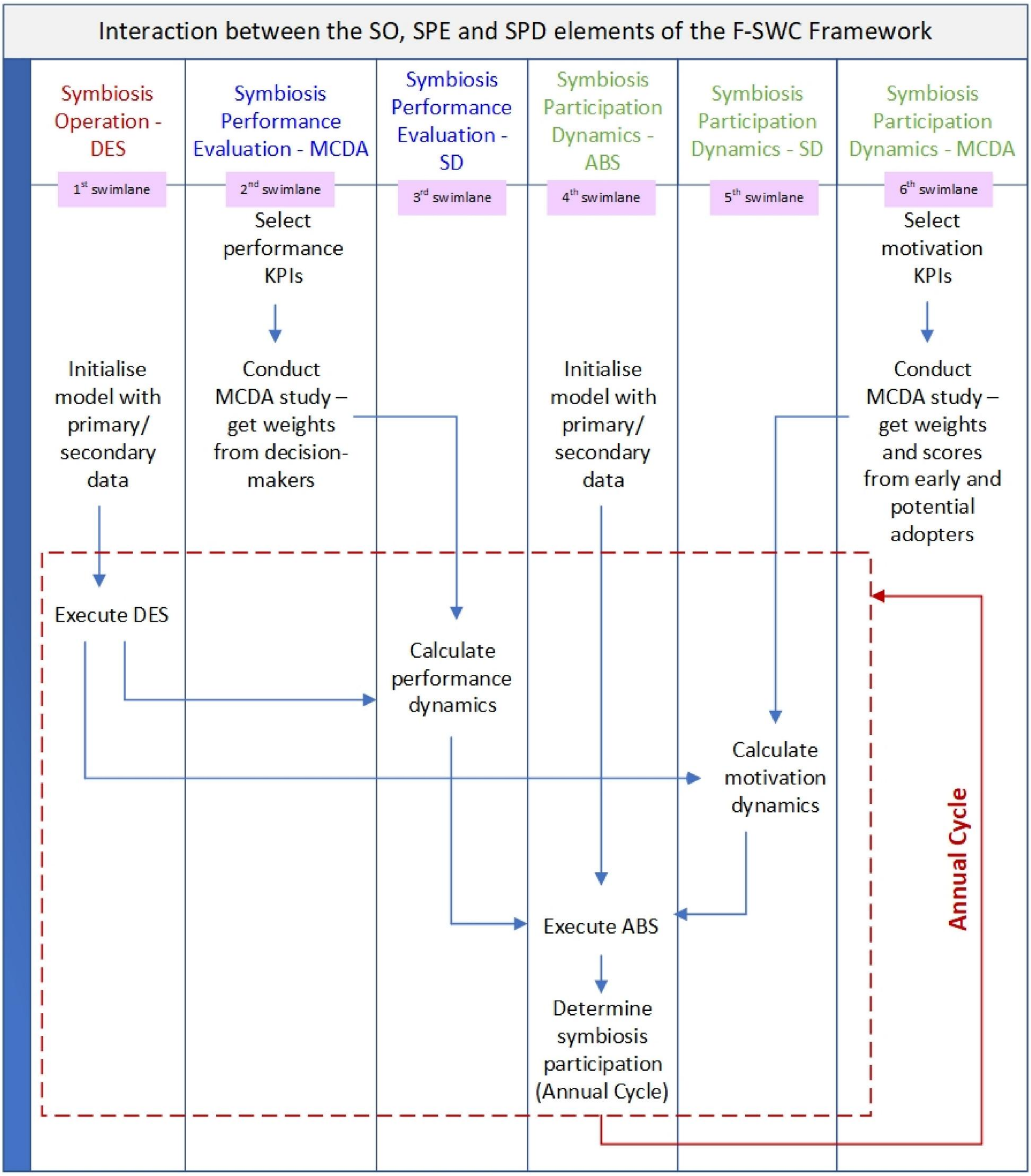


Figure 2. Interaction among the SO, SPD and SPE modelling components of the F-SWC framework.

implementation of F-SWC will also require primary and/or secondary data for the DES element of SO and the ABS element of SPD (4th swimlane). Similar to the MCDA study, the framework includes DES models (under SO) for both the *potential adopters* and *InSym decision-makers*.

The F-SWC element-level interactions are discussed next with reference to the three core computational aspects of the framework.

- **Calculating Motivation Dynamics** (5th swimlane): The output from the DES models for potential adopters (SO; 1st swimlane) is used along with MCDA weights and scores (6th swimlane) to dynamically calculate the motivation to join the symbiosis using the SD model for SPD (5th swimlane). The framework proposes using individual DES models to represent the operational processes of the potential adopters, which is used in conjunction with the weights and scores derived from the MCDA study in relation to SPD.
- **Calculating Performance Dynamics** (3rd swimlane): The output of the DES model for InSym

Table 1. Two Categories of DES models in the Symbiosis Operation (SO) element of the F-SWC framework.

Category of DES	DES description	Number of DES models	Interaction between the two categories of DES models
Potential Adopter/ InSym user	DES is used to model the individual processes of the potential adopters and/or current InSym users.	Several DES models are needed, one for each potential or current InSym user. DES output is used with MCDA to calculate motivation for potential adopters to join and for current users to leave InSym.	For potential adopters joining the InSym, some internal processes will transition to the InSym infrastructure and vice-versa.
InSym Decision Maker	DES is used to model the processes related to the shared InSym infrastructure.	One DES model. The output of the DES model is used with MCDA to calculate performance dynamics on the InSym.	With every new user, the InSym DES model must accommodate the processes which were hitherto modelled using individual user-level DES models. This requires the two categories of the DES models to be linked, either at a conceptual level or through modelling elements.

decision makers (SO; 1st swimlane) is used with MCDA weights (2nd swimlane) to calculate the performance dynamics of the symbiosis dynamically. As a "potential adopter" transitions to an "InSym user," it is expected that a part of the hitherto individual processes (e.g., user-level wastewater treatment) will transition towards the shared InSym infrastructure (e.g., a shared wastewater treatment facility). Thus, the SO element of the framework stipulates two categories of DES models (Table 1).

- **Determining Symbiosis Participation** (4th swimlane): The SPD element is an ABS that models individual entities that are either potential adopters or existing users of InSym. As mentioned earlier, primary/secondary data will enable a realistic representation of the entities. The execution of the ABS, which relies on dynamic calculations (i.e., the values change as the model progresses through simulation time) on the motivation to join (5th swimlane) and InSym performance dynamics (3rd swimlane), determines symbiosis participation. The performance KPIs will evolve at a global level (i.e., collective level), according to the changes in the underlying InSym operation. Potential adopters/existing users can join/leave the InSym during specific time frames (shown as an annual cycle with a feedback arrow in Figure 2). The feedback models a real-world scenario where a potential user agrees to join the InSym, but still needs time to implement the transition of processes, and who, having joined, may decide to leave as the InSym performs worse than was expected by the adopter. For example, at the start of each year, an individual business can transition from the status of a potential adopter (i.e., remain interested but not join) to a symbiosis adopter (i.e., join), and vice versa. This is also the moment to allow the criteria weighting of SPE MCDA to change at any point if planned, according to the change of annual performance (SPE), or other conditions that are designed for InSym context, e.g., different priorities planned for different periods. Thus, from a modelling perspective, it is necessary to compute performance and motivation through time and until the end of simulation. This continuous computation is illustrated as a dashed box in Figure 2.

3.3. Applicability of F-SWC as a generic framework

F-SWC is designed to support decision-making in diverse InSym settings involving water reuse and circular resource flows. While this particular paper focuses on a Dutch greenhouse cooperative (Section 4), the framework itself is not context-specific. Rather, it is modular and adaptable, combining ABS, DES, SD, and MCDA to allow flexibility across varying environmental, operational, and social conditions.

To demonstrate its versatility and robustness, the F-SWC has been applied in three different case studies under the EU Horizon 2020 ULTIMATE project:

- Dutch Greenhouse InSym – the subject of this paper, characterised by advanced horticulture, strict environmental regulations, and high water reuse potential.
- Mobile Rental Wastewater Treatment Service – implemented in the Peloponnesian region of Greece, addressing small-scale, decentralised wastewater treatment for seasonal agricultural data users in a semi-arid climate (Chen et al., 2025a).
- Olive Mill Wastewater Treatment – based in Karmiel, Israel, deals with high-strength industrial wastewater from olive processing, with complex regulatory and seasonal load variations (Chen et al., 2025b).

These additional applications—each in distinct geographic, climatic, industrial, and socio-economic contexts—demonstrate that the F-SWC is not confined to a single use case or region. While this particular paper presents the Dutch case in detail, in Chen et al. (2025a, 2025b), where the framework is customised to different industries, operational scales, and reuse pathways.

Regarding scalability, the framework was deliberately designed to allow scaling across:

- Industry types: from greenhouse agriculture to food processing and decentralised wastewater treatment;
- Scales: from small businesses to industrial clusters;
- Water-use profiles: including high-volume seasonal discharge, variable-strength effluents, and continuous reuse loops;
- Governance models: including cooperative-driven initiatives, utility-managed services, and private-public partnerships.

Each simulation component—ABS, DES, SD, and MCDA—is built with parameter flexibility and modular logic, allowing for recalibration according to different stakeholder structures, participation dynamics, policy contexts, and climate projections. This positions F-SWC as a general-purpose hybrid modelling framework for supporting industrial symbiosis planning and feasibility assessment across regions.

4. The Dutch greenhouse case study

The case study area—De Vlot—is located at 's-Gravenzande town in the South Holland province of The Netherlands. De Vlot is home to numerous modern agro- and food-cluster businesses. The key stakeholders are a cooperative with 60 businesses growing mainly ornamental crops in greenhouses. The greenhouse businesses face an upcoming zero-emission regulation in 2027. Thus, they not only have ambitions to reach zero liquid discharge for legal compliance but also seek better reuse of water and nutrients from greenhouse drain water (i.e., wastewater) for mitigating water resource deficit during dry months or droughts. Climate change also plays a part as the literature from De Vlot informs us of projected precipitation deficits and an increase in evaporation (Appendix A provides the rationale for considering scenarios related to climate change in our case study). Thus, the cooperative has proposed industrial symbiosis (InSym) as a strategy to explore water reuse possibilities through collaboration with individual businesses. The main element of the proposed InSym solution is the development of a shared wastewater treatment plant (WWTP).

4.1. Conceptual model

Figure 3 presents the conceptual model. There are two main levels: global and local (agent). The three elements of the F-SWC framework (SO, SPE, and SPD; refer to Figure 1) are arranged at the local and/or global level according to the interaction described in Figure 2. SPE is at the global level (system performance), SPD is at the local level, and SO exists at both local and global levels. Similarly, the entities implemented in the hybrid model, including 36 greenhouses and one collective WWTP, are also arranged as local greenhouse agents and as *the global* WWTP agent respectively. The performance

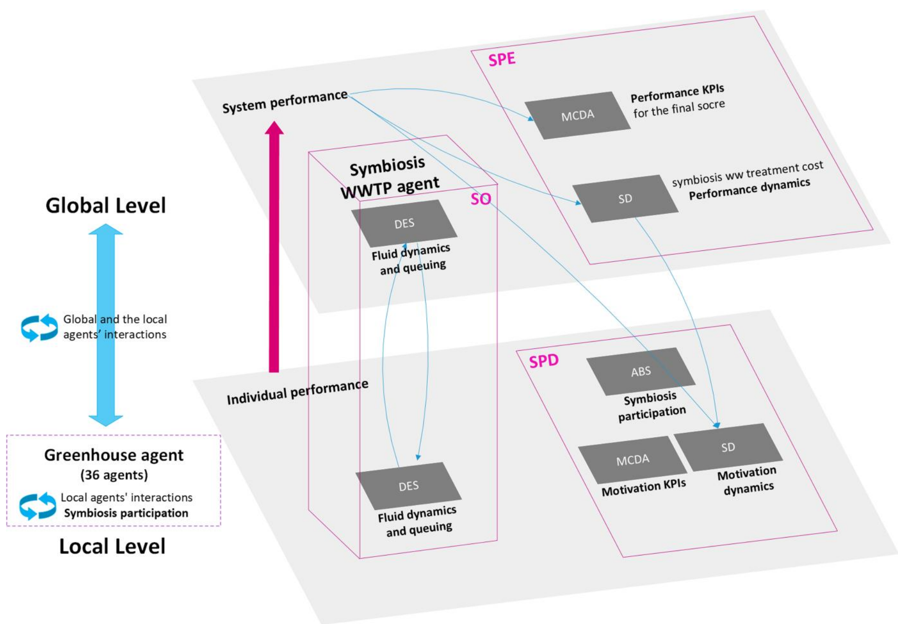


Figure 3. Conceptual model of the Dutch greenhouse case study.

reported by individual DES models (one model for each greenhouse agent) reflects on the system performance; the latter affects not only the annual final score of MCDA and treatment cost rate of SD in SPE, but also the motivation KPIs of SD in SPD.

The global level of the model includes an MCDA and an SD module in SPE. The MCDA component evaluates the overall performance of the symbiosis by turning the information on system performance into the final score. The SD module deals with the change in the cost rate of wastewater treatment, as the unit cost rate varies with the change in the treated volume of wastewater and the number of symbiosis adopters. The change in collective treatment cost also results in a change in the score of the KPI "Cost Advantage" in the SD module of SPD in greenhouse agents. Similarly, some system performance indicators, such as the change in the number of adopters, also affect the motivation KPIs of the SD module of SPD in greenhouse agents. The SD and MCDA modules for motivation KPIs (of SPD in greenhouse agents) will constantly update accordingly, resulting in an updated willingness level for the ABS module to assess its participation status annually throughout the modelling period, leading to changes in the number of adopters.

The DES module within the greenhouse agents models processes related to the water systems - from rainwater harvesting, water storage, irrigation, evaporation, and internal recycling to discharge wastewater and sending it to collective WWTP treatment. The DES module in the symbiosis WWTP agent deals with the wastewater treatment process, including the interactions of collecting from the greenhouse adopters and distributing recycled water back to the greenhouses. The agent interactions can happen amongst greenhouse agents and between the WWTP agent and greenhouse agents, which can be done through the ABS or SD modules. In this case study, the interaction amongst greenhouse agents is through the SD module of SPD, which is related to participation dynamics. The interaction between the WWTP agent and greenhouse agents is through the DES modules of SO, which relate to reclaimed water reuse scenarios.

4.2. Data

The data required for the model comprises three main components, with the first component including two key types of information—a baseline survey and data for MCDA.

The first component is the data from the individual businesses that participate in the modelling to better understand how the symbiosis and their business will perform once the symbiosis is formed. Whilst these businesses have the potential to adopt symbiosis in the future, participation in the modelling does not imply a guaranteed commitment to adoption. This component further includes two key types of information. First is the baseline data (collected from a baseline survey) used to simulate the participating greenhouses within the model, enabling them to function realistically prior to the formation of any symbiotic relationships. Second is the MCDA data used to evaluate symbiosis participation dynamics (SPD) and motivation for adopting symbiosis.

4.2.1. Baseline survey

The baseline information was obtained through the baseline questionnaire survey (Appendix B). This survey aimed not only to assess current operational conditions before the planned symbiosis but also to understand future water demands and concerns around water reuse in light of climate change and the forthcoming 2027 zero-emission regulations. Although most of the operational data obtained reflect actual greenhouse activities, we treated this information as secondary data in this study. This is because some responses related to concerns about using symbiotic treated water were applied in the modelling scenario experimentation, and these questions were not specifically designed to support our hybrid simulation research for InSym.

The survey was systematically designed to align with the study's objectives of understanding baseline conditions and growers' concerns regarding the use of treated wastewater. Conducted with the inputs of experts from the Dutch greenhouse horticulture sector (Glastuinbouw Netherland), the survey targeted greenhouse companies in the case study and was structured to gather data on 15 important sectorial parameters such as crop types, cultivation and irrigation methods, water sources, storage and preferences for wastewater quality and cost. The questions were crafted to address practical decision-making factors, such as water quality concerns and acceptable costs. The survey was designed as a questionnaire and conducted online over a span of 2 months. A total of 60 greenhouse growers were invited to participate. 39 responses were initially collected, which were subsequently cleaned to remove duplicates and incomplete entries, resulting in 34 valid responses, representing approximately 57% of all commercial enterprises in the study area. According to published literature for voluntary industry surveys, these respondent rates are considered strongly acceptable, particularly in applied sectors like greenhouse horticulture (Groves, 2006). The data was analyzed using descriptive statistics, including percentage distributions and averages, to identify trends and key insights. For instance, 44% of respondents indicated rainwater as their primary irrigation source, while 47% relied on surface water as a secondary source. The methodology provides robust insights, and any potential areas of improvement, such as ensuring full clarity of questions for all respondents, were addressed through planned follow-up interviews to gather additional perspectives and refine the findings further. This detailed approach strengthens the reliability of the survey outcomes and the derived KPIs for the framework.

4.2.2. MCDA data for symbiosis participation dynamics (SPD)

The latter type, the MCDA data for SPD, was collected through a targeted survey conducted in January and February 2022 (Appendix C). Prior to this, we identified relevant motivational KPIs based on a literature review (Albino et al., 2016; Ghali et al., 2017; Mantese & Amaral, 2017, 2018; Tamburino et al., 2020; Van der Salm et al., 2020), leading to the selection of six KPIs most relevant to this case study (see Table 2). The suitability of these KPIs and the MCDA questionnaire design were tested through a pilot survey involving industry professionals, including greenhouse owners, cooperatives, and experts. In accordance with the F-SWC framework, which recommends stakeholder-specific KPI identification for each symbiosis case. Note that the selected six KPIs for the Dutch case may not be applicable to other InSym cases due to varying stakeholder motivations and objectives. Despite multiple efforts, we were unable to collect sufficient primary MCDA data. We acknowledge this as a study limitation. To mitigate this, we asked the expert to derive MCDA data for 36 interested greenhouses, using part of the secondary baseline data related to participation willingness and attitudes towards water reuse, taking into account factors such as greenhouse size and water storage capacity.

As for the second component of the data, it concerns decision-making for the symbiosis itself, primarily supporting the symbiosis performance evaluation (SPE) within the model. The key MCDA input for the SPE was derived from expert consultations facilitated by the case study partner, KWR (see Table 3).

The third component of the data includes climate-related data, representing the potential impacts of climate change on the research area encompassing all 36 modelled greenhouses. Average monthly precipitation data for 1991–2020 was sourced from the Royal Netherlands Meteorological Institute (KNMI) (1991-

Table 2. The motivation KPIs of the decision-making for symbiosis participation (SPD).

Motivation KPI	Description of the KPI	Aspects	Parameters used in the hybrid model
Cost Advantage (CA)	The financial benefit from collective wastewater treatment vis-a-vis individual treatment of wastewater.	Economic	Treatment cost- symbiosis (global level) Treatment cost- individual (agent level) Reuse policies (global level)
Peer Recommendation (PR)	Recommendation for participation from greenhouses who have decided to join the collective treatment.	Social	The number of adopters (global level)
Group Advantage (GA)	The potential advantages of the collective system, including better negotiation power towards contractors and service providers, information exchange, and cost and risk sharing.	Social	The number of adopters (global level) The volume of treated wastewater (global level)
Resource Utilisation (RU)	The advantage of the availability of water resources through collective treatment to cope with water deficits during dry seasons or future climate change. In addition to improvement in water quality for reuse, a more extensive system will also create a flexible buffer for mutual support, meaning someone's surplus can support others who are suffering a shortage.	Operational	Water deficit (agent level) The number of adopters (global level)
Contractual Condition (CC)	The degree of satisfaction with the conditions and performance of the contract of the collective treatment. An ideal and fair contract where the rights and obligations of all parties ensure successful and sustainable cooperation.	Operational	Reuse policies (global level) The number of adopters (global level)
Legal Compliance (LC)	To join the collective treatment (i.e., symbiosis) to comply with statutory requirements to be introduced in 2027.	Legal	The number of adopters (global level)/ The volume of untreated wastewater discharged (global level)

Table 3. The performance KPIs and MCDA weighting for symbiosis performance evaluation (SPE).

Descriptions of KPI	Weight	Consideration dimension regarding symbiosis
Storage basin alarm days	30	Water resource availability and stability
Tap water used	10	Financial dimension; water resource consumption
Unit WWTP treatment cost	30	Financial dimension
Rainwater used	10	Freshwater resource consumption and dependency
Discharge of wastewater and reclaimed water	20	Environmental protection; resource utilisation

2020, https://www.knmi.nl/kennis-en-datacentrum/uitleg/klimaatnormalen-1991-2020). Climate change parameters were drawn from the report by the Netherlands Environmental Assessment Agency (Van Minnen et al., 2013).

The authors acknowledge several potential biases and reliability concerns arising from the use of both primary and secondary data in the modelling process.

In the baseline questionnaire survey, self-reporting and social-desirability bias may have influenced responses. Regarding self-reporting bias, as participation was voluntary, growers with particularly strong opinions on treated wastewater might be overrepresented. To test this, we grouped responses by their stated willingness to adopt reclaimed water and examined whether other responses (e.g., cost preferences, salinity limits) showed significant variability. Distributions remained approximately normal, suggesting that self-selection did not meaningfully distort the broader dataset. Still, we acknowledge this as a potential source of bias. Another source of bias in the baseline survey is the social-desirability. Some questions, such as "percentage of annual irrigation met with rainwater" or "acceptable surface water quality," rely on recall and subjective interpretation. In addition, questions on risk perception or public acceptability may be susceptible to socially desirable responses. While the survey was developed with input from domain experts and policy stakeholders to reduce ambiguity, we recognise that these responses may still carry interpretation bias.

In some cases, questions intended to elicit preferences for the support MCDA survey were not specifically designed for modelling, introducing further bias. Thus, the current modelling results should be considered as an initial feasibility assessment of the Industrial Symbiosis (InSym) initiative for the greenhouse cooperative. A more formal feasibility study should be conducted at a later stage—preferably after obtaining preliminary stakeholder agreement, such as through an Expression of Interest (EOI). At that stage, participating greenhouses would be asked to share detailed operational parameters through a new survey, which would also help mitigate earlier data limitations.

Regarding the MCDA survey for participation dynamics (SPD), the main limitation was the lack of complete primary data from all 36 greenhouses. To address this, some MCDA inputs were estimated by greenhouse experts. While this added valuable domain insight, it also introduced expert bias and subjectivity, especially when extrapolating findings to the broader cooperative. Additionally, selection bias may have been present, as the respondents could be those more receptive to InSym or more severely affected by water scarcity, thus not representative of the entire population. To mitigate these issues, the follow-up survey and modelling will be critical. A sensitivity analysis was conducted to examine how uncertainties—particularly in the MCDA and climate data—affect model outcomes. A Monte Carlo analysis was applied to the MCDA scores related to SPD, which will be discussed in detail in Section 5 later. Furthermore, structured expert elicitation methods were used to reduce bias and subjectivity. These included classifying the 36 greenhouses by business scale (large, medium, small), plant group (ornamental, seed, vegetable), soil type (soil and substrate), irrigation method (irrigation and drip systems), and main water source (rainwater, surface water, and tap water).

In terms of climate data, two main sources of bias are projection uncertainty and extreme weather variability. Climate models inherently carry uncertainty, as they are based on assumptions about future emissions pathways and global policy decisions. There is also a scale mismatch issue: regional climate projections for the Netherlands may not accurately reflect the microclimates affecting study greenhouses, especially when simulating rainwater capture or water reuse potential. To enhance model reliability and stakeholder engagement, we recommend incorporating sub-scenarios under the broader "with climate change" scenario in the follow-up survey and modelling. Specifically, testing three distinct climate projections—rather than relying on a single scenario—will allow for more representative input and help assess the greenhouse operators' preferences for reuse strategies under varying water deficit conditions. This approach is expected to improve both the robustness of the modelling and the practical value of its insights.

4.3. Implementation of hybrid model

Three primary agent types are implemented in the hybrid model—symbiosis WWTP agent type, greenhouse agent type, and pipe agent type. There is only one instance of the WWTP agent type. This is because symbiosis employs a collective approach for wastewater treatment to achieve zero emission by setting up one symbiosis WWTP. The agent includes a DES module that performs the symbiosis's wastewater treatment process. The DES is implemented in AnyLogic and uses the AnyLogic Fluid library (ANYLOGIC, 2023). There are 36 instances of greenhouse agents (one for every greenhouse that showed interest in adopting the symbiosis solution). Each greenhouse agent instance has a DES module that models the individual recycling processes for each business operation. An AnyLogic database is linked to each greenhouse agent and records data for individual parameters. The parameters are used to initialise the agents, e.g., location in latitude and longitude (see Appendix D on the supplement material for model implementation). Finally, there are 72 pipe agents (two for each of the 36 greenhouse agents). For each greenhouse agent, one pipe agent sends wastewater to the symbiosis WWTP, whereas the second pipe agent takes treated water back from the WWTP. The flow of water is also modelled using the Fluid library. We used the Strengthening the Reporting of Empirical Simulation Studies (STRESS) guidelines (Monks et al., 2019) to document the model. The STRESS documentation is included in Appendix E.

The implementation of the model consists of four main tasks (Figure 3): (a) Implementation of SO using DES, (b) implementation of SPD using ABS, SD, and MCDA (motivation KPIs), (c) implementation of SPE using SD, DES, and MCDA (performance KPIs), and (d) implementation of SO-SPE-SPD interactions. These are discussed next.

4.3.1. Implementation of so using DES

Since the SO happens and spans two settings, one at the local level and the other at the global level, DES, which is primarily used for performing operational processes, is also applied in the two settings. For the case study, the local level comprises DES in each greenhouse agent (Figure 4a); the global level includes the DES of the symbiosis WWTP agent

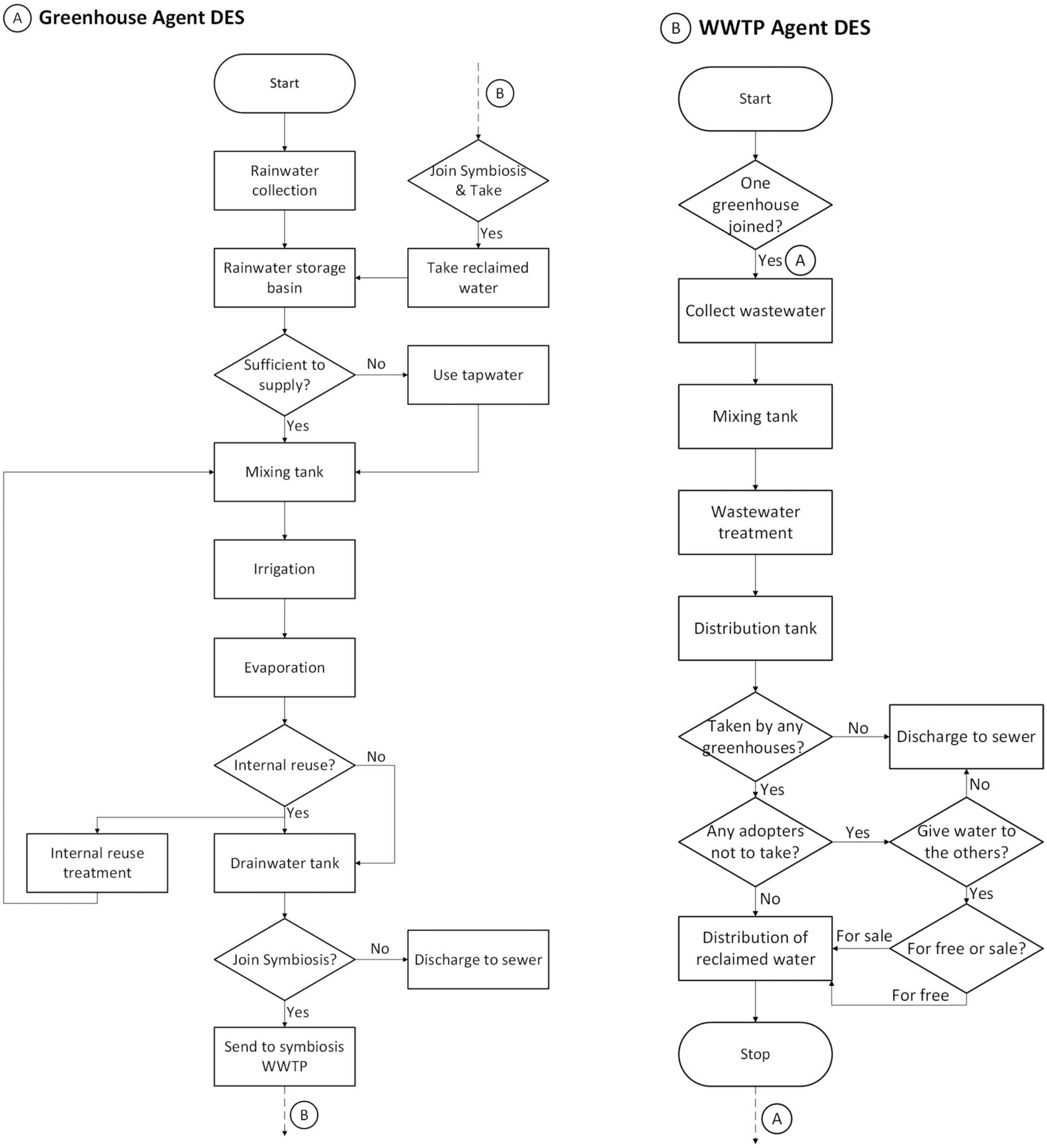


Figure 4. DES module for water utilisation process in the local-level greenhouse agent (a) and global-level symbiosis WWTP agent (b).

(Figure 4b). Both DES modules apply the Fluid library of AnyLogic, with mainly tanks, pipes, and valves, to construct the process of water treatment, recycling, and utilisation, as well as the connections with the pipe agents to connect the greenhouse agents with symbiosis WWTP.

The majority of 36 greenhouses use rainwater collected as the main water resource for irrigation in their water utilisation process (i.e., DES module, Figure 4a), whereas they need to use tap water for irrigation when the rainwater collected is not sufficient, which mostly happens in dry seasons. Only a few of the 36 greenhouses use tap water as the primary water resource (rather than rainwater) due to some specific crop types they grow. The model applies the same DES process to each greenhouse whilst it allows each greenhouse to perform differently, for instance, for those greenhouses using tap water as the main water resource, by collecting lower volumes of rainwater, storing it in tiny storage basins, and utilising lots of tap water (these initial parameters are set in the model).

As recycling nutrients from used irrigation water is a common practice in greenhouse operations, the majority of the 36 greenhouses are currently applying internal treatment and recycling to part of the drain water (i.e., the rest of the water used after irrigation, which is the wastewater that zero-emission seeks to tackle). Internal recycling can also benefit the greenhouses in terms of water resource availability. The drain water, which remains after being partly taken by internal recycling, is discharged as wastewater to the municipal sewer system or local environment. However, if a greenhouse adopts the symbiosis solution, the drain water will be sent to the symbiosis WWTP, and the treated water will then be reused circularly by the greenhouse.

Figure 4b illustrates the wastewater treatment process and the water distribution process. The water distribution part will perform different water reuse scenarios (discussed in the sub-section on scenarios for experimentation; Section 4.4).

4.3.2. Implementation of SPD using ABS, SD, and MCDA (motivation KPIs)

Figure 5a shows that the hybrid model calculates symbiosis participation dynamics (SPD) through the interactions of the two SD modules in the model. While SPD works in each greenhouse agent to determine its participation status, i.e., SPD is accommodated in each greenhouse agent (local level), it also interacts with the SD module to determine the global symbiosis treatment cost rate. The SD module of the greenhouse agent consists of the six motivation KPIs (i.e., MCDA scores). The dynamic evolvement of the KPIs works with the MCDA weights elicited from the questionnaire survey, leading to the change in the "willingness to join." The willingness level can be calculated using the following Equation (1):

$$WL = \sum_{i=1}^{n} (WCi * \ SCi)/5 \qquad (1)$$

where:

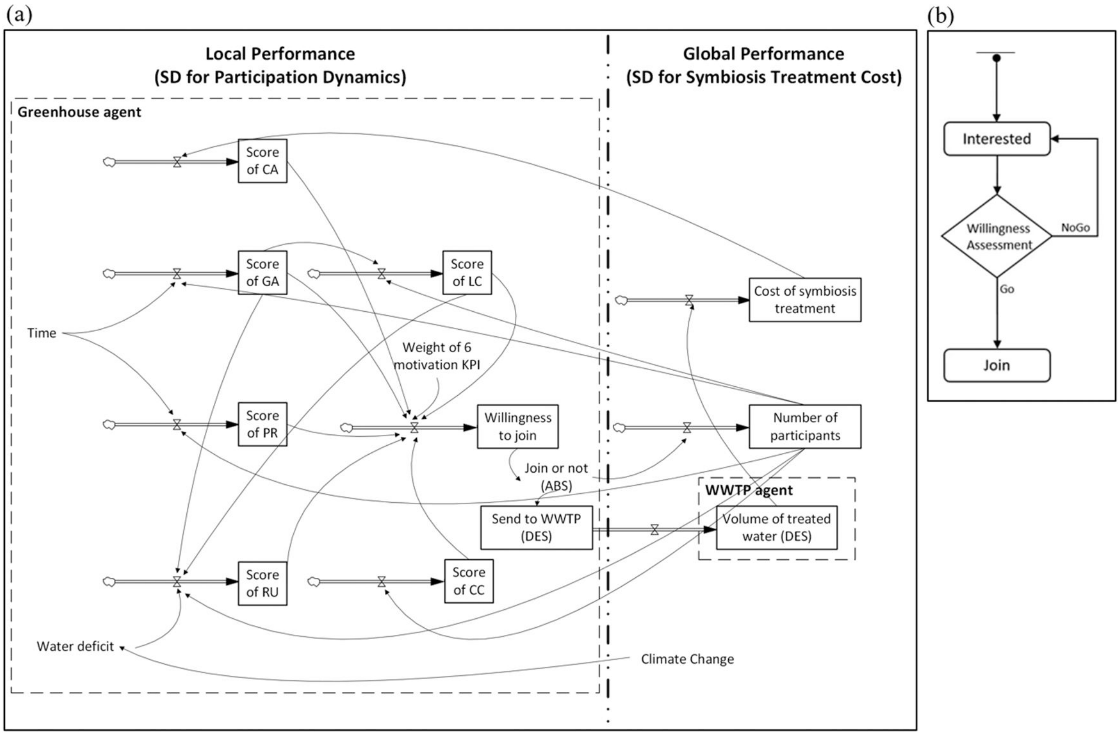


Figure 5. (a) SD module at the local level (greenhouse agent) and global/symbiosis level. (b) The process of the decision-making for joining the symbiosis by the potential adopters, i.e., ABM module.

- WL is the overall willingness level, ranging from 0 to 1 (i.e., 0% to 100%).
- *WCi* denotes the weight assigned to the i-th performance criterion (i.e., motivation KPI), with $i = 1, 2, \dots, n$. In this case study, $n = 6$ (criteria). Each weight ranges from 0 to 1, and the sum of all weights equals 1 (or 100%).
- *SCi* is the score of the i-th motivation KPI, ranging from 1 to 5. These scores are dynamically generated by the System Dynamics (SD) module, and are based on a scale designed to support initial motivation KPI scoring in the questionnaire survey.
- The division by 5 standardises the scores to a 0–1 scale for consistent aggregation.

The "willingness to join" will then be dealt with by an ABS module in the greenhouse agent, which applies a threshold (i.e., 3) to determine the participation status, i.e., whether to join (if $>=3$) or not (if <3), as shown in Figure 5b. If it changes its status to "join," the wastewater of the greenhouse will be sent to symbiosis WWTP, which will increase the volume of wastewater treated in the WWTP agent. The change in the volume will further reflect on the cost rate of symbiosis treatment through the SD module at the global level, which will conversely influence the SD module of participation dynamics.

4.3.3. Implementation of SPE using SD, DES, and MCDA (performance KPIs)

The SPE refers to the performance of symbiosis WWTP (shown on the right side of Figure 5a above) and the performance of the individual greenhouses. The design of F-SWC thus acknowledges that both individual businesses and symbiosis operations should be healthy and benefit from the conduct of InSym. The performance of the collective WWTP will be presented by some indicators obtaining evaluation from its own DES module. The change of some symbiosis performance will dynamically lead to changes in performance-related values at the global level, such as the lower cost rate of WWTP treatment caused by the increased treated volume of wastewater. An SD module performs this dynamic at the global level.

On the other hand, the performance evaluation of individual greenhouses, obtained from its DES module, will be presented through global statistics indicators. As all the performance indicators calculated from the two sources, i.e., global and local levels, would not necessarily perform in the same trend in different simulation scenarios, a single indicator is needed to determine the ranking of scenarios tested. Besides, the decision-making stakeholders usually have divergent views on what constitutes good performance of the symbiosis. We, therefore, apply the MCDA approach at the global level, with performance KPIs selected as the MCDA scores, as well as the MCDA weights elicited from the survey towards decision-makers. An MCDA final score will be calculated and used to rank the scenarios (refer to Section 4.4).

It Is noted that the decision makers are exactly the same as the symbiosis adopters in this case study, whilst in other cases applying F-SWC, the decision makers and symbiosis adopters may involve rather different members. The composition of the decision-making stakeholders can either be as simple as businesses merely from the potential adopters, or as complex as a group including potential adopter enterprises, local authorities, treatment providers, and other investors. For the former case, i.e., the decision-making stakeholders are merely from the potential adopter enterprises, the modelling can be considered as "participatory modelling," as the potential adopters who participate in the simulation also eventually make decisions. It is also worth mentioning that, even in the former case, the same people who have two roles as an adopter and a symbiosis decision-maker may have different views towards the interest of symbiosis and the interest of their own business. Therefore, a different KPI set (i.e., the performance KPIs) from the motivation KPI set is needed.

The final score is calculated year by year, along with the evolvement of SPE. Calculating the final score is the same as the weighted average method, by summing up the weighted score of each year using Equation (2).

$$SF = \sum_{j=1}^{m} \sum_{i=1}^{n} (WCi,j * \; SCi,j/100) \tag{2}$$

where:

- SF is the final aggregated score of the evaluated scenario.
- *WCi,j* represents the weight of the i-th performance criterion (i.e., performance KPI) in year j, where $i = 1, 2, \dots, n$. In this case study, $n = 6$ (criteria). Each weight ranges from 0 to 100 (i.e., 0% to 100%), and the sum of all weights for each year j equals 100%.
- *SCi,j* is the standardised annual score of the i-th performance criterion in year j, also ranging from 0 to 100 (i.e., 0% to 100%). These scores are derived from the raw performance KPI values through a standardisation process.
- $j = 1, 2, \dots, m$ denotes the simulation years, where m = 8 in this case study.

However, the F-SWC recommends that this MCDA should allow the weighting to be changed at a given time during the simulation period, as a long-term symbiosis alloes the pursuit of different priorities at different stages, e.g., environmental priority (zero emission) before 2027 and economic priority (i.e., cost improvement) at a later stage.

4.3.4. Implementation of SO-SPE-SPD interactions

The interaction between SO, SPE, and SPD determines the operation performance and participation dynamics of the InSym. The three elements of the framework are implemented to model the interactions between local and global levels, through multiple interactions amongst ABS, DES, SD, and MCDA modules (please see Figure 3). Through this, the F-SWC framework addresses the complexity of real-world InSym by comprehensively modelling the reciprocal and synergetic relation between the individual business and the InSym solution.

Since the modelling framework was designed to be adaptable to various hybrid simulation platforms beyond AnyLogic, and considering that some readers may be unfamiliar with AnyLogic, the authors chose to present the framework and modelling approach from a generic modelling perspective rather than focusing solely on the specifics of the AnyLogic implementation. However, the authors acknowledge that visualising the AnyLogic model can enhance readers' understanding of how the ABS, DES, SD, and MCDA modules correspond to the SO, SPD, and SPE elements, and how these modules interact within the system. To support this, Appendix D has been provided.

The simulation and the SO-SPE-SPD interactions work on an annual loop basis before the end of the simulation period. After manually setting up parameters for the tested scenario and the weights of MCDA KPIs for SPE (mentioned in Section 3.3 Table 3), the simulation of the InSym operation (SO) will start as the first-year simulation. At the end of each year, the KPIs of performance evaluation (SPE) will be updated, simultaneously affecting the evolvement of the SD module of participation dynamics (SPD) whilst carrying on the InSym operation (SO) of the following year. Meanwhile, at the start of each year, it is the moment for each business to start their new status of participation, e.g., they can change their status from potential adopter (i.e., remain not join) into symbiosis adopter (i.e., join), according to the SD module of SPD that is affected by the annual symbiosis performance changes (of SPE) and by some changes of InSym operation (SO) at individual agent during the previous year. On the other hand, it is also the moment to allow the criteria weighting (of performance MCDA, SPE) to change if it is planned, according to the change of annual performance (SPE), or other conditions that are designed for InSym context, e.g., different priorities planned for different periods.

The hybrid model is implemented using AnyLogic (version 8.7.9). The simulation period was eight years, from 1st January 2023 to 31st December 2030. The upcoming zero-emission regulation in 2027 (Van Paassen & Welles, 2010) helped us investigate whether the greenhouses achieve zero wastewater discharge before 2027.

4.4. Scenarios for experimentation

Table 4 lists the 32 scenarios being tested by the hybrid model. The experiments focus on evaluating the performance of symbiosis under different water reuse strategies, considering the impacts of climate change and the participation conditions of the adopters. Seven parent scenarios (B0, B1, A0, A1, J0, J1, and JQ1) are categorized based on participation conditions and whether climate change is considered. The value 1 indicates that a parent scenario considers climate change (e.g., B1, A1). Concerning the participation condition, the scenarios allow us to experiment with whether the number of adopters can evolve and the level of participation commitment (i.e., whether an existing adopter is allowed to quit). Parent scenarios B0 and B1 are the baseline, i.e., no symbiosis. They are followed by the ideal scenarios A0 and A1, with all 36 greenhouses joining in the beginning. The remainder of the parent scenarios (J1, J0, and JQ1) all start from 10 adopters. JQ1 is the only scenario that allows existing adopters to quit the symbiosis. For parent scenarios A0, A1, J0, J1, and JQ1, six sub-scenarios are defined based on the reuse policies of reclaimed water. These sub-scenarios are numbered 1-6 and are prefixed with the parent category designation followed by a hyphen, for example, A0-1 and JQ1-6.

5. Discussion of results and analysis

A symbiosis is considered a long-term investment with extended longevity of operations. We modelled 36 adopters with their respective water treatment processes using AnyLogic's DES-based fluid flow library. As the modelling of fluid flow is computationally demanding, we determined that executing the experiments for eight years, from 1st January 2023 to 31st December 2030, was sufficient to see all the scenarios reach the full participation, i.e., 36 adopters, the time when achieving zero discharge/emission to comply with the new 2027 regulation (Van Paassen & Welles, 2010). Amongst 32 scenarios, 18 scenarios were selected to be run for five

Table 4. List of parent scenarios and sub-scenarios for experimentation. A total of 32 scenarios are tested.

Scenario	Sub-scenarios	Description
B0 B: **Baseline**; 0: no climate change	N/A	Individual greenhouse operation (no symbiosis); no climate change
B1 B: **Baseline**; 1: with climate change	N/A	Individual greenhouse operation (no symbiosis); with climate change
A0 A: **All** join; 1: no climate change **All** 36 adopters joining from the inception of the symbiosis. Climate change is not considered.	A0-1	Water sent to the symbiosis *must be taken back* (no non-takers). Climate change is not considered.
	A0-2	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is *shared equally* by takers.
	A0-3	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is *shared proportionately* as per the volume sent by the takers.
	A0-4	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is *shared according to the deficit level* of the takers.
	A0-5	Water sent to the symbiosis by takers must be taken back; water from non-takers is *sold according to the deficit level* of the takers.
	A0-6	Water sent to the symbiosis by takers must be taken back; water from non-takers is *discharged after treated.*
A1 A: **All** join; 1: with climate change **All** 36 adopters joining from the inception of the symbiosis. Climate change is considered.	A1-1	Water sent to the symbiosis *must be taken back* (no non-takers). Climate change is considered.
	A1-2	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is *shared equally* by takers.
	A1-3	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is *shared proportionately* as per the volume sent by the takers.
	A1-4	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is *shared according to the deficit level* of the takers.
	A1-5	Water sent to the symbiosis by takers must be taken back; water from non-takers is *sold according to the deficit level* of the takers.
	A1-6	Water sent to the symbiosis by takers must be taken back; water from non-takers is *discharged after treated*.
J0 J: allow new **joining**; 0: no climate change Ten adopters joined from the beginning; the remaining are potential adopters who can join anytime, **no** climate change.	J0-1	Water sent to the symbiosis *must be taken back* (no non-takers). Climate change is considered.
	J0-2	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is shared equally by takers.
	J0-3	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is shared proportionately as per the volume sent by the takers.
	J0-4	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is shared according to the deficit level of the takers.
	J0-5	Water sent to the symbiosis by takers must be taken back; water from non-takers is sold according to the deficit level of the takers.
	J0-6	Water sent to the symbiosis by takers must be taken back; water from non-takers is discharged after treated.
J1 J: allow new **joining;** 1: with climate change Ten adopters joined from the beginning; the remaining are potential adopters who can join anytime, with climate change.	J1-1	Water sent to the symbiosis must be taken back (no non-takers). Climate change is considered.
	J1-2	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is shared equally by takers.
	J1-3	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is shared proportionately as per the volume sent by the takers.
	J1-4	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is shared according to the deficit level of the takers.
	J1-5	Water sent to the symbiosis by takers must be taken back; water from non-takers is sold according to the deficit level of the takers.
	J1-6	Water sent to the symbiosis by takers must be taken back; water from non-takers is discharged after treated.
JQ1 J: allow new **joining**; Q: allow **Quit**; 1: with climate change Ten adopters joined from the beginning; the remaining are potential adopters who can join anytime, **allow quit**, with climate change.	JQ1-1	Water sent to the symbiosis must be taken back (no non-takers). Climate change is considered.
	JQ1-2	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is shared equally by takers.
	JQ1-3	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is shared proportionately as per the volume sent by the takers.
	JQ1-4	Water sent to the symbiosis by takers must be taken back; water donated by non-takers is shared according to the deficit level of the takers.
	JQ1-5	Water sent to the symbiosis by takers must be taken back; water from non-takers is sold according to the deficit level of the takers.
	JQ1-6	Water sent to the symbiosis by takers must be taken back; water from non-takers is discharged after treated.

Table 5. Simulation results for the 32 scenarios (grouped into the baseline and five parent scenarios).

Scenario	Brief descriptions	Final score	Zero emission	Alarm days	Tap water
B0	No symbiosis (B); No climate change (0)	256	Never	2666	350157
B1	No symbiosis (B); With climate change (1)	248	Never	2893	382787
A0: 36 adopters all (A) join; no climate change (0)					
A0-1	Everyone must take back water (no non-takers).	461	2023	2332	229964
A0-2	Water donated by non-takers is shared equally by takers.	462	2023	2399	210334
A0-3	Water donated by non-takers is shared proportionately as per the volume sent by the takers.	461	2023	2411	217896
A0-4	Water donated by non-takers is shared according to the takers' deficit level.	462	2023	2405	179013
A0-5	Water from non-takers is sold according to the takers' deficit level.	462	2023	2405	179013
A0-6	Water from non-takers is discharged.	453	2023	2466	248531
A1:36 adopters all (A) join; with climate change (1)					
A1-1	Everyone must take back water (no non-takers).	452	2023	2428	253348
A1-2	Water donated by non-takers is shared equally by takers.	454	2023	2486	235938
A1-3	Water donated by non-takers is shared proportionately as per the volume sent by the takers.	452	2023	2522	243838
A1-4	Water donated by non-takers is shared according to the takers' deficit level.	454	2023	2497	202288
A1-5	Water from non-takers is sold according to the takers' deficit level.	454	2023	2497	202288
A1-6	Water from non-takers is discharged.	439	2023	2600	275392
J0: 10 adopters joining from the beginning; Allow new joining (J); No climate change (0).					
J0-1	Everyone must take back water (no non-takers).	375.5 [372.2, 379.4]*	2031	2457	299415
J0-2	Water donated by non-takers is shared equally by takers.	425.1 [420.5, 431.6]*	2027	2407	244013
J0-3	Water donated by non-takers is shared proportionately as per the volume sent by the takers.	425.4 [420.3, 430.2]*	2027	2427	241253
J0-4	Water donated by non-takers is shared according to the takers' deficit level.	428.3 [423.3, 432.2]*	2027	2419	227373
J0-5	Water from non-takers is sold according to the takers' deficit level.	428.6 [424.1, 433.1]*	2026	2415	228652
J0-6	Water from non-takers is discharged.	362.7 [361.2, 365.1]*	2031	2503	307918
J1: 10 adopters joining from the beginning; Allow new joining (J); With climate change (1).					
J1-1	Water must be taken back by everyone (no non-takers).	388.8 [374.7, 402.9]*	2029	2539	299476
J1-2	Water donated by non-takers is shared equally by takers.	418.8 [415.8, 421.7]*	2027	2511	265249
J1-3	Water donated by non-takers is shared proportionately as per the volume sent by the takers.	416.4 [411.7, 421.1]*	2027	2557	270852
J1-4	Water donated by non-takers is shared according to the takers' deficit level.	419 [418.1, 419.8]*	2027	2525	252422
J1-5	Water from non-takers is sold according to the takers' deficit level.	422.6 [421.5, 423.7]*	2026	2519	249101
J1-6	Water from non-takers is discharged.	391.6 [385.9, 397.3]*	2029	2644	306390
JQ1: 10 adopters joining from the beginning; Allow new joining (J); Allow quit (Q); With climate change (1).					
JQ1-1	Everyone must take back water (no non-takers).	396.6 [393.2, 400]*	2029	2526	295560
JQ1-2	Water donated by non-takers is *shared equally* by takers.	419.6 [416.2, 423]*	2027	2509	263431
JQ1-3	Water donated by non-takers is *shared proportionately* as per the volume sent by the takers.	417.8 [413, 422.6]*	2027	2526	251287
JQ1-4	Water donated by non-takers is shared according to the takers' deficit level.	419 [415.6, 422.4]*	2027	2526	251287
JQ1-5	Water from non-takers is sold according to the takers' deficit level.	422.2 [420, 424.4]*	2026	2518	249074
JQ1-6	Water from non-takers is *discharged*.	383.2 [379.8, 386.6]*	2029	2526	251287

*$n = 5$ replications.

replications each for Monte Carlo analysis. Replications were not applied to all 32 scenarios because the Monte Carlo analysis specifically targets the scores of six motivational KPIs. The remaining 14 scenarios are not influenced by stochastic variation and therefore yield consistent results regardless of replication. Table 5 lists the simulation result of the 32 scenarios tested; the 18 scenarios with multiple replications (J0-1 to J0-6; J1-1 to J1-6; JQ-1 to JQ-6) include a range for the MCDA final score (Table 5; column 3 "Final Score").

The use of fixed, single-time weightings in the SPE MCDA across all scenario experiments presents a limitation, particularly given the dynamic nature of industrial symbiosis. In real-world systems, priorities evolve over time, and the model could be significantly enhanced by enabling dynamic adjustments to KPI weightings throughout the simulation period.

In the SPE framework, dynamic weighting was part of the original design, allowing weightings to be updated annually—or at any specified time (in the simulation)—based on the collective perspective of the symbiotic group (i.e., the cooperative). This flexibility reflects the shifting focus and priorities that naturally emerge in collaborative industrial systems.

Similarly, for SPD, dynamic weighting could be incorporated through annual surveys conducted after the first model run. For example, a review meeting could be held at the end of the first year to administer a second MCDA survey. This would capture both updated weightings and revised scores, supporting a data assimilation process. By combining different sources of information—such as the initial survey, the updated survey, and forecasts from the initial model run—the model can generate a more accurate estimate of the system's current state for subsequent simulation runs in the years to come.

This approach is analogous to continuously updating a model with new information, ensuring that it remains aligned with evolving real-world conditions and stakeholder priorities. It is noted that whilst the model allows the testing of multiple SPE MCDA weightings over the simulation period, we only applied one fixed weighting for the experimentation. The other columns of the results table include:

1. "Zero emission" – This refers to the year when all 36 greenhouses reach the target of zero untreated wastewater discharge to the sewer system.
2. "Alarm days" - The total days over the simulation period (8 years) that all 36 greenhouses have experienced low storage levels of rainwater in the storage basin of each greenhouse.
3. "Tap water" - The total volume of tap water used by all the 36 greenhouses over the simulation period.

Given the presence of multiple uncertainties in the model—such as the quality of the MCDA survey results, the representativeness of baseline data, and the reliability of climate projections—it is essential to address these factors effectively within the modelling framework. We recommend incorporating probabilistic or sensitivity analysis to account for these uncertainties. For example, the willingness to adopt (as represented by the MCDA score) and its associated weights derived from survey responses across individual businesses are inherently subjective, introducing variability into the model. A probabilistic approach can mitigate this by transforming survey responses into ranges. For instance, a score of 3 can be expressed as a range between 2.5 and 3.5, from which a random value is selected for each simulation run. By increasing the number of runs and replicating scenarios in line with Monte Carlo confidence intervals, the model can capture the influence of uncertainty on the final outcomes. This approach enhances the understanding of the model's robustness and reliability. For the selected scenarios with five replications performed for each, the replication level is sufficient to achieve 95% confidence intervals based on Monte Carlo analysis.

Table 5 (above) enables us to compare and rank individual scenarios. However, the scenarios must be considered jointly for further analysis. The analysis is thus presented in three parts. Part A (Section 5.1) will identify how climate change affects the greenhouses and the benefits of joining the InSym (Table 6). Part B (Section 5.2) will compare the performance of six water reuse alternatives for symbiosis wastewater treatment; the objective is to identify the most advantageous alternative. With the best water reuse alternative identified in Part B, Part C (Section 5.3) will analyse how different participation scenarios affect individual and symbiosis performance (Figure 6).

5.1. Part A – comparing base scenarios (B0, B1) with two parent scenarios (A0-1, A1-1) to address the effect of climate change and symbiosis operation towards individual greenhouses (B0, B1, A0-1, A1-1)

We selected the 1st water reuse scenario for A0 and A1 because it is the most basic reuse service of symbiosis, i.e., every greenhouse must take back the

Table 6. The list of four scenarios being compared in Part A.

Name of scenario	Description
B0 (B: Baseline, 0: no climate change)	Individual greenhouse operation (no symbiosis); Climate change is not considered.
B1 (B: Baseline, 1: with climate change)	Individual greenhouse operation (no symbiosis); Climate change is considered.
A0-1 (A: all join, 0: no climate change)	Water sent to the symbiosis must be taken back by everyone (no non-takers). Climate change is not considered.
A1-1 (A: all join, 1: with climate change)	Water sent to the symbiosis must be taken back by everyone (no non-takers). Climate change is considered.

volume of recycled water based on the original volume of wastewater sent to the WWTP. Firstly, we investigate how the usages of water resources differ amongst the four scenarios, of which four possible sources of water for the 36 greenhouses are rainwater, tap water, internal reclaimed water, and symbiosis reclaimed water. From Figure 6a–d, it is evident that climate change has increased both rainwater use and tap water use (i.e., B1 > B0 and A1-1 > A0-1 in Figure 6a and b), mainly due to higher evapotranspiration from plants after irrigation, as well as less rainfall during the dry season. As tap water resource, for the majority of 36 greenhouses, is an expansive backup when rainwater is not sufficient from the storage basin (only a few greenhouses use tap water as a primary resource due to crop types), the increase of tap water use (i.e., B1 > B0 and A1-1 > A0-1 in Figure 6b) implies the situation of storage basin insufficient of stored rainwater is worse with climate change. Figure 6c and d show that climate change causes no impact on internal reclaimed water and symbiosis reclaimed water, respectively, as we reflect the additional demand for irrigation water caused by the dry condition of climate change solely on crops' evapotranspiration that is a process prior to internal water reclaiming and symbiosis reclaiming.

On the other hand, the symbiosis application has reduced rainwater use by over 20% for both with and without climate change (i.e., B0 > A0-1 and B1 > A1-1 in Figure 6a). The same trend can be seen in Figure 6b for tap water (i.e., B0 > A0-1 and B1 > A1-1 in Figure 6b). However, it is notable that the decrease in the climate change pair, i.e., B1 > A1-1, is more than the decrease in the no-climate change pair, i.e., B0 > A0-1, which shows that, with climate change, applying symbiosis can better reduce the use of tap water, implying the investment will have better payback.

The effects of climate change and symbiosis application can also be reflected in the storage basins, as shown in Figure 6e and f. Figure 6e shows the distribution of the average storage rate of individual greenhouses. The storage rate decreased when scenarios with climate change (i.e., B0 > B1 and A0-1 > A1-1). Meanwhile, the rates were lifted when applying symbiosis (i.e., A0-1 > B0 and A1-1 > B1). As the water level fluctuates during a year, the average storage rate cannot by itself determine whether the fluctuation level is improved by symbiosis application. By checking the average alarm days of the individual greenhouse, as shown in Figure 6f, the ones who experienced alarm days see substantial improvement due to symbiosis application (i.e., A0-1 < B0 and A1-1 < B1), apart from those who have very small basin (primarily because they use tap water as the main source) such that they usually have very high alarm days. We can use a greenhouse as an example, as shown in Figure 7. The top figure shows the fluctuation of the water level of its storage basin. The daily water levels stopped falling under the alarm rate (30%) after the entity joined InSym in 2025 (indicated by the orange line). Also, the range of fluctuation decreased. Figure 7 also shows that the number of alarm days and tap water used has significantly decreased since the entity joined InSym. With the introduction of climate change prediction in the region, the modelling can provide individual businesses with information regarding how much lower water deficit the storage basin will confront if the greenhouse joins the symbiosis and how to optimise the utilisation of the basin through future climate change scenario exacerbating the water deficit.

5.2. Part B – comparing six water reuse Sub-scenarios to address the effect on symbiosis participation of individual greenhouses (J1-1, J1-2, J1-3, J1-4, J1-5, J1-6)

Part B investigates the water reuse sub-scenarios, which directly affect the symbiosis participation dynamics (by SD), leading to different symbiosis performances. We present three figures (Figure 8a–c) with annual performance throughout the simulation period to better understand the relation between participation numbers and symbiosis performance. In relation to the final scores (Figure 8a), the fifth water reuse sub-scenario (J1-5) has the highest ranking, which means the fifth sub-scenario is the most advantageous one agreed upon by all the decision-making stakeholders through the MCDA approach. Note that the rise in participation numbers will reflect an increase in final scores (i.e., steeper slope) in the following year, and both participation numbers and final scores are cumulative through the simulated years. The J1-5 sub-scenario had been climbing fastest to the full 36 adopters since the end of 2024, substantially reflecting the leading position on the final score.

With reference to water discharge (Figure 8b, consisting of untreated wastewater being discharged from greenhouses and symbiosis reclaimed water being discharged from symbiosis WWTP due to non-takers of the sixth sub-scenario—J1-6), the performance of water discharge is affected by the change of participation numbers. The faster the participation numbers increase, the faster the water discharge line becomes flat, i.e., zero discharge. However, lower cumulative participation numbers in the early stage may be more effective than in the late stage. For example, for J1-5, the jump in

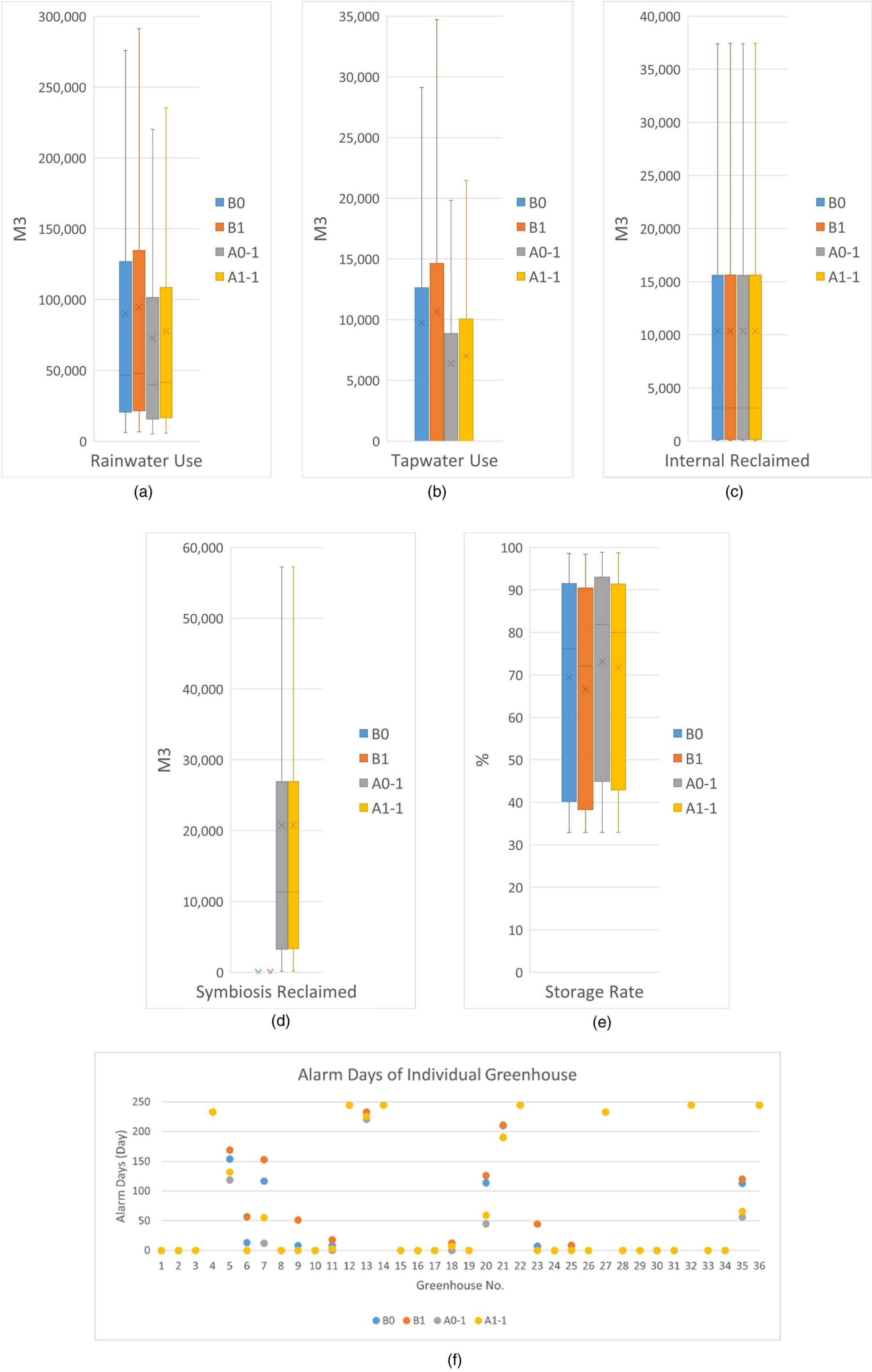


Figure 6. (a) Rainwater use. (b) Tap water use. (c) Internal reclaimed water. (d) Symbiosis reclaimed water. (e) Storage rate. (a-e) Water use of the individual greenhouses. (f) Alarm days of the individual greenhouse.

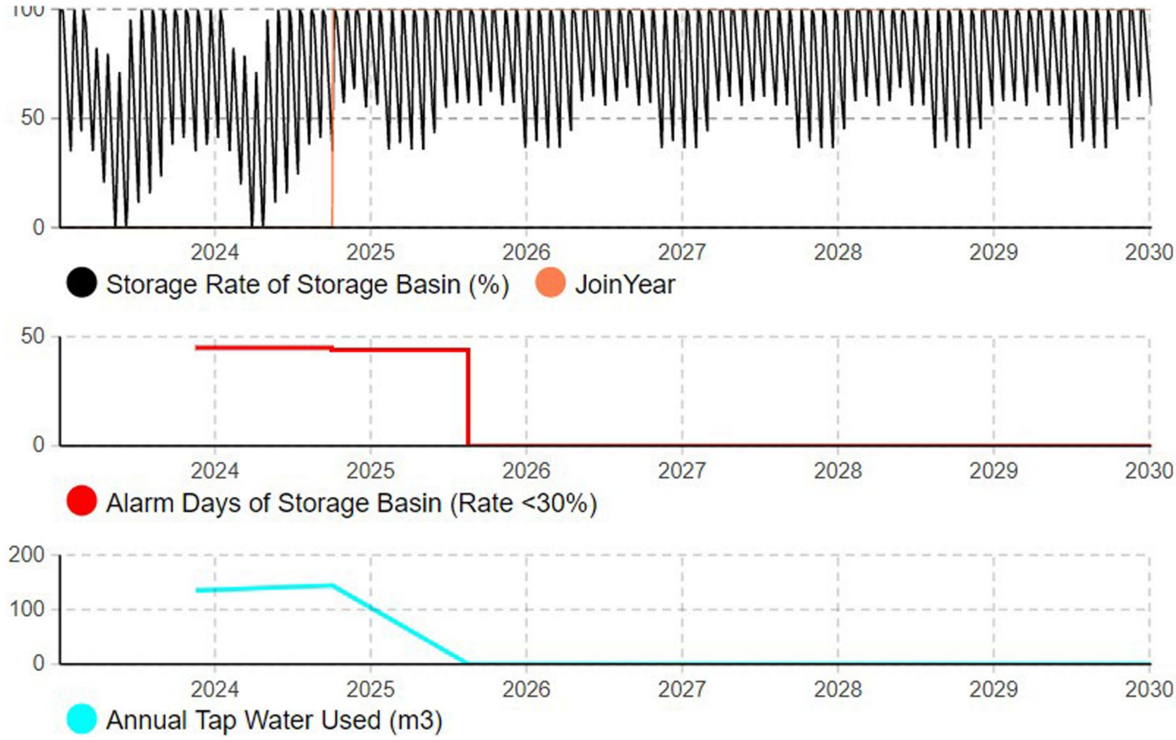


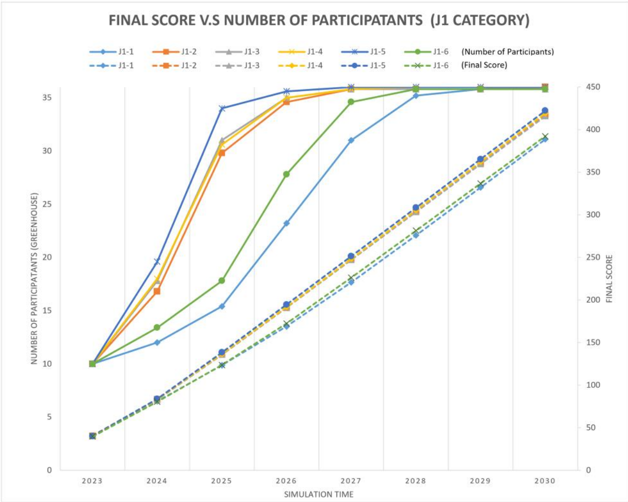
Figure 7. Results from a greenhouse agent show storage rate, alarm days, year of joining (orange line) and annual tap water use.

participation from the end of 2023 to the end of 2024 is apparently less than the jump from the end of 2024 to the end of 2025, whilst the slope change in water discharge (i.e., becoming flat) from the end of 2025 to the end of 2026 was not much bigger than the change from the end of 2024 to the end of 2025. This arguably reflected that bigger greenhouses had joined earlier (before the new regulation in 2027). The sub-scenario (J1-5) has the best water discharge performance, while J1-1 has the worst. Note that both participation numbers and water discharge are cumulative through the years. It is remarkable that whilst the J1-5 and the J1-1 sub-scenario eventually reached 36 full adopters, the water discharge of J1-1 sub-scenario can be more than two times that of J1-5. It is interesting to note that although the sixth sub-scenario has water discharge from symbiosis WWTP due to non-takers (whilst J1-1 does not), the performance of water discharge of the J1-6 had been better than J1-1. This is because J1-6 had a better increase in participation numbers all the way through. It implies that, taking into account the unwillingness of some greenhouses to reuse the symbiosis reclaimed water by giving them the flexibility of not taking water back, is still considered relatively more attractive, which led to better symbiosis participation.

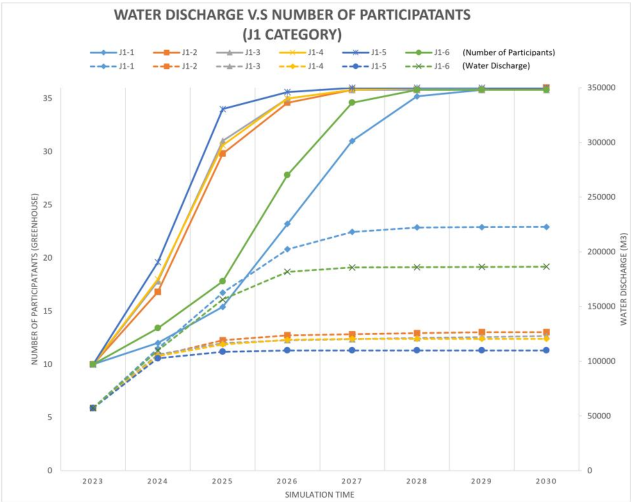
Figure 8c shows a different trend in performance from the previous final score and water discharge, which is also a good example of why we apply MCDA so that the ranking can solely rely on the final score. Note that the rise in participation numbers is cumulative through the years, whilst the rainwater and tap water performance are individual annual volumes. The different trend presented in this figure is that whilst the J1-6 sub-scenario has a faster rise in participation numbers than the J1-1 sub-scenario, J1-6 consumed more rainwater and tap water (i.e., worse performance) than J1-1, mostly rainwater as the primary difference is reflected on rainwater. This was reflected by the fact that those non-takers discharged symbiosis reclaimed water from symbiosis WWTP instead of reusing the water as a resource in the cluster to substitute for rainwater demands. However, we know that the J1-5 sub-scenario is consistently the best in terms of different ways of water reuse affecting participation.

5.3. Part C – same water reuse alternative (i.e., sub-scenario 5) for each parent scenario (A0-5, A1-5, J0-5, J1-5, JQ1-5)

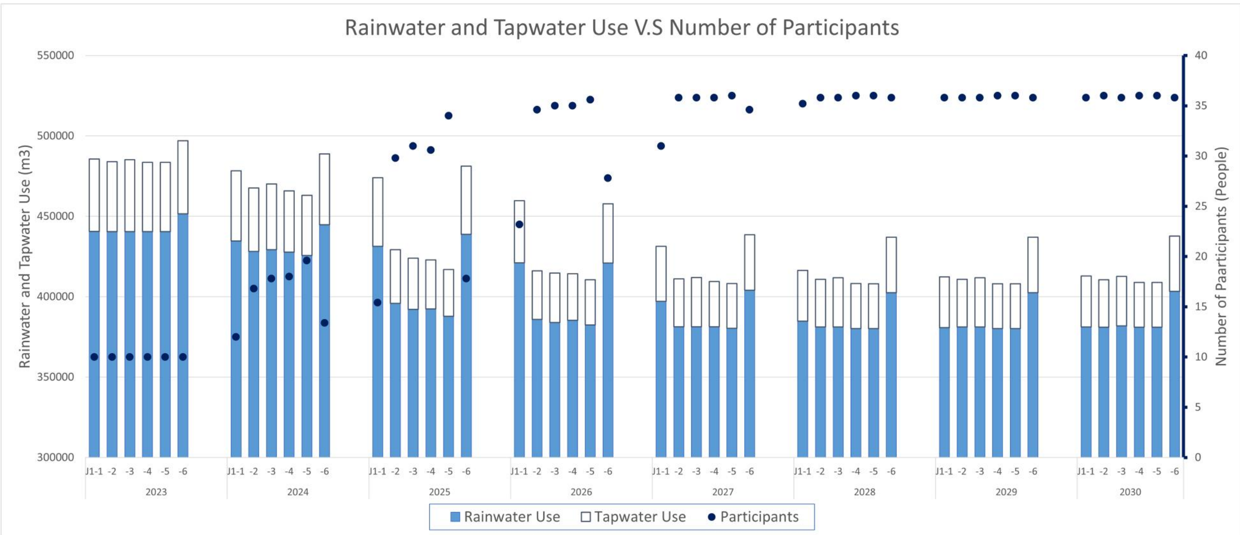
We used parent scenario J1 in Part B to investigate the water reuse sub-scenarios. We concluded that the J1-5 sub-scenario is the best. From Table 5 (column “final score”), we also note that sub-scenario 5 performs as the best (or the joint best) for all the five parent scenarios. In Part C, to better understand how participation conditions affect the performance of 36 greenhouses, we compare the performance of the parent scenarios to sub-scenario 5.



(a)



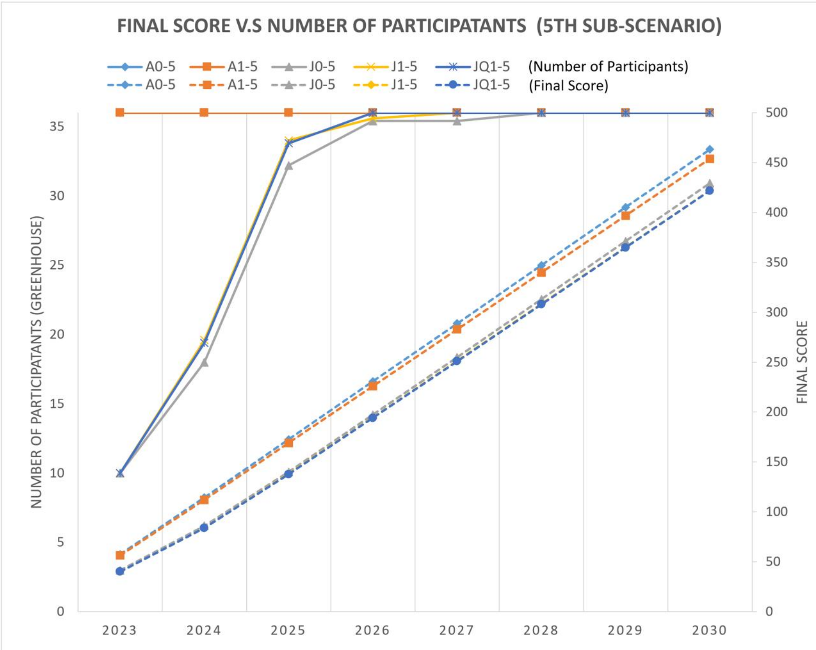
(b)



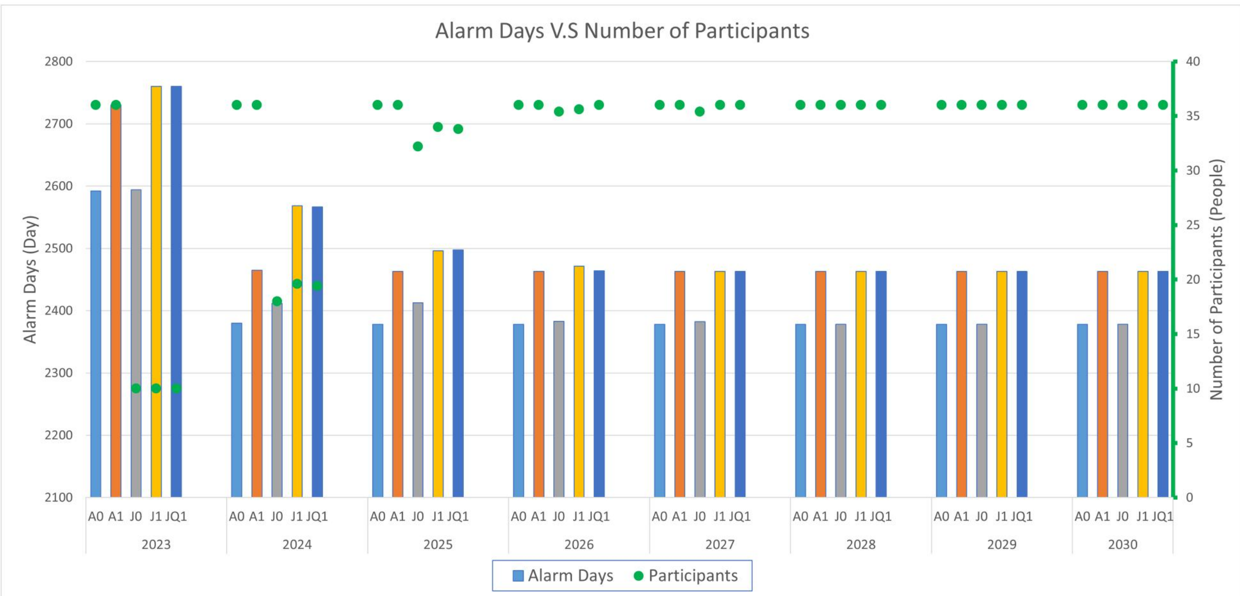
(c)

Figure 8. (a) The comparison of the final score (sub-scenarios of the J1 parent scenario). (b) The comparison of water discharge (sub-scenarios of the J1 parent scenario). (c) The comparison of rainwater and tap water use (sub-scenarios of the J1 parent scenario).

Firstly, we look at Figure 9a, which shows an expected trend that scenarios with climate change have worse final scores than scenarios without climate change, i.e., A1 < A0 and J1-5 < J0-5, of which the reasons and climate change impacts have been explained in Part A. There is an interesting trend that scenarios with climate change have better participation climb than scenarios without climate change, i.e., J1-5 is faster than J0-5, because potential adopters can see higher resource demands under climate change to be able to see more benefits from symbiosis under climate change context. However, another interesting trend is that the final scores are not necessarily consistent with the trend of participation numbers, particularly when there are small differences in participation numbers; as we can see the slowest participation does not lead to the worst final score, i.e., J0-5 has the worst participation numbers whilst JQ1-5 has the worst final score, which is because the effects of climate change on the final score happen to outweigh the effects of climate change on the participation number in this comparison. In Figure 9a, we would particularly like to see the comparison between J1-5 and JQ1-5 because they are closer to the real situation, i.e., both with climate change and starting the symbiosis from 10 adopters instead of the most optimistic scenario–with full 36 adopters at all times. It shows that the two scenarios' final scores and participation numbers are nearly completely overlapped. J1-5 has a better final score, whilst it is a rather tiny win. It shows allowing to quit (from the end of 2025) is not considered very attractive to potential adopters so as to affect the participation dynamics.



(a)



(b)

Figure 9. (a) The comparison of final scores between parent scenarios in relation to the 5th sub-scenario. (b) The comparison of alarm days between parent scenarios in relation to the 5th sub-scenario.

Figure 9b communicates the following: firstly, when a scenario simulation reaches 36 participants, the alarm days reach minimum and stable. Secondly, there are only two minimum alarm days, one for scenarios without climate change (i.e., lower ones) and the other for scenarios with climate change (i.e., higher ones). Other trends are similar to Figure 9a, including an expected trend that scenarios with climate change have better performance in alarm days than scenarios without climate change, i.e., A0-5 < A1-5 and J0-5 < J1-5. Also, with faster participation, alarm days of J1-5 drops faster and deeper than J0-5, whilst J0-5 still ends up with lower alarm days because the effect of climate change on alarm days due to higher stress on the storage basin outweighs the effect of participation speed on alarm days. Moreover, both alarm days and participation numbers of the J1-5 and JQ1-5 scenarios are nearly completely overlapped and identical.

Allowing quitting is not an attractive participation condition that will affect participation dynamics and performance, as JQ1-5 and J1-5 are almost identical, with just a tiny win for J1-5 (Figure 9a and b). However, we would like to show that allowing a quitting scenario does cause participation dynamics in some cases. We compare JQ1-5 with one scenario allowing quitting from the end of 2025 (original setting) and the second scenario allowing quitting from the end of 2023 (Table 7). In relation to the total number of participants that joined the symbiosis and the year of joining, the two scenarios are exactly the same (Table 7; refer to the two rows labelled "Total Joined"). The first scenario does not have any adopters that quit; in the 2nd case, one adopter quit at the end of 2023. By comparing the two scenarios, we can see that allowing quitting earlier results in one member leaving and then rejoining the following year. In summary, our analysis in Part C demonstrates how this hybrid modelling featuring participation dynamics can assist the design of symbiosis, as the performance of symbiosis is simultaneously affected by multiple internal and external factors, including social, regulatory, environmental, economic and technical factors, which are something that the F-SWC modelling framework seeks to capture.

While the numerical results discussed above (e.g., tap water savings, year of achieving zero emissions) provide quantifiable indicators of system performance, we acknowledge the importance of complementing these outcomes with a deeper qualitative interpretation to enhance the practical relevance for stakeholders considering InSym. The hybrid modelling framework integrating SD, DES, ABS, and MCDA, was deliberately designed to capture both the technical feasibility and social dynamics of InSym adoption amongst greenhouses. The modelling not only simulates environmental and economic outcomes, but also reflects stakeholder behaviours and decision-making pathways over time.

To support practical implementation, the results should be interpreted through the following qualitative lenses:

- *Stakeholder decision-making and participation dynamics:* The SPD models how individual greenhouses decide to participate in InSym based on evolving cost advantages, peer influence, and contractual conditions. These behavioural insights allow stakeholders to understand the likely adoption pathways and identify tipping points or barriers. For example, results showing slow early adoption may suggest the need for early incentives or peer champions.
- *Feedback Loops and Strategic Planning:* The SD module of SPE models how treatment costs evolve with scale. Stakeholders can use this to explore strategic entry points, e.g., determining when it becomes economically advantageous to join based on projected membership growth. The modelling also identifies risks of under-participation, which could make InSym economically unsustainable.
- *Resource Allocation and Infrastructure Planning:* The SO element captures operational interactions between individual greenhouses and the symbiosis WWTP. By tracking flows of untreated, treated, and reused water, stakeholders can plan for infrastructure investments (e.g., pipe

Table 7. Participation dynamics for JQ scenario allowing quitting at the end of 3rd year and 1st year respectively.

	Start of 2023	End of 2023	End of 2024	End of 2025	End of 2026	End of 2027	End of 2028	End of 2029	End of 2030
JQ1-5 allowing quit at the end of 3rd year:									
Initial Join at Beginning	10	10	10	10	10	10	10	10	10
New Join	10	9	15	2	0	0	0	0	0
New Quit	N.A	N.A	N.A	0	0	0	0	0	0
Total Joined	10	19	34	36	36	36	36	36	36
JQ1-5 allowing quit at the end of 1st year:									
Initial Join at Beginning	10	10	10	10	10	10	10	10	10
New Join	10	10	15	2	0	0	0	0	0
New Quit	N.A	1	0	0	0	0	0	0	0
Total Joined	10	19	34	36	36	36	36	36	36

networks, treatment capacity) that match projected participation scenarios. These outputs also reveal potential bottlenecks in resource utilisation, supporting the detailed design of the WWTP.

- *Scenario Testing and Climate Resilience:* Through the integration of climate projections, the model tests how changing rainfall patterns and water deficits affect stakeholder preference for reuse. This provides qualitative insight into climate adaptation potential, suggesting that stakeholders with high water risk may become natural early adopters or advocates for reuse solutions.
- *Policy and Governance Implications:* The MCDA results, especially when analysed through Monte Carlo and sensitivity analyses, highlight the robustness of decision pathways under uncertainty. This offers guidance to policy-makers and cooperative managers on how to structure agreements (e.g., EOI-based stages) that are both inclusive and adaptive to emerging trends or data.
- *Customisation and Scaling Potential:* The modular structure of the model allows replication in other regions or sectors. Stakeholders in different contexts can adapt the model by redefining business scales, plant types, water sources, and participation rules, offering a customisable decision-support tool rather than a one-size-fits-all solution.

6. Conclusion

Valorising resources within the water cycle is considered the holy grail for circular economy and environmental sustainability. In this context, industrial symbiosis (InSym) can offer collective advantages for co-located businesses by enabling a circular exchange of water, energy, and material. However, developing InSym solutions and business models also represents a challenge since they involve multiple agents representing different stakeholder groups and displaying non-linear interacting/dynamic behaviours. The stakeholders often have competing interests, and one's decision may also affect the decision-making of other entities. Assessment of such complex adaptive systems is possible through decision models developed using OR tools and techniques. Further, using a hybrid modelling approach enables the deployment of multiple OR methods for the best possible representation of both InSym operational processes and participation dynamics.

Towards InSym decision-making for the water cycle, the paper proposes the hybrid modelling *Framework for the Symbiotic Water Cycle (F-SWC)*. Our framework is based on the methodological aspects of discrete-event simulation, agent-based simulation, system dynamics and MCDA. Together, they capture the evolving dynamics of InSym, which is considered a critical factor in the sustainability of a symbiosis. A case study based on a proposed InSym solution, a collective wastewater treatment plant (WWTP) in the De-Volt region of The Netherlands, is presented as an example implementation of F-SWC.

The Dutch greenhouse industry is poised to face stricter national regulations towards discharges, i.e., zero-emission, from 2027 (Van der Salm et al., 2020; Van Paassen & Welles, 2010). The policy is expected to impact the Dutch greenhouse practice and may have a broader future influence on other sectors and territories. The local greenhouse industry is also experiencing a water deficit during the dry season, substantially worsened by climate change. Both challenges reveal the urgent demand for better water reuse and valorisation approaches. Thus, an InSym WWTP is proposed as a solution in the case study region as it offers collective advantages for responding to regulation and water deficit. Our use of the hybrid approach to model the Dutch greenhouse symbiosis that involves an upcoming national regulation of zero-emission in 2027, as well as a regional water deficit issue that will be exacerbated by climate change, not only presents a proof-of-concept but also provides insight as to how the predicted climate change in our case study region will affect the current business, and how symbiosis can benefit these greenhouse members in the future.

The study has some limitations. First, it is a proof-of-concept that includes some assumptions and simplifications. In addition, the behavioural System Dynamic models (motivation KPIs) embedded in the agents are simplistic and can be improved. Enhancement of the models will require a validation process and comparison with actual numbers from the realisation of the InSym; this is only possible after a certain period, e.g., two years. Finally, the MCDA study included questionnaires for the farmers. However, due to low response, we were assisted by an industry expert who provided value ranges based on knowledge of greenhouses.

Developing a hybrid model for InSym represents a significant investment in time and resources. As such, stakeholders should consider the opportunities to reuse existing InSym models or specific components of existing models for possible application to other industrial symbiosis contexts. Implementing F-SWC using Free and Open-source software (FOSS) simulation libraries (FSL) and approaches such as STARS (sharing tools and artefacts for reusable simulations) will aid in model reusability (Monks et al., 2024). However, as the framework supports hybrid simulation, using FSL to implement

F-SWC will likely involve considerable effort and is arguably research on its own accord. We hope the F-SWC framework and our hybrid modelling approach will complement existing tools used for InSym decision-making.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Rights Retention

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ORCID

Navonil Mustafee http://orcid.org/0000-0002-2204-8924

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