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New business models for the circular economy of water: A hybrid simulation study of a mobile rental wastewater treatment service

Otto Chen [a,b,*], Navonil Mustafee [b], Barry Evans [a], Mehdi Khoury [a], Lydia Vamvakeridou-Lyroudia [a,c], Albert S. Chen [a], Slobodan Djordjević [a], Dragan Savić [a,c]

[a] Centre for Water Systems, University of Exeter, Harrison Building, North Park Road, Exeter, EX4 4QF, UK
[b] Centre for Simulation, Analytics and Modelling, Business School, University of Exeter. Exeter, EX4 4ST, UK
[c] KWR Water Research Institute. Groningenhaven 7, P.O. Box 1072, 3430 BB, Nieuwegein, the Netherlands

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ABSTRACT

Food processing industries confront challenges in dealing with wastewater due to seasonal fluctuations. This can lead to potentially untreated wastewater discharge and regulatory non-compliance. Untreated water can also adversely affect the efficiency of municipal wastewater treatment and the local environment. A mobile rental wastewater treatment service for the food processing industry has been proposed as an innovative solution, simultaneously promoting the Circular Economy through water reuse and material recovery. It enables on-demand and on-site wastewater processing, particularly during peak operation. Moreover, it provides additional services for extracting value-added compounds (e.g., polyphenols), delivering further financial benefits. To assess the sustainability of this new business model, this paper presents a hybrid simulation study using agent-based, discrete-event simulation, system dynamics, and Multiple Criteria Decision Analysis. The hybrid model is applied to a new mobile wastewater service being trialled in the Peloponnesian region of Greece. By considering factors such as customer composition and the volume of wastewater to be treated, logistics (mobile units and hubs), and staggered investments in capacity boosting, the model supports the commercialisation efforts of the rental business model put forward in the case study. The paper contributes to modelling methodology, especially in the use of hybrid simulation within the context of the circular economy of water; it also contributes to the practice of modelling and simulation by exploring their role in assessing the feasibility of novel business models.

1. Introduction

Industries that use water as a predominant resource in manufacturing often strive to valorise resources within the water cycle and to promote environmental sustainability and circular economy (CE). CE represents a transition to a regenerative system, where maximum value is extracted from resources during use through the closing of material loops and sharing of resources between firms (Foundation, 2020). It aims to extend the lifespan of materials, ensuring they are used efficiently and regenerated at the end of their life cycle. This approach stands in contrast to the traditional linear economy, which follows a linear 'take, make, dispose' model. Firms that successfully adopt CE will see avoidable waste eliminated and unavoidable waste reduced, reused or recycled (Howard et al., 2022). In the context of wastewater management, CE plays a crucial role by enabling the recovery of valuable resources such as clean water, nutrients, and energy. Additionally, it mitigates environmental pollution by treating and reusing wastewater, thereby reducing the release of harmful pollutants into natural ecosystems.

Industrial symbiosis (InSym) can play a crucial role in achieving the goal of environmental sustainability and CE. InSym aims to harness the advantages of geographic proximity between business entities to foster a collective approach, thereby realising synergistic benefits (Chertow, 2000). In the context of CE and valorisation of resources, InSym enables the circular exchange of water, energy, and materials amongst businesses and industries. For example, the higher the number of firms adopting symbiosis, 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). Whilst the potential of InSym in closing the water cycle is widely acknowledged, its implementation is

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* Corresponding author. Centre for Water Systems, University of Exeter. Harrison Building, North Park Road, Exeter, EX4 4QF, UK.
E-mail address: c.chen2@exeter.ac.uk (O. Chen).

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challenging as the stakeholders first need to assess the potential of the symbiosis in relation to their individual operations and then decide whether to join.

Several studies have used Operations Research (OR) methods for modelling industrial symbiosis; refer to Mustafee and Katsaliaki (2020) for an overview of OR methods. Modelling and Simulation (M&S) is a sub-discipline of OR and is particularly well suited to computationally capture the dynamics of an evolving InSym. InSym demonstrates non-linear and interacting behaviours amongst its components that evolve dynamically over time. Using M&S techniques such as agent-based simulation (ABS), discrete-event simulation (DES), and system dynamics (SD), and a hybrid of these techniques–referred to as hybrid simulation (Mustafee et al., 2017), can take advantage of their individual strengths and capture such complex system behaviour. The hybrid approach enables strategic experimentation and feeds into the individual stakeholders' decision-making process. Yazıcı et al. (2022) examined OR/M&S in InSym decision problems and noted that approximately 50% of the reviewed papers used simulation methods. Additionally, they identified that multi-criteria decision-making (MCDA) was widely employed to determine the priority values of criteria impacting the InSym network and rank alternatives. Demartini et al. (2022) identified ABS and SD as amongst the nine most commonly used approaches for modelling InSym (other approaches include MCDA/DEMATEL, mixed integer linear programming, Input-Output model (IOM), Lifecycle Assessment (LCA) and material flow analysis (MFA), etc.). The study also observed that ABS was integrated with other modelling methods like IOM, LCA and MFA and that the use of a hybrid approach effectively represented InSym's dynamic complexity and uncertainty within the system. Ghali et al. (2017) observed that only a few ABS models considered social embeddedness that could impact InSym dynamics; this meant that most ABS models could not predict the potential influence of social activities and networking on the collective system. To address this limitation, Ghali et al. proposed a model that represents social embeddedness using a set of dependent variables that describe the evolution of trust, reputation, and knowledge sharing within various social dynamics and structures, highlighting their significance in influencing the development of InSym.

The literature includes several examples of tools developed for InSym. Lawal et al. (2021) categorised these tools into process integration (PI) and mathematical optimisation (MO). PI and MO tools for InSym design and planning have mostly operated in isolation and concentrated on individual resources, e.g., heat, water, carbon, waste, and power. They have also focused solely on resource aspects of InSym, such as reclamation, exchange, and utilisation. Yeo et al. (2019) conducted a comprehensive review of InSym tools, covering the entire process of InSym creation. They proposed a framework comprising six steps: preliminary assessment, engaging businesses, identifying synergy opportunities, determining feasibility, implementing transactions, and documentation. The review highlighted that many tools focus on identifying synergy opportunities and assessing InSym's performance during implementation. However, most of these tools are developed for specific purposes and only address a single aspect or a limited part of the InSym creation process. The review by Yazıcı et al. (2022) observed that InSym studies predominantly concentrate on matter and energy exchange whilst neglecting other important aspects such as logistics, finance, machinery equipment, and operational management.

From the aforementioned studies, it is evident that decision-making support modelling in the InSym field is still limited. Furthermore, decision-making problems can arise at various levels, including operational, tactical, and strategic levels (Suzanne, 2021). These observations highlight the gap for a comprehensive modelling framework that addresses decision-making challenges across different spheres of InSym processes and operational management. Additionally, there is a lack of tools that consistently evaluate performance at individual and symbiotic levels whilst considering the dynamics of InSym membership. These gaps have motivated us to develop a modelling framework called the *Framework for the Symbiotic Water Cycle (F-SWC)* that bridges some of the limitations and thus contributes to the literature on modelling methods for InSym development.

The F-SWC supports the modelling of InSym decision problems. The framework combines a hybrid DES-ABS-SD simulation (Brailsford et al., 2019) with the MCDA approach. The combined application of ABS, DES and SD as a hybrid simulation leverages the strengths of individual methods and can comprehensively represent the dynamic complexities of a system being modelled (Mustafee et al., 2020). It is particularly suited to capture the non-linear and evolving behaviour of InSym operations. To the best of our knowledge, only one study (Kobayashi et al., 2020) proposed an ABS-SD-DES hybrid simulation for calculating dynamic material flow in connected lifecycle systems for InSym contexts. 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. Therefore, it does not address the multi-aspect challenges identified by the preceding literature review.

The F-SWC further extends the DES-ABS-SD *hybrid simulation* by integrating methods from the broader OR discipline, namely MCDA, to develop a *hybrid model* (Tolk et al., 2021); the distinction between hybrid simulation and hybrid model has been explored by Mustafee and Fakhimi (2024). The MCDA approach captures the different views of stakeholders in the decision-making process; for individual participants, it also deals with decision-making matters involving multiple criteria or objectives. DES models the current and future InSym operational processes. ABS uses agents to model the different behaviour of InSym stakeholders. The SD approach has an advantage in dealing with interactive relations amongst factors impacting the symbiosis business model, particularly when relations are dynamically variable due to the change of context.

The F-SWC is applied to a case study on InSym of wastewater treatment in the food processing industry (FPI), based in the Peloponnesian region of Greece. A mobile rental wastewater treatment service has been proposed as an innovative solution to increase the conformity of FPI businesses with local regulations for wastewater discharge, whilst also promoting the Circular Economy of the water cycle through water reuse and material recovery (nutrient mining and reuse). Unlike conventional modelling approaches that usually set up scenarios with fixed business participants, we consider the number of business participants to be dynamic in the long term, which plays a critical role, particularly in InSym decision-making. Therefore, the F-SWC not only considers multiple aspects of InSym operation simultaneously, including symbiotic operation, individual stakeholders' demands and conditions, natural uncertainty such as climate change and its implications on available water resources, but particularly, the simulation of participation dynamics.

The remainder of the paper is structured as follows. Section 2 presents a short review of the literature on studies related to our case study context, namely, mobile wastewater treatment plant (WWTP) service. Section 3 presents our hybrid modelling F-SWC that supports decision-making for industrial symbioses of the water cycle. Section 4 is on implementing the F-SWC for a Greek FPI case study involving a novel mobile InSym solution for mobile WWTP service. Section 5 presents the InSym scenarios and the results of simulation experiments. Section 6 is the concluding section of the paper. It discusses the key findings and identifies relevant modelling applications of InSym with F-SWC, research limitations, and potential future works.

2. Literature review on mobile wastewater treatment plants (WWTPs)

Mobile WWTPs are designed to be self-contained and adaptable, making them ideal for dispatch to various locations and being configured to support various business needs. They effectively address critical challenges that traditional treatment infrastructures cannot handle, thanks to their mobility and flexibility in location, time, and treatment capacity, enhancing overall treatment performance. They are vital in disaster relief, military operations, remote sites, and discharge scenarios with variable concentration and/or volume. As shown in Fig. 1, these units typically include pre-treatment units, main treatment units (Part B of Fig. 1, including primary, secondary, and tertiary treatment depending on the demand), and sludge management. Pre-treatment units remove large solids and debris (Part A of Fig. 1), whilst primary treatment employs physical separation techniques to reduce suspended solids and organic matter. Secondary treatment often uses biological processes such as activated sludge and membrane bioreactors (MBR) to further degrade organic matter. Tertiary treatment incorporates advanced processes like filtration (e.g., reverse osmosis, ultrafiltration (UF), nanofiltration (NF)), disinfection, and nutrient removal to polish the effluent, particularly for reuse purposes. Sludge management systems handle by-products of the treatment process, whilst advanced oxidation processes like UV light and ozone effectively remove persistent organic pollutants. Mobile units can also include additional components for value-added compound extraction (e.g., part C of Fig. 1) to support a circular economy. Together, these components ensure efficient wastewater treatment that meets regulatory standards or specific demands, such as reuse.

Panaitescu and Petrescu (2016) emphasised the urgency of rapid accidental pollution treatment due to its detrimental effects on the environment. The study underscores the effectiveness of mobile WWTPs, whilst also highlighting operational risks stemming from ecosystem complexity and adaptability challenges during treatment. Litaor et al. (2015) discuss the environmental challenges posed by winery wastewater, particularly for small wineries with limited resources for

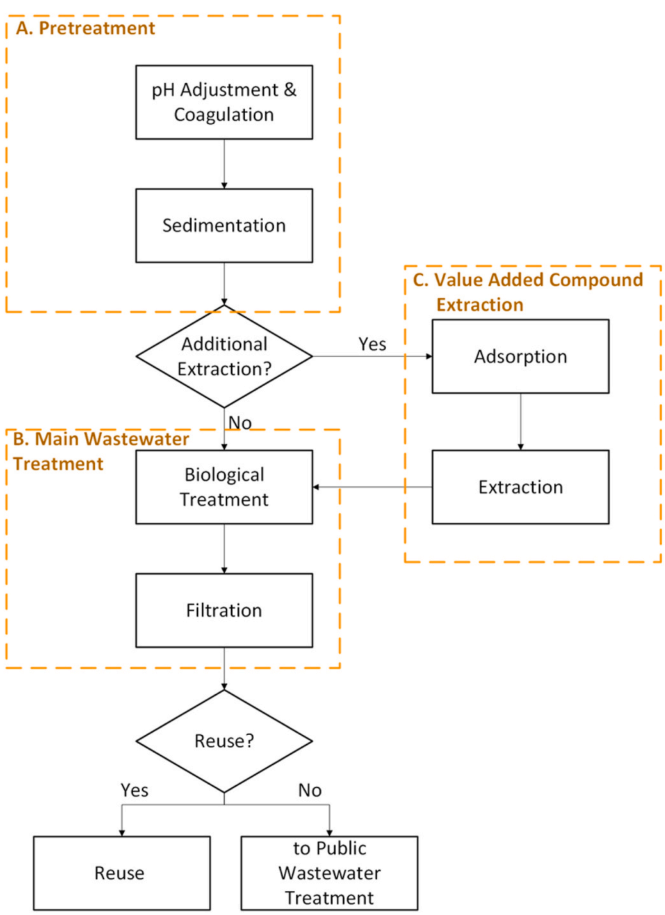

Fig. 1. The schematic diagram presents an example of components that could be configured in mobile wastewater treatment units.

advanced treatment plants. The study reported an integrated mobile system which was tested to meet the stringent discharge requirements for municipal WWTPs. Forbis-Stokes et al. (2021) presented a mobile septage treatment unit designed and implemented in India, which utilised readily available filters and membranes to process septage from holding tanks. The system proved effective in providing onsite treatment, reducing reliance on costly septage emptying services, and offering the potential for flooding disaster relief applications. Joni et al. (2022) investigated the applicability of a mobile mini WWTP designed to provide clean water during flooding incidents where access to clean water is limited, highlighting its potential for providing clean water in emergency situations.

Our review of the literature identified a few studies on mobile WWTPs that are relevant to the circular economy, with a focus on resource reclamation from wastewater. Kyllönen et al. (2021) explored the potential of physico-chemical technologies in wastewater purification for nutrient and carbon recovery, offering a promising solution for water reuse and resource optimisation. Through the utilisation of various unit operations assembled in a mobile container, wastewater treatment demonstrated efficient separation of solids, precipitation of phosphate, and capture of ammonium nitrogen for fertiliser production. Lin et al. (2021) explored the production of renewable biogas from wastewater through anaerobic fermentation, utilising a mobile bioenergy generation station based on high-efficiency hydrogenesis & methanogenesis technology (HyMeTek). The mobile bioenergy system demonstrated commercial potential with favourable economic indicators, including an initial rate of return of 59% and a payback time of 2.7 years, showcasing its feasibility for converting wastewater into valuable biogas. Okano et al. (2016) tested a mobile pilot-scale plant designed for on-site examination and demonstration of phosphate (Pi) recovery from wastewater. The study underscores the utility of the mobile pilot plant as a simple and potentially low-cost tool for on-site Pi recovery from wastewater (e.g., fertiliser).

However, several challenges accompany their deployment. These units must be highly adaptable to varying wastewater compositions and flow rates. Ensuring consistent treatment efficiency and meeting regulatory standards in diverse conditions can be complex. Particularly, mobile units require robust logistics for transportation, setup, and maintenance, which can be resource-intensive, particularly if a rental business model is applied. However, our review identified only one study that explored the techno-economic and logistics aspects of the mobile WWTP service. Cole et al. (2022) addressed the challenge of managing wastewater from unconventional oil and gas wells, proposing on-site treatment followed by surface water discharge as a viable alternative to injection. Through the application of capacity factor analysis, optimal deployment logistics for packaged treatment units in Weld County, Colorado, are determined, considering factors such as unit capacity, deployment length, and number of units deployed. The study identifies Pareto optimal logistics from a techno-economic and environmental standpoint, highlighting the importance of capacity factors in optimising deployment strategies and presenting opportunities for further application of the model developed. Overall, the research provides valuable insights into the optimal planning and deployment of on-site WWTP units, emphasising the need for flexible and efficient management strategies in the oil and gas industry. The study pointed out an important challenge inherent in using WWTP plants of a specific capacity, which is that the flow rate of each location may be larger than the designed treatment capacity of a unit. This has provided insight into exploring some of the InSym decision problems relevant to our case study, namely, whether multiple mobile WWTPs may need to be dispatched to client locations. Several experimental scenarios have been designed concerning this (Section 4).

3. Materials and methods

3.1. OR Methods for modelling industrial symbiosis (InSym)

The OR field provides a wide array of techniques for enhanced decision-making. InSym is a Complex Adaptive System (CAS) with non-linear, dynamic behaviours involving diverse stakeholder groups. Employing a single OR approach such as M&S, MCDA, or mathematical modelling falls short of capturing the underlying intricacies of CAS. In this paper, we adopt a hybrid modelling approach that draws on various OR and simulation techniques to leverage the strengths of individual methods (Mustafee et al., 2020). We apply the hybrid approach to comprehensively represent the dynamic complexities of the CAS system and its novel application to the circular economy of water. More specifically, our hybrid modelling approach integrates ABS, DES, SD and MCDA for modelling the water cycle within the InSym framework.

- *ABS* simulates the actions and interactions of autonomous decision-making entities (agents) like individual businesses, water authorities, and InSym cooperatives. It provides a bottom-up perspective, modelling the dynamics of complex systems that self-organise and create emergent order, characteristics inherent to InSym.
- *DES*, rooted in queuing theory, models real-world systems displaying discrete sequences of events over time. DES is relevant for InSym, particularly when individual and collective processes form the core of its operation.
- *SD* is a top-down modelling approach that helps understand feedback mechanisms in complex systems, providing a holistic representation. It involves identifying causal loops and modelling stock and flow relations using equations, capturing dynamic changes in the system.
- *MCDA* evaluates conflicting criteria in decision-making, which is crucial for InSym's dynamic nature, which involves stakeholders' decisions that require balancing multiple factors. MCDA is pertinent from both the perspective of individual adopters and the collective symbiosis within InSym.

The justification for a hybrid approach lies in InSym's manifestation of non-linear and interacting behaviours amongst its components, which are dynamically evolving over time. For instance, a business might initially join InSym for reported efficiencies but may leave over time due to less favourable benefits, impacting a broader array of stakeholders. Modelling such intricacies requires a hybrid approach, representing InSym at various resolutions, from detailed (i.e., individual operational) to holistic levels (i.e., symbiosis system). The subsequent overview introduces individual techniques used in the hybrid modelling approach.

3.2. The Framework for symbiotic water cycle (F-SWC)

The F-SWC consists of three parts: *Symbiosis Operation* (SO), *Symbiosis Performance Evaluation (SPE, regarding* system performance*)* and *Symbiosis Participation Dynamics (SPD)*. Fig. 2 illustrates the components of the framework and their inter-relationship. SO uses event-based logic as a DES to simulate continuous processes. DES-based fluid flow modelling is the methodology of choice. It enables the analysis and optimisation of water resources (further details included in section 4.3). MCDA can offer better 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); thus, 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., transport vehicles and shared water treatment facilities); the resources are modelled as agents. SD calculates the motivation dynamics.

The interaction between the SO, SPE and SPD elements of F-SWC is illustrated through a swimlane diagram (Fig. 3). 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 Fig. 3, the performance KPIs and motivation KPIs related to the MCDA elements for SPE and SPD, respectively, must be selected first. This is based on primary data

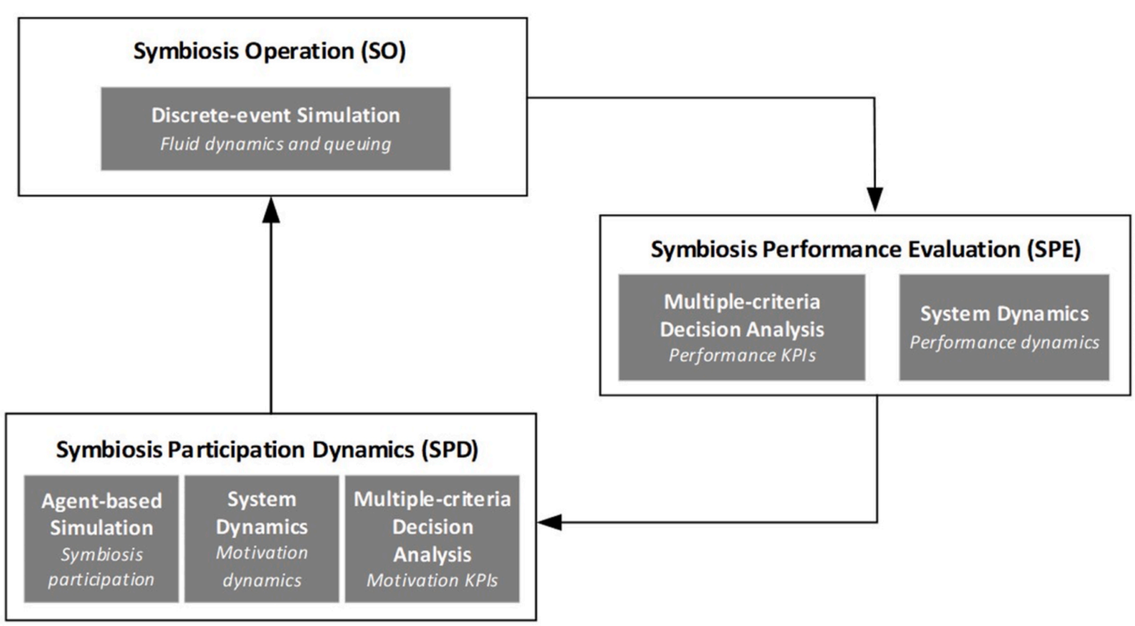

Fig. 2. The relations between the components of the F-SWC modelling framework.

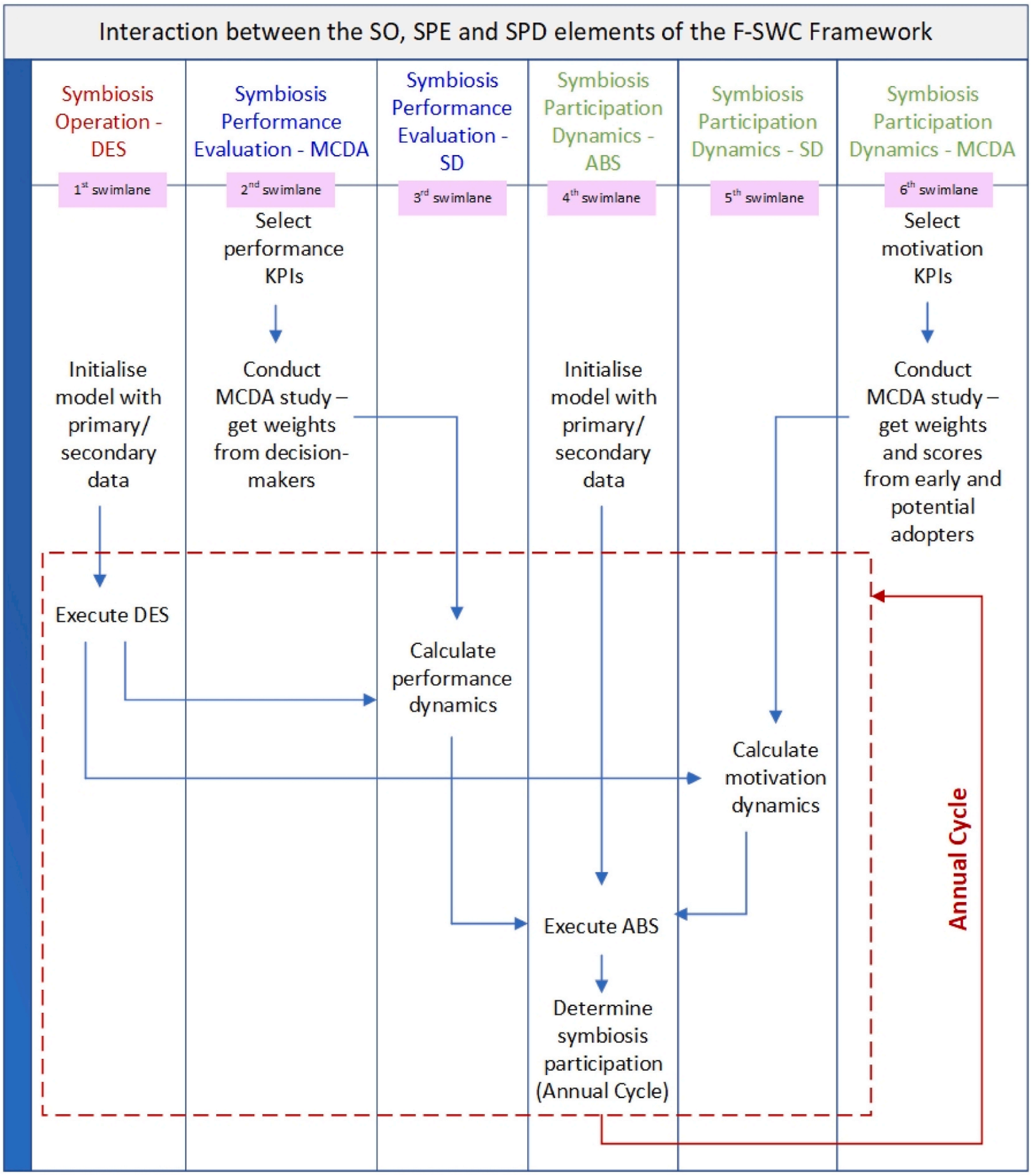

Fig. 3. Interaction amongst the SO, SPD and SPE modelling components of the F-SWC.

collection (through MCDA surveys) from two groups of stakeholders. (I) ***A survey for potential adopters*** (Fig. 3; 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*** (Fig. 3; 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 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 decision makers (SO; 1st swimlane) is used with MCDA weights (2nd swimlane) to calculate the performance dynamics of the symbiosis dynamically. Unlike multiple DES models for potential adopters, InSym will only have one DES that models the InSym. 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).

Table 1
Two categories of DES models in the SO element of the F-SWC.

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, namely, 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.

- **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 Fig. 3). 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, but not join) to a symbiosis adopter (i.e., join), and vice-versa. This is also the time to adjust the criteria weighting of SPE MCDA if planned, based on changes in annual performance (SPE) or other conditions specific to the InSym context, such as shifting priorities for different periods. Thus, from a modelling perspective, it is necessary to compute performance and motivation through time and until the simulation end time. This continuous computation is illustrated as a dashed box in Fig. 3.

The F-SWC 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. It comprises multiple modelling techniques that support the development of a hybrid model. Fig. 4 presents a flowchart to aid the implementation of the framework using simulation software such as AnyLogic. The figure also includes the list of important tasks for the F-SWC stages.

- **Stage 1 – Understanding the Business Model:** The first stage is associated with activities that further our understanding of the business context of setting up an InSym operation. The key stakeholders and their motivation for developing the proposed symbiosis are recognised; motivation and performance KPIs are identified (Fig. 3; 2nd and 6th swimlane).
- **Stage 2 – Conceptual Modelling (including primary and secondary data collection):** The conceptual model is developed. It contextualises the DES, SD and ABS modelling elements based on the case study. Here, it is also necessary to consider primary and secondary data sources. For example, the framework proposes using primary data and MCDA analysis to determine weights and scores. However, if sufficient participants do not respond to surveys, expert opinions or values from the literature can be used to determine the MCDA values. An optional step is the co-development of the conceptual model and the modelling scenarios with the stakeholders. Although co-development is preferred, it may not always be possible to include stakeholder representation through, for example, *Living Labs* or *Communities of Practice*; in this case, periodic meetings with individual stakeholders may serve as a good proxy.
- **Stage 3 – Implementation of Hybrid Model:** The third stage implements the hybrid model. It is illustrated as a white rectangle in the flowchart (Fig. 4). Two dashed arrows from the earlier stages connect to it, signifying the need for both conceptual model and primary/secondary data before model implementation. However, this is often an iterative process (shown as a decision box at a subsequent stage of the flowchart). The implementation follows the SO, SPE and SPD elements and the modelling techniques defined for each (Fig. 2).
- **Stage 4 – Develop Scenarios for Experimentation:** The scenarios for experimentation are outlined (scenarios could be co-developed with the stakeholder in the earlier stages). The stage also focuses on experimentation and ranking of the scenarios based on MCDA final scores, the latter computed dynamically at runtime.
- **Stage 5 – Documentation and Long-term Validation:** The documentation and validation stage is shown as a green rectangle in Fig. 4. It recommends the use of frameworks such as *Strengthening the Reporting of Empirical Simulation Studies (STRESS)* (Monks et al., 2019) to document the underlying logic of the hybrid model and its inputs and outputs, which aids stakeholder validation. Validation also involves demonstrating the model to the stakeholders and outlining the results obtained for the various scenarios. A long-term validation (optional) is included; its purpose is to test whether the model predicts the real-world InSym adopters and the synergies realised over time. Based on validation, further changes may be needed in the next iteration of the model, depicted as a feedback loop from the decision box *'Changes Needed?'* to Stage 1 (gaining an understanding of the business model).
- **Stage 6 – Explore Opportunities for Reusing the Hybrid Model:** 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 hybrid models, or specific components of existing models, for possible application to other industrial symbiosis contexts.

4. Case study on industrial symbiosis (InSym) using mobile wastewater treatment plant (WWTP)

Food processing industries (FPIs) often process products that are linked with the seasonal harvest of fruits and vegetables, and thus, they generate wastewater only in certain months of the year. The businesses may be opposed to setting up advanced wastewater treatment facilities with sufficient capacity to cover seasonal peak discharge. This often leads to illegal discharge of untreated water, a serious burden to the local municipal sewage treatment system and the environment. However, there are opportunities for the FPIs to generate additional value during the wastewater treatment process. One of the primary benefits is

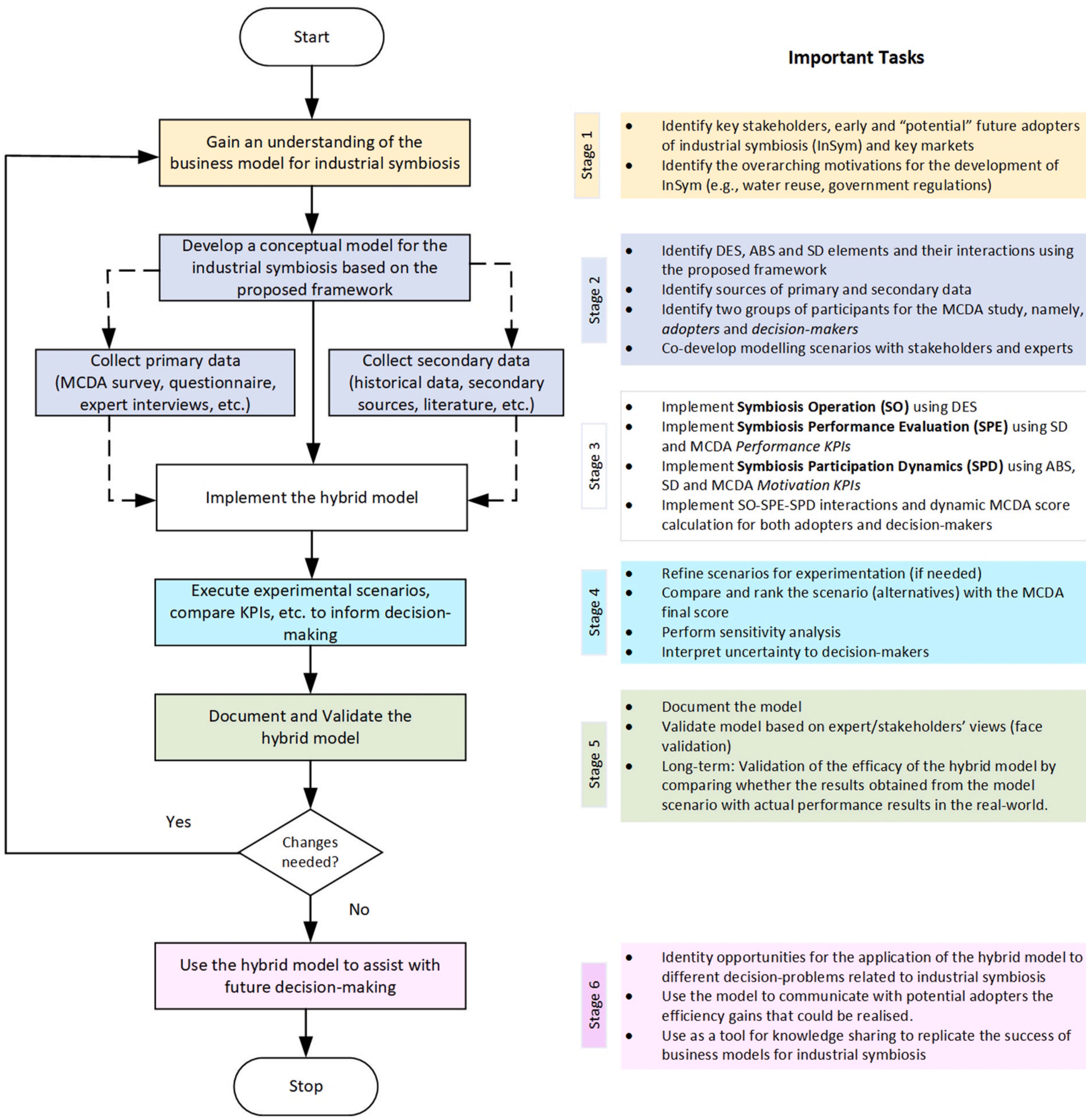

Fig. 4. Flowchart to aid the implementation of the F-SWC.

reusing the water to reduce costs and dependence on tap water. Water reuse can also mitigate water deficit situations that may occur locally. Yet another benefit is the valorisation of wastewater by extracting valuable compounds such as polyphenols.

Our case study is on the FPIs in Greece, mainly the eastern Peloponnese, one of the most productive regions in Greece (and Europe) in terms of citrus fruit. Our project partner in the ULTIMATE project (EU H2020) is offering novel rental Mobile Treatment Units (MTUs) and technicians as an on-demand wastewater treatment solution. The innovative feature of the solution is the advanced technology in wastewater treatment and value-added compounds (VAC) extraction. Furthermore, a new business model of offering rental services for tackling seasonal demand fluctuation is expected to lead to an InSym that brings a win-win advantage to the local FPIs.

This section discusses the development of the hybrid model through stages 1–4 of the F-SWC implementation (as shown in Fig. 4). Stages 5 and 6 are on long-term validation and the opportunities for model reuse; these are discussed in the concluding section.

4.1. Stage 1: Understanding the Business Model

The innovative business model of providing rental mobile WWTP service using MTUs and technicians has certain challenges. For example, the rental service and the MTU operations involve a high level of dynamics and uncertainty as the FPIs have various patterns of seasonal demands. These make it very challenging for the service provider to plan for future investments and operations. As the new business model is a relatively new service and historical data is limited, a decision support system based on computer simulation could benefit our project partner (service provider) for the experimentation of 'what-if' scenarios, which will aid in better estimations of resource requirements and planning for the future. Thus, the case study was a good application of the F-SWC. Implementing the framework through a hybrid model will enable experimentation of InSym strategies and allow for better and more informed decision-making. Questions such as the following could be answered using the hybrid model: What should be the investment strategy for manufacturing mobile MTUs? When should such investments be made? Does the investment in local hubs (as a deport for placing the MTUs so that they do not always need to travel long distances back to the main base depot) benefit in reducing transport costs? What are the factors influencing the sale of the rental service? How does the sale of service, i.e., the number of service users and orders, affect our partner's profit?

The business model's success lies in the balance of utilisation of MTUs and customer satisfaction, whilst the customers in the InSym will change dynamically (i.e., customer loyalty), with the hybrid modelling approach being used to analyse these underlying complexities and dynamics. In the context of our case study, the benefits from InSym would be threefold – (1) the reduction in illegal discharge of wastewater by FPIs; (2) water reuse for mitigating resource deficit of the local area; (3) VAC extraction for achieving circular market/economy.

4.2. Stage 2: conceptual modelling (including primary data collection)

Building on the generic discussion on conceptual modelling in Stage 2 of F-SWC (Section 3.2), this section presents the conceptual model (CM) for our case study (Fig. 5). Our CM includes two main levels: the global level and the local level. The main three elements of the F-SWC conceptual framework (SO, SPE, and SPD; refer to Fig. 2) are arranged at the local and/or global level, respectively, according to the interaction described in Fig. 3. SPE is at the global level (regarding system performance), SPD is at the local level (regarding individual participation), and SO spans both local and global levels. Similarly, the entities implemented in the hybrid model, including 25 FPI businesses, mobile units, and one service provider, are also arranged as agents locally or globally. The individual performance, mainly from the operation (simulated by DES of FPI agent), reflects on the system performance through statistics. The system performance 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 accommodates an MCDA module and an SD module in SPE. The MCDA module 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 of collective treatment cost also results in the change of score of the KPI 'Profit Advantage' in the SD module of SPD in the FPI agents. Similarly, some system performance indicators, such as the change in the number of adopters/customers, also affect the motivation KPIs of the SD module of SPD in FPI agents. The SD and MCDA modules for motivation KPIs (of SPD in FPI agents) will constantly update accordingly, resulting in an updated willingness level for the ABS module to assess its participation status. The participation assessment goes year-by-year through the simulation period, leading to a change in the number of adopters.

The DES module within the FPI agents simulates processes of wastewater discharge, either to the sewer or the mobile MTU units. The DES module in the mobile unit agent deals with the wastewater treatment process, including basic VAC extraction service and distributing recycled water back to the FPI business. The agent interactions can happen amongst FPI agents and between the mobile unit agent and FPI agents. In this case study, the interaction amongst FPI agents is through the SD module of SPD, which is related to participation dynamics. The interaction between the mobile unit agent and FPI agents is through the DES modules of SO and the ABS module of SO, which is related to the dispatch scenarios of the mobile units.

4.2.1. Data for the hybrid model

The data used for the model come from multiple sources. The business and operational parameters of the mobile units and rental service,

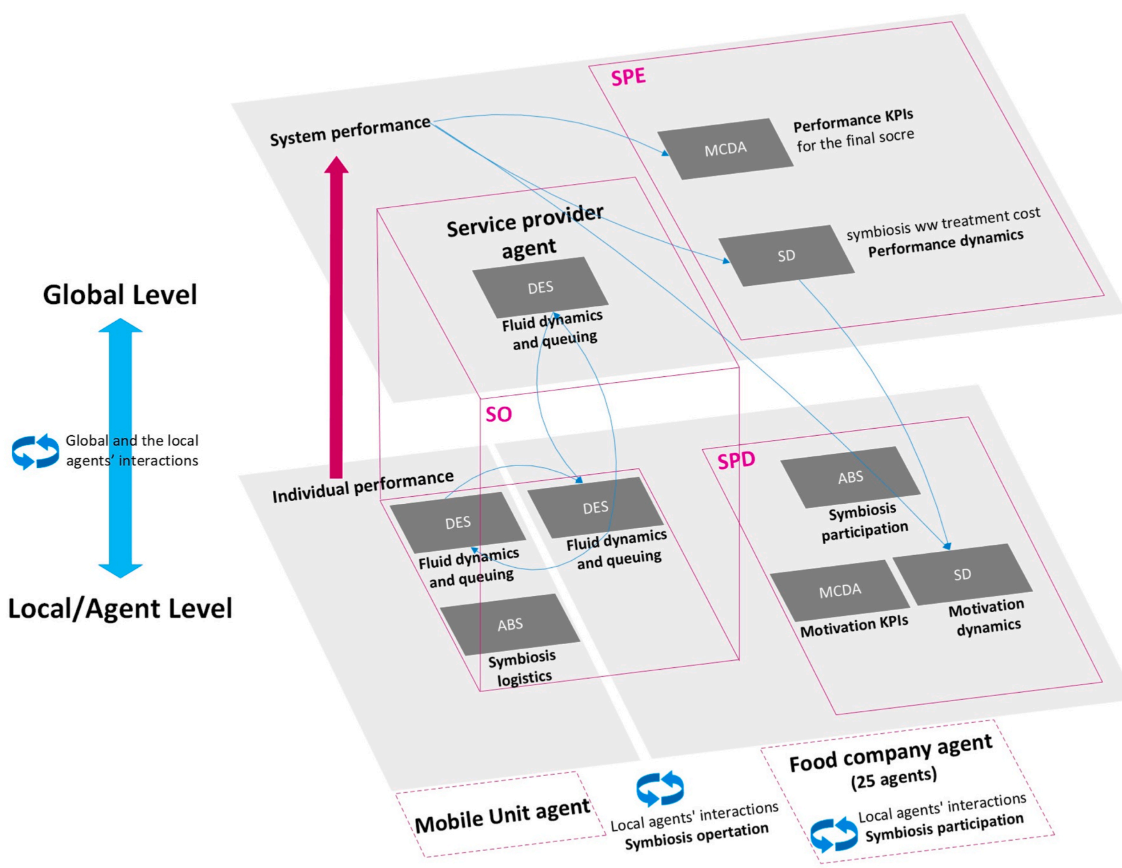

Fig. 5. Conceptual model for the mobile WWTP case study related to InSym in Greek FPIs.

including cost and financial parameters, applied primary data from the rental service provider. It is noted that, as some of the data involves marketing and operational know-how and commercially sensitive information, the authors are not allowed to reveal real values due to commercial competition (e.g., wholesale price), whilst we have adjusted those values with reasonable market price.

An MCDA survey has been conducted for the SPD to address participation dynamics. First, we identified the motivation KPIs that can represent the decision-making factors in adopting the rental service and the idea of symbiosis. Through a review of related literature (van der Salm et al., 2020; Tamburino et al., 2020; Albino et al., 2016; Ghali et al., 2017; Mantese and Amaral, 2017, 2018), we identified six most relevant KPIs for the case study, which are listed in Table 2. The KPIs' adequacy and the MCDA questionnaire's design were verified by consulting FPI professionals and the rental service provider (Appendix A, MCDA survey). The survey was conducted in 2023. Our survey aligned with the F-SWC's recommendation that each symbiosis case should survey its stakeholders to identify the most significant motivation KPIs, as each symbiosis stakeholder group is unique and the objectives and motivation of developing InSym solutions differ from case to case. The six KPIs identified for the case study are as follows.

(1) **Profit advantage**: The financial benefit gained from the reuse of reclaimed water and VAC extraction.
(2) **Peer recommendation**: Recommendation for participation from FPIs who have hired the MTUs to those who are still considering adopting.
(3) **Staying ahead**: The potential benefit of reputation gained through the ambition and attitude of FPI company to always adopt new/innovative technologies and management strategies (staying ahead in the industry!).
(4) **Resource utilisation**: The advantage of using water resources and VAC compounds through the rental treatment service to cope with regional water deficit and the waste of resources.
(5) **Operational advantage**: The degree of operability when applying mobile treatment. An effortless and manageable operational practice that is achieved through remote control (by the service provider) and automatic operation.
(6) **Legal compliance**: To hire MTUs and adopt InSym to enhance the capability of wastewater treatment to comply with statutory requirements of wastewater discharge.

We conducted the MCDA survey to capture data (motivation KPIs) for the framework's symbiosis participation dynamics (SPD) element. The survey was targeted at 25 FPI companies–the potential adopters of InSym. However, despite several efforts, we could not obtain sufficient data. Thus, based on discussions with stakeholders and consultation with FPI professionals, we decided to replicate the limited primary data on a full scale, i.e., 25 FPI companies, regarding participation as the input data for the MCDA SPD. We acknowledge this as a limitation of the study. However, to circumvent the drawback, the service provider has expressed their interest in conducting future MCDA surveys towards a wider area of potential service users beyond the selected 25 businesses as part of their marketing analysis, which may be considered as the improvement plan of this study. On the other hand, the data required for the SPE MCDA comes from the consultation of the service provider (Table 3).

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

Motivation KPIs	Aspects	Related Variables or Parameters
Profit advantage	Operational; Financial	Treatment cost- symbiosis (global level) The number of adopters (global level) The volume of treated wastewater (global level)
Peer recommendation	Social	The number of adopters (global level)
Staying ahead	Operational; Strategical	The number of adopters (global level) Treatment cost- symbiosis (global level)
Resource utilisation	Operational; Environmental	Treated rate (agent level) The number of adopters (global level)
Operational advantage	Operational	Satisfaction level towards installation and operation (agent level)
Legal compliance	Legal	The number of adopters (global level)/Treated rate (agent level)

4.3. Stage 3: Implementation of Hybrid Model

Following the F-SWC, our hybrid model combines ABS, DES, SD, and MCDA. ABS models the individual actions of agents, including mobile treatment units, the businesses that rent these units for mobile wastewater treatment, and the service provider who manages logistics and technical operations. DES models the fluid processes, such as wastewater treatment and reuse. The SD module represents dynamics and changes over time, including participation dynamics and time-dependent parameters. MCDA elicits preferences involving multiple criteria, such as participation willingness and scenario ranking.

Three primary agent types are implemented in the hybrid model – mobile unit agent type (i.e., mobile WWTP or MTUs), FPI business agent type, and service provider agent type.

- Mobile treatment unit (MTU) agent: Multiple instances of the mobile treatment agent type exist. The number of mobile units is dynamic in the hybrid modelling, which depends on the investment scenarios of the service provider. The agent includes a DES module that performs the symbiosis composed of wastewater treatment and VAC extraction. The DES is implemented in AnyLogic and uses the Fluid library (AnyLogic, 2023).
- FPI business agents: There are 25 instances of FPI agents (one for each company that showed interest in hiring the symbiosis solution). Each FPI agent instance has a DES module (with AnyLogic Fluid Library) that models the individual wastewater discharging process for each business operation. An AnyLogic database is linked to each FPI agent and records data for individual parameters. The parameters are used to initialise the agents, e.g., location in latitude and longitude (see Appendix B on the supplement materials for model implementation – Figures B-1 to B-4).
- Depot agent type: Although there is only one service provider, the modelling explores whether multiple hubs/depots may benefit the logistics and utilisation of the mobile units. As the headquarters of the service provider also functions as a hub/depot to accommodate

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

Descriptions of KPI	MCDA Weight	Consideration dimension regarding symbiosis
Financial performance	80	Financial dimension, including the total profit and return on investment (ROI)
Treated rate	12	Customer satisfaction dimension. The percentage of wastewater treated by the rental service.
The amount of water treated	2	The utilisation dimension of the revenue-generating asset, i.e., the mobile WWTP units. The amount of wastewater treated by the rental service.
The number of clients	6	Market share dimension

the mobile units, *one depot* is considered the baseline scenario of the number of depots. The modelling also investigates the second scenario, which is *two depots* covering the logistics operation of the rental mobile treatment service. Therefore, there are two agent instances of this type.

The implementation of the model consists of four main tasks (Fig. 4), which are discussed in the sub-sections below.

4.3.1. Implementation of SO using DES

Since the SO happens and spans three settings, two 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 three settings. For the case study, the local level comprises DES in each FPI agent (Fig. 6a); another local level includes the DES of the mobile WWTP agent (Fig. 6b). Both DES modules apply the Fluid library of AnyLogic (2023), with mainly tanks, pipes, and valves to construct the process of wastewater treatment, VAC extraction, as well as reuse of reclaimed water back in the FPI agent.

The model applies a similar DES process to each FPI business (i.e., DES module, Fig. 6a), whilst it allows each business to perform differently; for instance, they produce a wide range in terms of the volume of wastewater. For those businesses producing more wastewater, a second mobile unit would be needed to cover all the discharge. Due to the limited response to the MCDA survey, and also considering that most of the FPIs that responded to the survey avoided revealing the actual quantity of wastewater that would be discharged without proper treatment, we made some assumptions. We divided the 25 FPI businesses into two groups; one group with less wastewater production would only need one mobile unit in each service, whilst the other group with more wastewater production would request two mobile units in each service. In the latter case, if a second mobile unit were not available, the excess wastewater would be discharged into the sewer. Fig. 6b illustrates the wastewater treatment and VAC extraction process (only basic scheme, the advanced VAC extraction would be implemented in the headquarters' lab).

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

Fig. 7a illustrates that the hybrid model calculates SPD through the interactions of the two SD modules in the model. Whilst SPD works in each FPI agent to determine its participation status, i.e., SPD is accommodated in each FPI agent (local level), it also interacts with the SD module to affect the global symbiosis treatment cost rate (part of SPE). The SD module of the FPI agent consists of five motivation KPIs out of six MCDA KPIs. The number of motivation KPIs applying the SD module would differ from case to case, depending on whether the individual KPIs change involves time and/or relatively complex causal relations. 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' (i.e., willingness to hire the rental service). The willingness level can be calculated using the following equation (1):

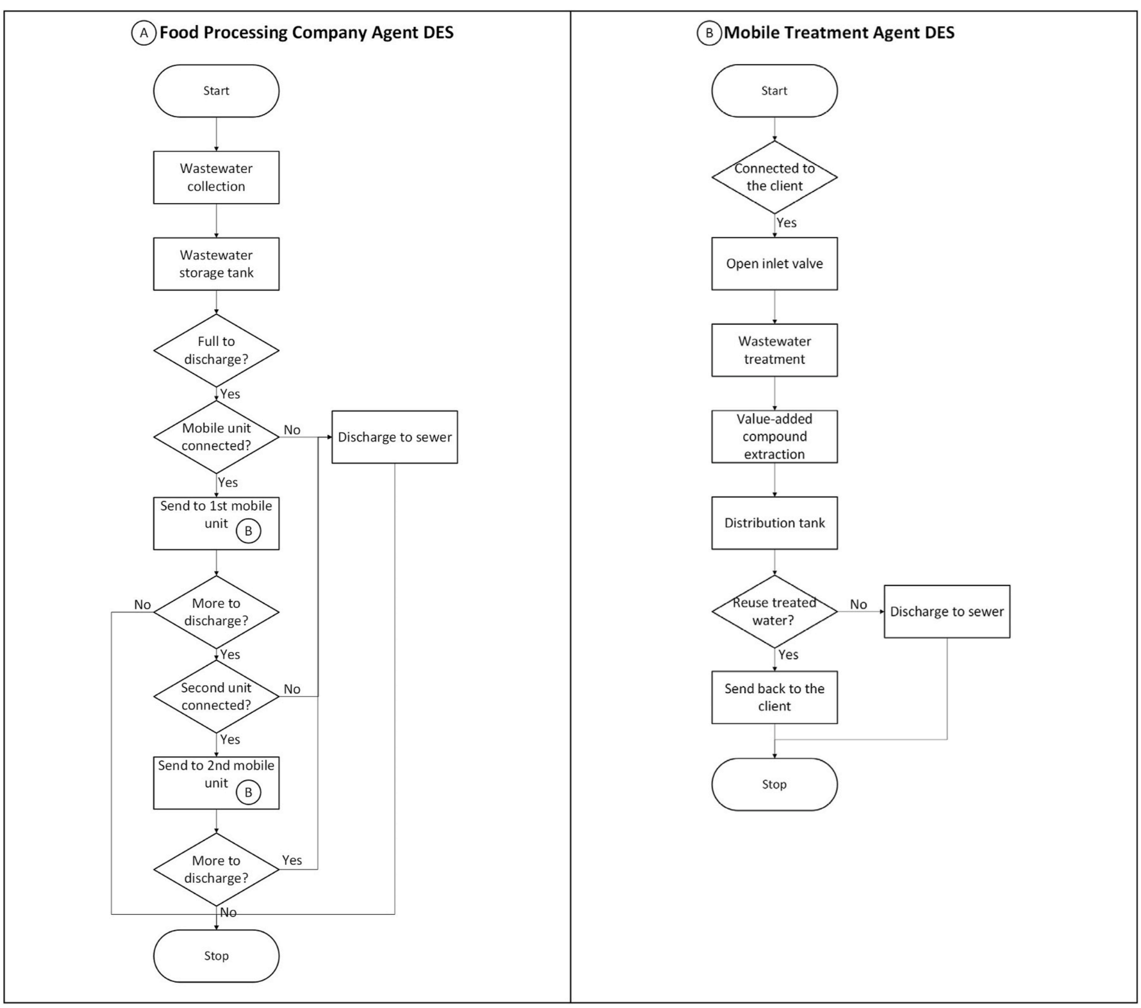

Fig. 6. DES module for water utilisation process in the local food company agent (6a) and local mobile unit treatment agent (6b).

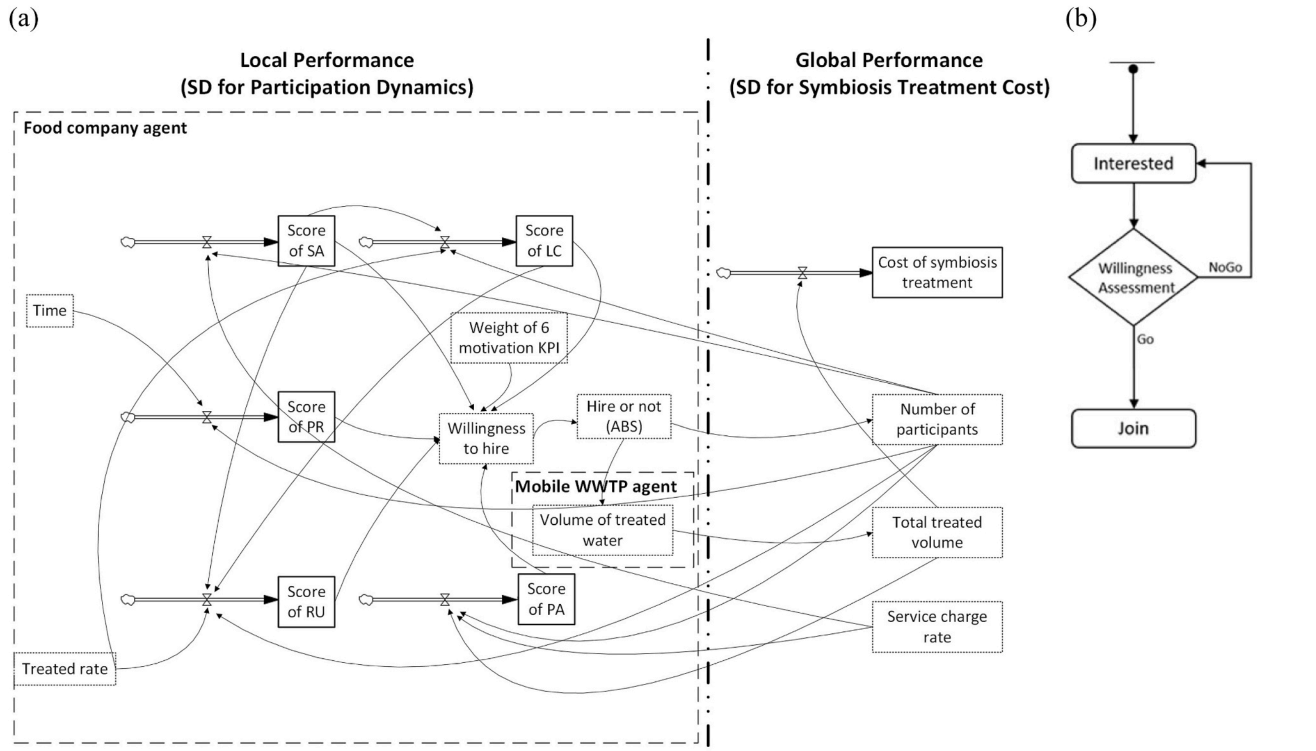

Fig. 7. (a) SD module at the local level (food company agent and mobile unit agent) and global/symbiosis level. (b) The decision-making process for hiring the symbiosis mobile treatment by the potential adopters, i.e., the ABS module.

$$WL = \sum_{i=1}^{i=6} WCi^* \, SCi \Big/ 6 \tag{1}$$

where WL is the willingness level between 0 and 1 (100%), $WC_1, WC_2, WC_3, \ldots WC_6$ are the weights of six performance criteria (motivation KPIs) between 0 and 1 (100%), $SC_1, SC_2, SC_3, \ldots SC_6$ are the scores of six motivation KPIs between 1 and 5 (dynamically performed by the SD module) that are designed as a scale for facilitating initial motivation KPIs scoring in the questionnaire survey.

The 'willingness to join' will then be dealt with by an ABS module in the FPI 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 Fig. 7b. If it changes its status to 'join', the FPI agent will send a request to book the rental service, increasing the total volume of wastewater treated in the service provider agent (at the global level). 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 two kinds of performance: the performance of symbiosis WWTP (shown on the right side of Fig. 7a) and the performance of the individual FPI companies. The design of the F-SWC considers both individual business and symbiosis operations to be healthy and benefit from the conduct of symbiosis. Otherwise, the symbiosis and individual businesses will not be able to sustain the InSym initiative in the long run. The performance of symbiosis, i.e., the service provider for this case, 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 wastewater treatment caused by the increased treated volume of wastewater. An SD module performs this dynamically at the global level.

On the other hand, the performance evaluation of individual FPIs, obtained from its DES module, will be presented through statistics indicators located globally. 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. Therefore, we apply the MCDA approach at the global level, with performance KPIs selected as the MCDA scores and the MCDA weights elicited from the survey towards decision-makers. A final MCDA score will be calculated and used to rank various competing strategies.

It is noted that the decision-makers represent the service provider in this case study, whilst in other cases applying F-SWC, the decision-makers could be composed mainly of symbiosis adopters. 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 investors. 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, one aligned to the interests of the symbiosis and the other reflecting 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, which is summing up the weighted score of each year using equation (2).

$$SF = \sum_{T=1}^{T=j} WCi, Tj^* \, SCi, Tj \Big/ 100 \tag{2}$$

where SF is the final score of the scenario experimented, $WC_1, WC_2, WC_3, \ldots WC_n$ are the weight of n performance criteria (performance KPIs) between 0 and 100, $SC_1, SC_2, SC_3, \ldots SC_n$ are the annual score of n

performance criteria/KPIs between 0 and 100 that is standardised from their raw performance KPIs, T = 1 to j (j = 20 in the case study) refer to the year of simulation time. 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 should allow pursuing different priorities at different stages, e.g., statutory priority, such as the introduction of zero-emission at a certain year, and market share expansion at a later stage.

4.3.4. Implementation of SO-SPE-SPD interactions

The interactions between SO, SPE, and SPD are the core features designed for the F-SWC modelling framework because they reflect the most crucial natures of real-world InSym, i.e., operation, performance, and participation dynamics. Each of them also performs the interactions between local and global levels, through the different combinations of agents, ABS, DES, SD, and MCDA modules, as the preceding three implementation points of this stage. It can be seen from Figs. 6 and 7a (including the interaction between the FPI agents at the local level and service provider agent at the global level, the interaction between the DES of FPIs at the local level and the DES of mobile unit agents in the local level, the interaction between SD in local FPI agent and SD in global level, and the application of participation MCDA in local FPI agent and performance MCDA in global level), that the framework seeks to address the complexity of InSym by comprehensively performing the reciprocal and synergetic relation between the individual business and the symbiotic thing (e.g., operation, facility, business model, and even market).

We applied the F-SWC to build a hybrid model with the AnyLogic platform (version 8.7.9). The simulation period was twenty years, from January 1, 2023 to December 31, 2042. The simulation procedure 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 4.2, Table 3), the simulation of the SO will start as the first-year simulation. At the end of each year, the KPIs of SPE will be updated, simultaneously affecting the evolvement of the SD module of SPD whilst carrying on the 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/hire the rental service) into symbiosis adopter (i.e., join/hire the rental service), according to the SD module of SPD that is affected by the SPE and by some changes of 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 SPE, or other conditions that are designed for InSym context, e.g., different priorities planned for different periods.

4.4. Stage 4: scenarios for experimentation

As mentioned previously, the mobile WWTP case study seeks to identify the most advantageous operational policies for the service provider (our project partner) by implementing the F-SWC modelling framework designed for InSym decision-making. Table 4 lists four groups of scenarios (Scenario Group [SG]-A to D) being tested by the hybrid model, which modelled 25 FPI businesses that had expressed interest in adopting the symbiosis (i.e., hiring the rental service) through participating in our baseline survey. The primary focus of the scenarios is to evaluate the performance of symbiosis under different operational conditions and policies from the service provider's perspective.

The **first scenario group (SG-A)** analyses the utilisation and dispatch of the MTU resources. The four main scenarios in SG-A, namely, *SM*, *SO*, *LM* and *LO* (Table 4; SG-A), are based on the permutations of two operational conditions, both related to the resourcing of the MTUs based on client orders for mobile WWTP service. The first operational condition is related to the duration of the MTU service at the FPI client

Table 4

Scenarios for experimentation (categorized as per Scenario Groups A-D: SG-A, SG-B, SG-C and SG-D).

Scenario Group (SG)	Scenarios (with sub-scenarios indicated in *italics*)	Description
SG-A: Comparing four main scenarios	**SM** (SM-1 to SM-10) **SO** *(SO-1 to SO-10)* **LM** *(LM-1 to LM-10)* **LO** *(LO-1 to LO-10)*	S: **S**hort service allowed L: **L**ong service only M: **M**ultiple mobile units to cater to one FPI client service request O: **O**ne mobile unit to cater to one FPI client service request Sub-scenario numbers refer to the number of mobile units; e.g., SM-2 refers to two mobile units.
SG-B: Comparing four *equity capitals* of 100k (baseline), 200k, 250k, 300k (using LM from SG-A)	**100kEC** *(LM-1 to LM-10)* **200kEC** *(LM-1 to LM-10)* **250kEC** *(LM-1 to LM-10)* **300kEC** *(LM-1 to LM-10)*	100k equity capital was the baseline condition applied in SG-A. Sub-scenario numbers refer to the number of mobile units; e.g., LM-2 refers to two mobile units.
SG-C: Comparing two wastewater processing *charge rates* of 2.5 Euro/m^3 (baseline) and 3.0 Euro/m^3 (in LM)	**2.5 Euro/m^3** *(LM-1 to LM-10)* **3.0 Euro/m^3** *(LM-1 to LM-10)*	2.5 Euro/m3 was the baseline condition applied in SG-A and SG-B. Sub-scenario numbers refer to the number of mobile units; e.g., LM-2 refers to two mobile units.
SG-D: Comparing one *depot* (baseline) and two depots (one additional depot causing additional rental costs) (in LM)	**One depot** *(LM-1 to LM-10)* **Two depots** *(LM-1 to LM-10)*	One depot was the baseline condition applied in SG-A, SG-B and SG-C. Sub-scenario numbers refer to the number of mobile units; e.g., LM-2 refers to two mobile units.

premises: short (S) or long (L) service duration. The second condition is based on the number of MTUs that can be dispatched in response to an FPI client's request for service: multiple (M) or one (O) mobile unit. Thus, SM translates to an experimental scenario wherein short service duration is allowed (i.e., MTUs can be dispatched for short service), and multiple MTUs can also be sent in response to a client request (this happens in cases where the volume of wastewater discharged by the clients' processes is in excess to the processing capacity of a single MTU). Within each of the four main scenarios, the number of mobile WWTP units/MTUs in service is taken into consideration as sub-scenarios; the numeric part of the sub-scenario names, for example, SM-1 and SM-5 (Table 4), refers to the number of MTUs that are introduced in the model. Thus, SM-5 indicates that the experimental scenario SM is being executed with five MTUs.

The operational scenarios are discussed briefly.

- The first operational condition is to test whether to allow short (S) or long (L) service. As the seasonal wastewater treatment demands span from one month to a couple of seasons, when one mobile unit finishes a service and becomes available to serve another client, the latter client's demand may only exist for a couple of weeks or even days. If the mobile unit serves the short demand, there is a potential risk that travel, technician and installation costs cannot be covered by the fee payable by the FPI for the service. On the contrary, if the mobile unit does not serve the short demand, it will lead to the order for the service being cancelled, and the client will be unsatisfied.
- The second operational condition is to explore whether to dispatch multiple (M) MTUs towards the fulfilment of a single service request from an FPI client, or just one (O) mobile unit (even if the client produces more wastewater than the treatment capacity of one MTU). The importance of this condition is that allowing multiple MTUs will affect the availability of mobile units that could be sent to other

clients, thereby potentially serving fewer clients at the same point in time. This implies the service provider needs to turn down the orders for rental service more often when there are not enough mobile units available. Declining orders for MTUs will lead to a loss of interest in hiring the service and a loss of the service provider's reputation. However, note that the study simplified it by only testing two mobile units to represent the 'multiple' option.

For both operational conditions, the investment by our project partner in mobile units is critically relevant. Although having a higher number of MTUs will likely increase the satisfaction of FPI clients as more resources are available to meet their wastewater processing needs, higher investment during the business inception years will cause financial risks and additional costs (e.g., interest on loans) for our project partner.

The **second scenario group (SG-B)** includes experiments to assess the different self-owned equity capitals to invest in manufacturing mobile units. It is noted that this scenario group will only test with the LM scenario. This is because, as will be seen in the results section, LM has been identified as the most advantageous scenario from SG-A. The more equity capital at the beginning, the lower the loan costs at the later stage. However, the service provider will need more time and effort to obtain more equity capital at the early stage. SG-B tests four main scenarios referred to as 100kEC, 200kEC, 250kEC and 300kEC (Table 4; SG-B) and which map to the start-up equity capital of 100K, 200K, 250K and 300K, respectively. For each scenario, a further ten sub-scenarios (LM-1 to LM-10) allow us to experiment with the number of mobile units.

The **third scenario group (SG-C)** experiments with different service charge rates that affect the FPI client's interest and willingness to hire the service and the trade-off between income and customer satisfaction. The two main scenarios are referred to as *2.5 Euro/m^3* and *2.5 Euro/m^3* (Table 4; SG-C), with 2.5 and 3.0 Euros reflecting the cost of treating one cubic meter (m^3) of wastewater. Each scenario has ten sub-scenarios (LM-1 to LM-10).

The **fourth scenario group (SG-D)** includes two main experimental scenarios – *one depot* or *two depots* (Table 4; SG-D). These experiments aim to assess whether an additional depot can benefit the MTU dispatch and logistics aspect towards providing services to 25 FPI companies or whether the rental cost of an additional depot outweighs the potential benefits. The two scenarios have ten sub-scenarios (LM-1 to LM-10).

5. Results and discussions

As symbiosis is typically regarded as a prolonged investment reliant on operational sustainability and a sustained business model, we deemed it appropriate to conduct experiments spanning 20 years, from January 1, 2023 to December 31, 2042. This duration was chosen to observe all scenarios, allowing many of them (at least one scenario) to achieve full participation, i.e., the involvement of all 25 InSym adopters. In our model implementation (refer to section 4.4), we employed a DES-based fluid flow library (AnyLogic, 2023) for MTU and FPI business agents to simulate the intricacies of wastewater treatment processes within the system. Table C-1 (in Appendix C) presents the simulation results for a total of 110 experimental scenarios, which is made up of 40 experimental scenarios from SG-A, 30 from SG-B, 20 from SG-C and 20 scenarios from SG-D, with a set of weightings for the MCDA final score (column 3 of Table C-1, Appendix C). It is important to note that although the model allows testing various MCDA weightings over the simulation period, we applied only one fixed weighting for the experimentation selected by the mobile unit service provider for its best interest.

5.1. Comparing four main scenarios in terms of symbiosis system performance (scenario Group-A)

In this section, we compare the four main scenarios from SG A (SM, SO, LM, and LO) to identify the most advantageous way of operation, considering that the four main scenarios are composed of the full permutations of two sets of operational conditions. One set concerns whether to allow MU to provide short service, whilst the other set is about allowing more than one MTU to cater to one FPI client service request for mobile WWTP service.

Fig. 8 shows the overall performance of the four main scenarios, i.e., MCDA final score (Table C-1 in Appendix C), which is contributed by four factors, namely financial performance (criterion #1), treated rate (criterion #2), the amount of water treated (criterion #3), and client number (criterion #4), which are described in Table 3. LO has the highest MCDA score for the scenarios corresponding to one and two MTUs. However, LM has a higher MCDA final score when three or more MTUs are considered. Compared to this, LO has the lowest scores (together with SO) when scenarios with four or more MTUs are considered. Therefore, LM is considered the most advantageous main scenario amongst the four. Note that the performance of the final score is the reflection of interaction amongst four criteria. It is worth further exploring the effect of individual criteria to obtain the rationale behind scenario ranking.

Fig. 9 illustrates the comparison of the total profit, the most crucial factor composing criterion #1, financial performance. A similar pattern to the final score (Fig. 8) is evident in the total profit performance, with LM presenting as the most profitable amongst the four main scenarios. LM achieved the highest profit in the three MTU scenarios (LM-3 in SG-A). Interestingly, increasing the number of mobile units in service in LM does not always lead to increased profit; particularly, it appears to decline beyond six mobile units. Several reasons account for this phenomenon. A reason for this can be identified in Fig. 10, where the increase in client numbers in LM from six mobile units upwards is relatively small compared to the other main scenarios.

Additionally, as shown in Fig. 11, despite LM and SM steadily increasing the amount of treated water, this does not necessarily result in increased profit. Profit is impacted by costs from loan interest for manufacturing mobile units, as self-owned capital can only afford the first few units. Notably, in Fig. 10, although SM and LM have relatively lower client numbers, they both exhibit a better range of increase when the number of mobile units available increases. This pattern suggests that SM and LM, both of which commonly provide 'multiple' mobile units to individual clients, lead to better client satisfaction regarding wastewater treatment demands, rendering them relatively more attractive to the market as service availability expands.

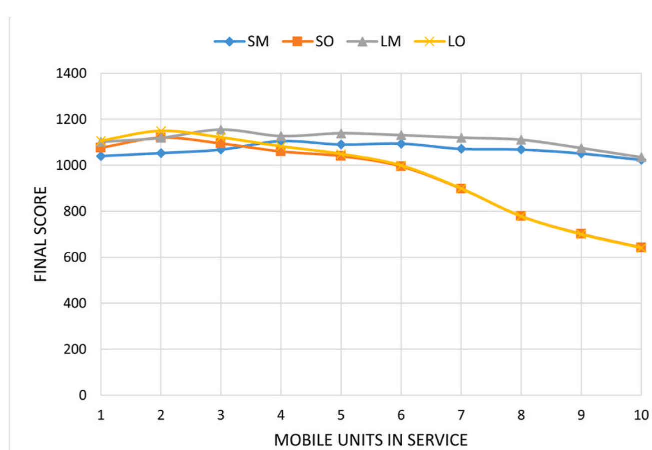

Fig. 8. Final MCDA score for the four main scenarios (SM, SO, LM and LO) that form Scenario Group-A.

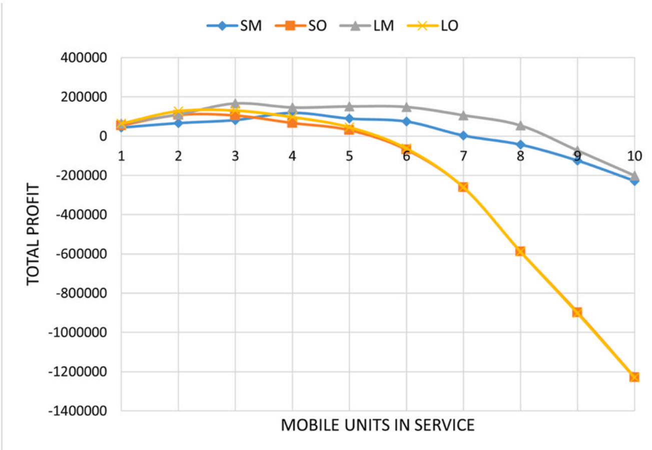

Fig. 9. Total profit generated by the four main scenarios (SM, SO, LM and LO) that form Scenario Group-A.

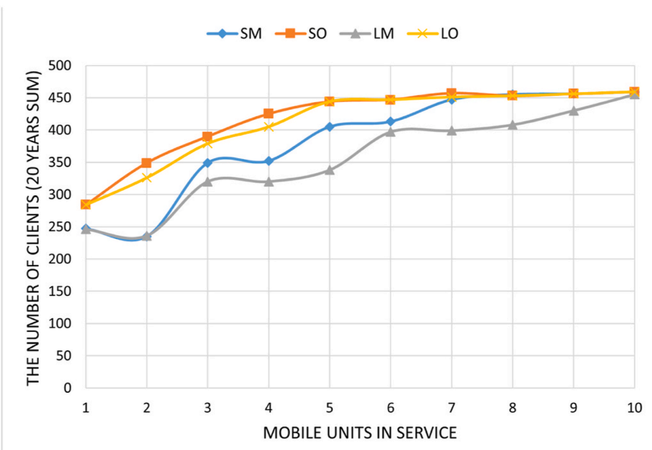

Fig. 10. Total client number for the four main scenarios (SM, SO, LM and LO) that form Scenario Group-A.

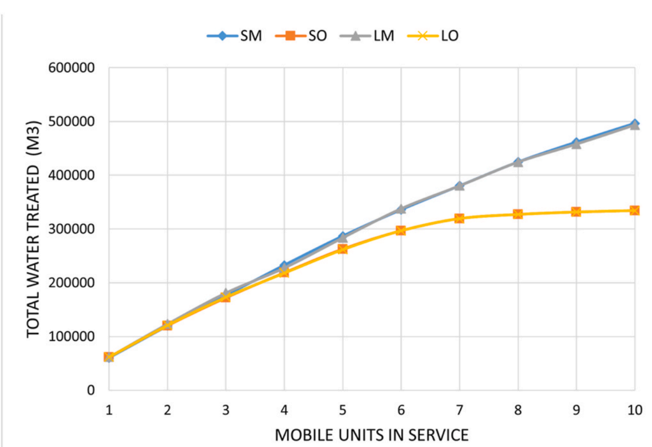

Fig. 11. The total wastewater treated by the four main scenarios (SM, SO, LM and LO) that form Scenario Group-A.

5.2. Comparing four main scenarios in relation to MTU clients (scenario Group-A)

After identifying LM as the most advantageous main scenario in SG-A (Section 5.1), we investigated how individual MTU client performance was influenced by different scenarios. Fig. 12 illustrates the total treated rate, a critical factor in customer satisfaction. SO and LO both face the restriction of sending only 'one' mobile unit to individual clients during the service period. Whilst this restriction may increase availability for mobile units to serve other clients in demand, implying serving more clients simultaneously, it may lead to longer service time for individual clients (Fig. 13). Both scenarios present a ceiling of maximum treated rate (around 50%, Fig. 12), significantly impacting customer satisfaction.

In contrast, SM and LM commonly provide multiple units in one service, differing in whether to allow short service. Comparing LM with SM in Fig. 12, LM exhibits longer service time to individual clients, contrary to the expectation that not allowing short service would waste service time/opportunity, even if the time may be brief. This unexpected outcome may stem from the fact that the mobile unit is occupied during short service and may miss opportunities for longer service elsewhere. Surprisingly, Fig. 12 indicates that LM consistently leads throughout the increase in mobile availability, suggesting that not allowing short service may enhance the total treated rate to individual clients (relevant to customer satisfaction), with an average increase of 5%–10%. Furthermore, LM and SM both perform relatively better from the two MTU scenarios upwards, steadily benefiting from the increase in mobile units. Figs. 12 and 13 reveal that although SO and LO provide longer service times for individual clients (only one mobile unit for each client), the limited treated rate still dominates the trade-off in customer satisfaction, ultimately affecting overall performance.

5.3. Comparing the four best main scenarios (scenario Group-A)

Having identified LM as the top-performing scenario amongst the four main options (Sections 5.1 and 5.2), we further compare the best sub-scenario of each main scenario of SG-A (SM, SO, LM and LO) to determine whether LM consistently outperforms the others as we progress through the simulation time (January 1, 2023 to December 31, 2042). The best sub-scenarios are observed at different levels of mobile unit availability, namely SM-4 (four mobile units), SO-2 (two mobile units), LM-3 (three mobile units), and LO-2 (two mobile units). Fig. 14 illustrates that LM-3 performs the best overall (i.e., final score), although the differences are minimal. Fig. 15 displays the ranking based on total profit (the most critical factor in criterion #1 financial performance), demonstrating that LM-3 notably outperforms the other three best sub-scenarios. This indicates that whilst LM-3 excels in certain aspects, there may be other criteria where it does not perform as well, such as the number of clients (criterion #4) in Fig. 14. However, this discrepancy is understandable, given the variance in mobile unit availability across sub-scenarios. Through the analysis and discussion presented in Sections 5.1, 5.2 and 5.3, we have concluded that LM represents the optimal main scenario, with LM-3 (i.e., three mobile units) emerging as the most advantageous plan for business investment.

Various challenges faced by rental businesses can be found in the literature, including equipment downtime, inventory management, pricing and billing complexity, managing complex reservations, monitoring equipment availability, processing equipment returns, evaluating the ROI of assets, and customer service (van der Heide, 2016; Slaugh et al., 2016; Tainiter, 1964; Coelho et al., 2018). These challenges highlight the reasons for our research to select the experimental scenarios (i.e., the four scenario groups). Jain (1966) pointed out that a critical challenge in rental service is devising an optimal policy that maximises company profits whilst minimising customer loss due to insufficient inventory and turndown. This reflects the situation where the rental service provider lacks available inventory when an order

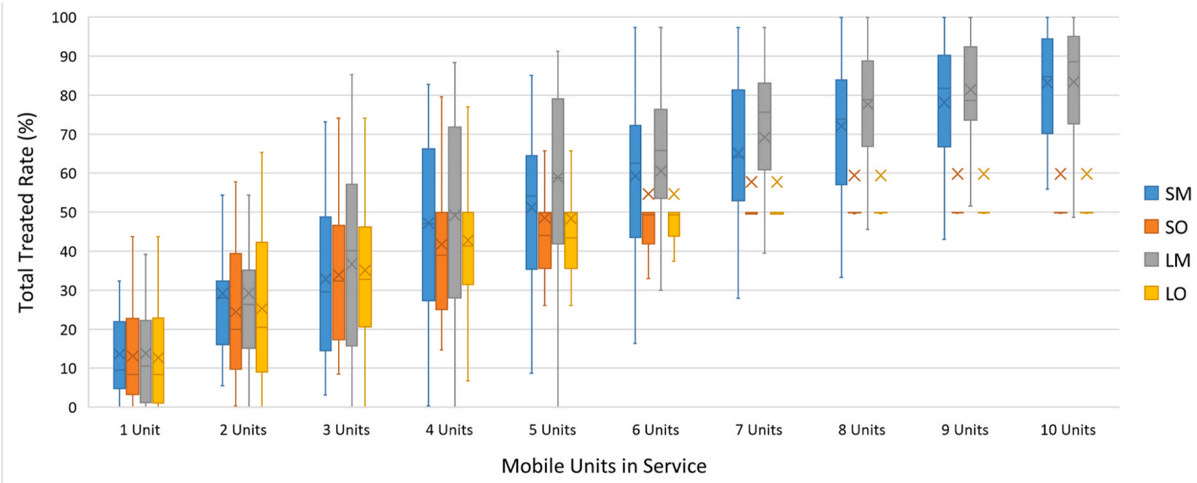

Fig. 12. Total wastewater treated rate of individual MTU client towards the four main scenarios (SM, SO, LM and LO) that form Scenario Group-A.

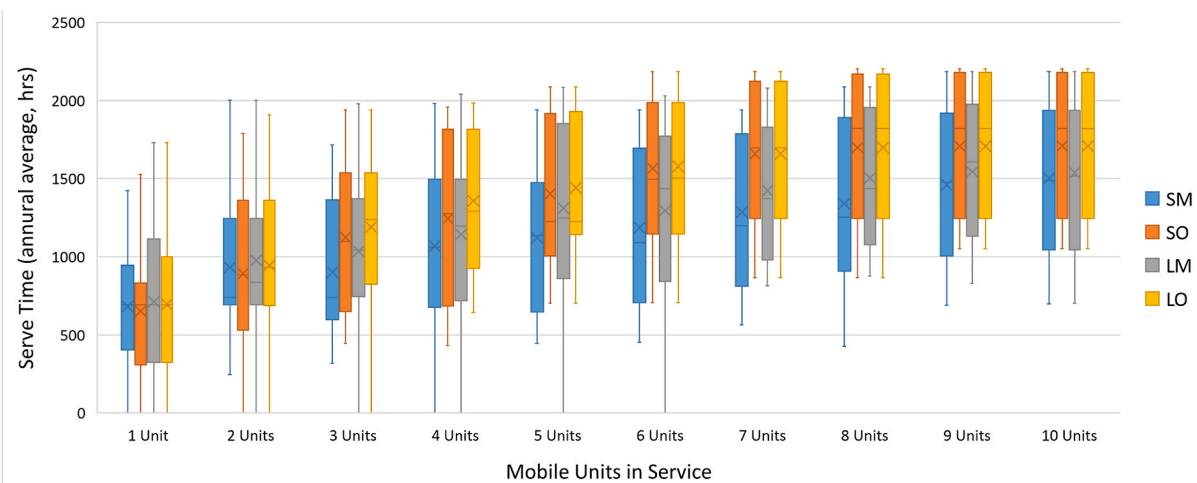

Fig. 13. Total service time (in hours, annual average) of individual MTU clients towards the four main scenarios (SM, SO, LM and LO) that form Scenario Group-A.

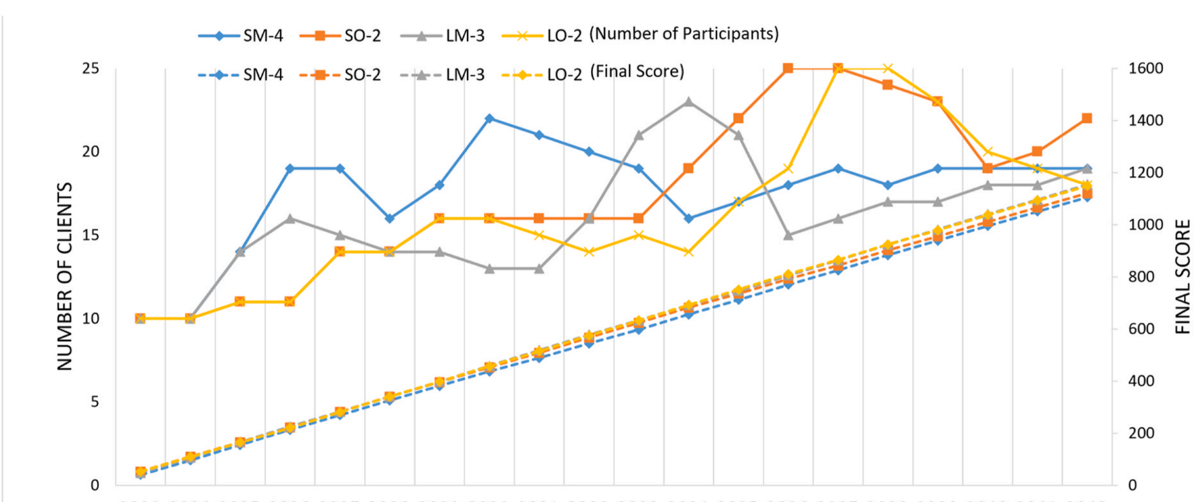

Fig. 14. Comparison of the MCDA final score vs. the number of MTU clients for the four best sub-scenarios (SM-4, SO-2, LM-3 and LO-2) related to Scenario Group-A (simulation time presented in the x-axis).

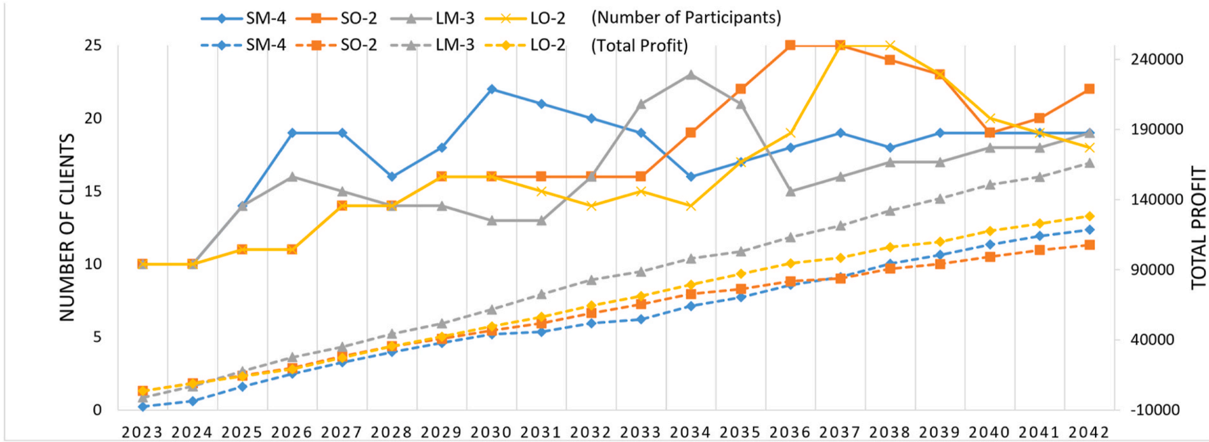

Fig. 15. Comparison of the total profit vs. number of MTU clients for the four best sub-scenarios (SM-4, SO-2, LM-3 and LO-2) related to Scenario Group-A (simulation time presented in the x-axis).

arrives, causing customers to wait and potentially lose interest in the service. Conversely, maintaining a large inventory is not financially sustainable due to investment capital and storage costs. Coelho et al. (2018) concluded that simulation is a promising tool for studying rental processes due to the uncertain and variable environment concerning order timing, inventory levels, and logistics policy. However, relevant research on the rental business is rather limited. Their research DES tests inventory level scenarios and maintenance for improving operational performance. It quantified the relationship between inventory levels, repair activities, and turndowns. Susanto et al. (2012) used simulation to achieve optimal profit by balancing supply and demand for a car rental business. Our scenario testing results justify the significance of the special concern of hiring multiple units by one client due to various wastewater production volumes (as discussed in Section 5.1). It also provided valuable insight into ordering rule arrangement, i.e., whether short service is allowed, given the unique seasonal demands of the food processing industry (i.e., two to three months' peak time for one type of fruit or vegetable). Section 5.2 provides an understanding of how the tested scenarios affect modelled clients individually, as each client processes a range of fruits or vegetables, resulting in different seasonal demand patterns. This understanding can help the rental service provider in planning, particularly for targeting clients to acquire, as a better composition of active clients means a more distributed pattern of demand throughout the year. In Section 5.3, the results identify the optimal size of inventory from the most advantageous scenario LM (refer to Table 4).

In the subsequent sections, we further address the other important challenges, including investment scenarios (Scenario Group-B, Section 5.4), pricing complexity (Scenario Group-C, Section 5.4), and inventory base/location (Scenario Group-D, Section 5.4). This research seeks to address challenges holistically in one simulation, leveraging the proposed modelling framework that integrates hybrid simulation approaches and MCDA.

5.4. Comparing investment in terms of equity capital (scenario Group-B)

This section explores how different equity capitals affect the InSym mobile WWTP business. Using 100k Euro as the baseline amount in experiments conducted as part of SG-A (Sections 5.1-5.3), three additional financial scenarios, 200k, 250k, and 300k, were tested as per scenarios defined in SG-B (Table 4). The more equity capital the company has initially, the fewer loan and relevant costs will be incurred later to obtain the planned mobile units for service provision. From Fig. 16, with an increase in mobile units, we observe a generally rising trend in the total number of clients served. However, for the baseline scenario with 100k Euro equity capital, the total profit starts to decline significantly if the company intends to manufacture seven mobile units or more, primarily due to interest costs from loans. The other financial scenarios exhibit a similar dropping trend from seven mobile units onwards, albeit more moderately. The key difference lies in the fact that with more equity capital (200k, 250k, and 300k), the total profit at six mobile units performs very similarly to that at three mobile units (i.e., LM-3). This suggests that if the priority is to increase the number of clients, the company may consider LM-6 instead of LM-3 if higher equity

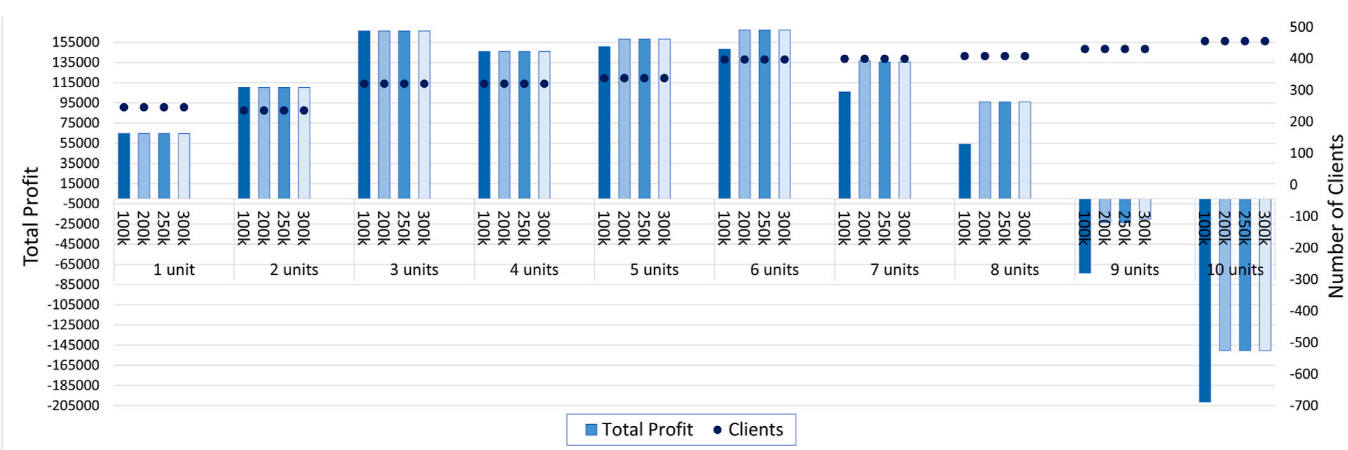

Fig. 16. Total profit vs. number of clients towards the equity capital scenarios related to Scenario Group-B.

capital at the beginning is available.

5.5. Comparing two wastewater processing charge rates (scenario Group-C) and provision for depots for MTUs (scenario Group-D)

In our final analysis, we consider scenarios from SG-C and SG-D, which are extremely important for decision-making concerning InSym's performance, viability and sustainability. For this analysis, we continue with our focus on the LM scenario. With experiments pertaining to SG-C, we explore the income side of finance, whilst, in SG-D, we examine the cost side to assess whether adding one MTU depot will lead to cost reduction. As both parts will be presented with the same figures, we discuss them together.

For SG-C scenarios (please refer only to the first two columns of each group in Figs. 17 and 18), comparing charging service fees of 2.5 and 3.0 Euro/m^3, we observe in Fig. 17 that the baseline charging of 2.5 Euro/m^3 yields the highest total profit with three mobile units (LM-3), whereas charging 3.0 Euro/m^3 achieves the highest total profit at six mobile units (LM-6). The profit difference between the two best scenarios is evident. However, when examining the final score (Fig. 18), the best scenario with a charge of 2.5 Euro/m^3 is LM-3. Conversely, the best scenario with a charge of 3.0 Euro/m^3 is LM-2 and LM-3, with LM-4, LM-5, and LM-6 also closely aligned with top performance. This indicates that the increase in service charges impacts financial performance, such as total profit, and other factors, such as customer satisfaction, as evidenced by the number of clients in both figures. We notice a decrease in client numbers in every group (LM-1, LM-2 …), with fewer mobile units experiencing a more significant drop in client numbers. This suggests that, without sufficient mobile units, a higher service charge fee is more likely to result in decreased customer satisfaction, reflected in the number of clients. Considering both Figs. 17 and 18, LM-6 charging 3.0 Euro/m^3 appears more advantageous than LM-3 charging 2.5 Euro/m^3 when considering the high level of client numbers rather than solely comparing final scores.

The comparison of the four main scenarios (SM, SO, LM, LO) reveals that LM (with three or more mobile units) consistently outperforms other scenarios in terms of overall performance and profitability. LM demonstrates better client satisfaction and profitability, particularly when compared to SM and LO, due to its ability to provide multiple mobile units and longer service times. Based on the findings, it is recommended that the LM scenario, particularly LM-3, be prioritised for investment due to its superior profitability and customer satisfaction. Consideration should be given to optimising equity capital and service charge rates to maximise profitability whilst maintaining high customer satisfaction levels. On the other hand, expansion plans, such as depot additions, may incur additional rental expenses. Proper evaluation is necessary to determine whether the benefits outweigh the costs, which should be carefully assessed to ensure cost-effectiveness and overall business sustainability.

As for the environmental benefits, we use our case study—the Argolida area—as an example. The illegal discharge has led to an increased cost of €0.43/m^3 (BOD <1000 mg/L) for treating these industrial wastewater discharges collected by the municipal treatment plant. Our FPI partner, where the pilot experiment of the mobile treatment application took place, revealed that the factory has a primary treatment unit with a capacity of about 480 m^3/day. During the peak production period (usually from November to March for citrus production and from August to October for grape and pomegranate production), the amount of wastewater treatment is about 3500 m^3/day, whilst during all the other months, it is about 500 m^3/day. This is a common example of equipping treatment capacity based on most months (i.e., non-peak time). It implies that for two periods in the year, totalling eight months, the company cannot fully treat the wastewater without additional capacity such as mobile treatment services. The amount of wastewater translates to €309,600/year in additional treatment costs if treated at the municipal treatment plant. Note that this is only from one company.

Furthermore, in the Argolida area, there is an increasing water demand for irrigation purposes, which, along with the high water consumption of the FPI, is exerting great pressure on the regional aquifer. This is because most water comes from irrigation wells, which are often legal. However, the water quality is rather poor, with high conductivity (around 3000 μS/cm). The most common treatment method is reverse osmosis, which involves increased energy consumption and operational costs. Mobile treatment can support the circular economy by reusing treated water in the region, such as for irrigation and manufacturing operations.

Given that the implementation of the model involves several uncertain factors—such as estimated information (e.g., wastewater volume, peak production pattern), and survey bias (e.g., the score of willingness to hire)—effectively addressing these uncertainties within the model is essential. We recommend incorporating probabilistic or sensitivity analyses into the proposed framework to manage these uncertainties. For example, the willingness to hire (represented by the

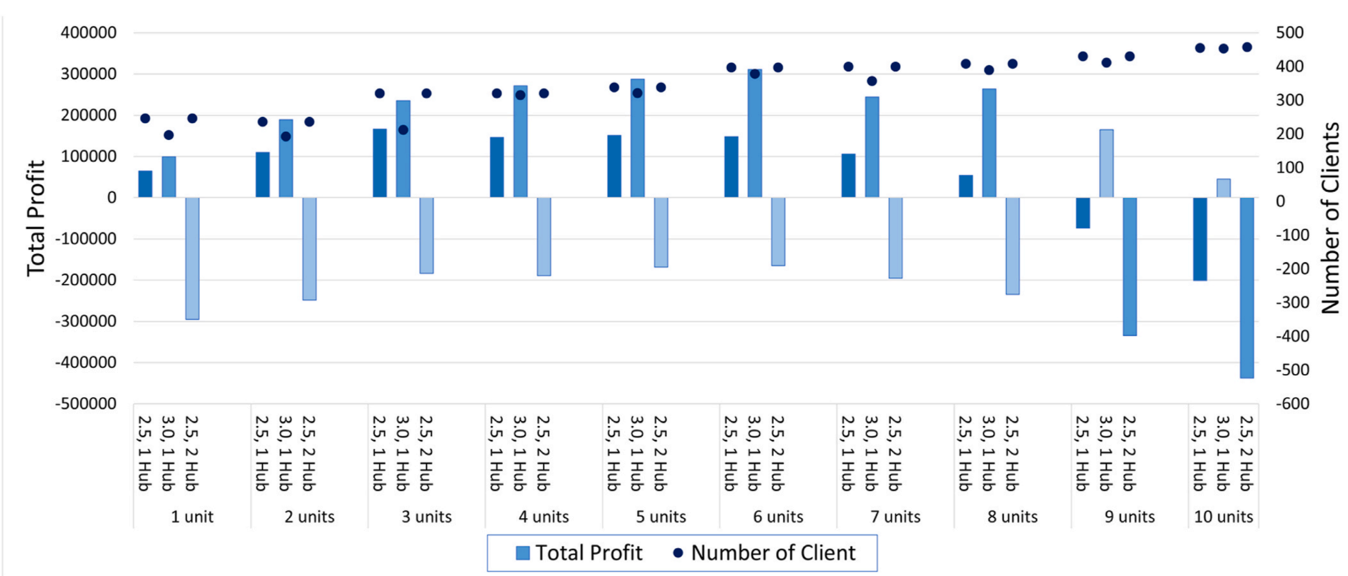

Fig. 17. Comparing total profit vs. number of clients for the scenarios related to Scenario Group-C (2.5 Euro/m^3 and 3.0 Euro/m^3).

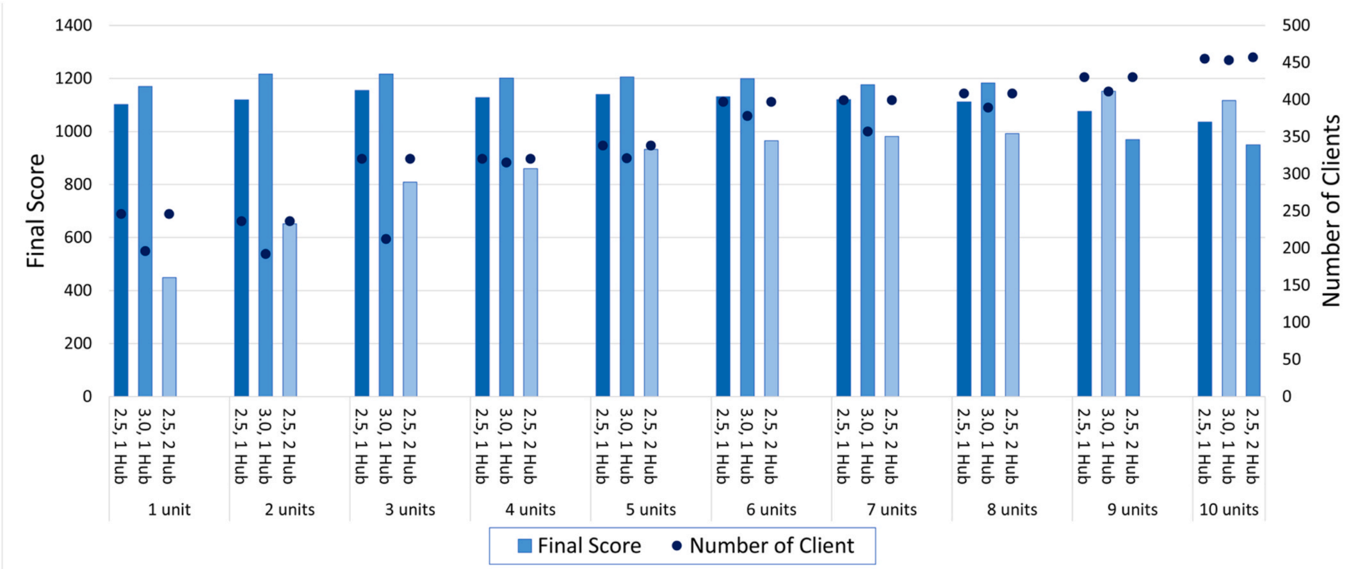

Fig. 18. Comparing the final score vs. the number of clients for the scenarios related to Scenario Group-D (one depot, two depots).

MCDA score) and its associated weights from the survey across individual businesses involve a high degree of subjectivity, introducing uncertainty. A probabilistic approach can address this by converting surveyed data into a range (e.g., a score of 3 could be represented as a range from 2.5 to 3.5). During each simulation run, a random value is selected within this range. By increasing the number of simulation runs we can observe how final scores are influenced by varying levels of uncertainty. This approach provides valuable insights into the robustness and reliability of the model. Future work will involve validation of the model. It will evaluate whether the model's predictions match the real-world behaviours and interactions of InSym adopters over time. The insights obtained from these tests will be used to iteratively refine the model, enhancing its accuracy and adaptability.

6. Conclusions

Industrial symbiosis (InSym) presents unique and complex challenges not typically encountered in traditional business models. For example, achieving a competitive advantage may take a long time. This is also true for mobile InSym solutions, such as the one presented in this paper. InSym is characterised by evolving priorities over time; higher adoption generally leads to greater profits and consequently increases the chance of attracting new InSym adopters (Demartini et al., 2020); the stakeholders (both current and potential adopters) view the system performance of symbiosis differently; the exchange of resources plays a critical role in InSym, and, finally, under this collective approach the businesses operate/behave differently due to their unique conditions and demands. Thus, compared to traditional business models, several factors impact InSym operations, and the relationship between the factors is usually dynamic, non-linear, and variable. This paper presents the F-SWC modelling framework to support InSym decision problems. The framework deploys multiple Operations Research (OR) methods, including agent-based simulation and MCDA, and applies it to a case study of mobile wastewater treatment plants (WWTP).

Our case study presents a dynamic and complex InSym environment which exemplifies SMEs with cutting-edge technologies and innovations that aim to valorise the circular economy of water by developing new and sustainable business models. In this context, our work on F-SWC and hybrid modelling provides valuable insights into the performance and viability of different operational scenarios, equipping the SME (the service provider) with the information needed to make informed decisions regarding investment and strategic planning for their business. Working closely with our project partners, we developed a hybrid model and compared four main scenarios and numerous sub-scenarios, which differed in terms of service design for the mobile WWTP service for the Peloponnesian region of Greece, and also in terms of number of mobile units available to service the demand for mobile wastewater treatment from businesses engaged with food processing industries. Our work has shown that the hybrid simulation modelling approach has its advantages as a decision support tool since it could be used for experimenting with various InSym strategies, especially when business models are to be tested before their implementation, but there is insufficient data for a pure empirical evaluation.

Some of the limitations of the study are now discussed. The MCDA survey conducted in 2023 to capture motivation KPIs of service users could not obtain sufficient data despite several attempts. Limited primary data related to participation was used to assign to 25 food processing companies. Moreover, the actual volume of wastewater production may not be provided or may be underestimated. This limitation also led to our simplification of testing only two mobile units in one request in the scenarios for experimentation (as 'M': multiple mobile units to cater to one FPI client service request). We acknowledge the above as the limitations of the study. They can be improved once further survey achieves better outcomes in the future beyond the project duration.

We discuss the avenues for future research concerning the F-SWC. Our work has implemented stages 1–4 of the F-SWC; however, there are opportunities to develop further scenarios for experimentation in stage 4. One such scenario is to enhance the 'multiple' MTU option (which presently considers only two MTUs), and instead allow all available MTUs to be hired at one time by one business. Further data from the case study partner will be needed to realistically model this scenario. Similarly, as the InSym matures, additional scenarios can be modelled in Stage 4 to support the business decisions of our case study partner. Stage 5 is on validation of the model, and it is expected that investment decisions by our partner in relation to the manufacture of MTUs and operational decisions on the dispatch strategies of the mobile WWTPs will provide us with data for validation. Stage 6 of F-SWC suggests opportunities to explore the reuse of models. In that regard, the F-SWC has been developed as a common frame to aid the development of hybrid models that focus on creating InSym. Thus, we will continue to explore the opportunity to reuse some of the implemented components of the current model for the other case studies.

CRediT authorship contribution statement

Otto Chen: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Navonil Mustafee:** Writing – review & editing, Supervision. **Barry Evans:** Investigation, Data curation. **Mehdi Khoury:** Visualization, Investigation. **Lydia Vamvakeridou-Lyroudia:** Supervision. **Albert S. Chen:** Supervision, Investigation, Funding acquisition. **Slobodan Djordjević:** Supervision. **Dragan Savić:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145041.

Data availability

Data will be made available on request.

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