Water Science & Technology

Water Science & Technology Vol 91 No 5, 501 doi: 10.2166/wst.2025.022

# Supporting decision-making for industrial symbioses using a hybrid modelling approach and its application to wastewater treatment

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

[a] Centre for Water Systems, Civil Engineering, 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
*Corresponding author. E-mail: c.chen2@exeter.ac.uk

OC, 0000-0003-2037-4889; NM, 0000-0002-2204-8924; BE, 0000-0003-1316-2087; MK, 0000-0002-2997-8948; LV-L, 0000-0002-8888-532X; ASC, 0000-0003-3708-3332; SD, 0000-0003-1682-1383; DS, 0000-0001-9567-9041

## ABSTRACT

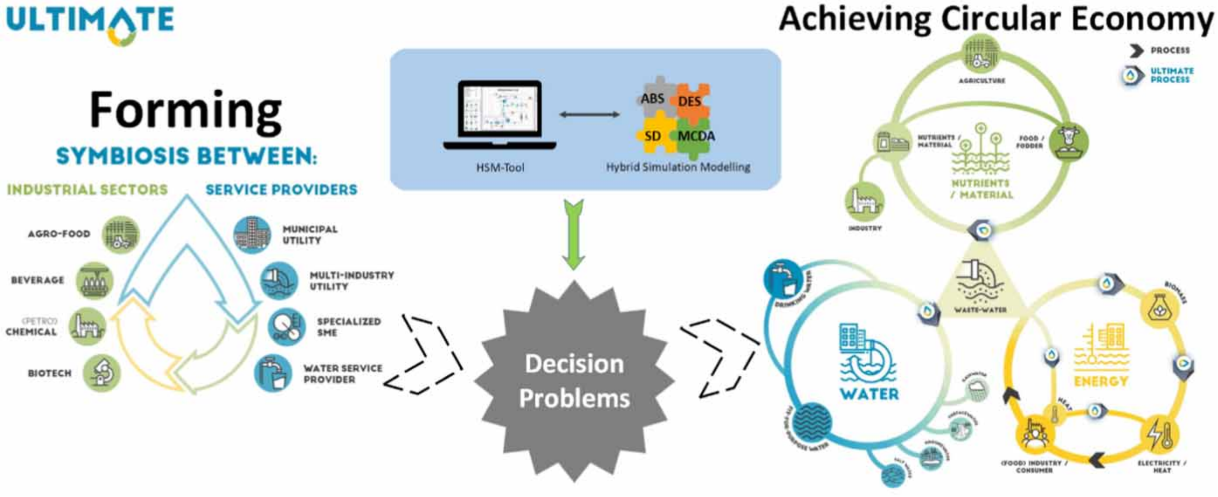
Industrial Symbiosis (InSym) capitalises on the proximity of entities to gain a competitive advantage through collective strategies. Within the Circular Economy, this involves the circular exchange and reuse of water, energy, and resources among participating businesses, enhancing resource valorisation in manufacturing. However, as a distinct business model, InSym requires collaboration among multiple stakeholders working toward a shared goal, posing challenges in achieving mutually beneficial outcomes. Operations Research (OR) – particularly computer modelling and simulation techniques – can help mitigate risks in InSym implementation by enabling an experimental approach to decision-making. This paper presents a hybrid modelling framework to support InSym decision-making. The framework integrates four OR techniques: Agent-Based Simulation (ABS), Discrete-Event Simulation (DES), System Dynamics (SD), and Multiple Criteria Decision Analysis (MCDA) to develop a hybrid InSym model. ABS captures stakeholder behaviour, DES simulates operational processes, SD represents dynamic interactions, and MCDA incorporates stakeholder perspectives. The model evaluates collective treatment strategies for olive mill wastewater, addressing key challenges such as scattered small-scale olive mills, seasonal wastewater discharge, and high organic loading. This innovative framework addresses InSym decision-making at operational, tactical, and strategic levels, transforming the economy-environment dilemma into a win-win scenario for olive oil businesses and local authorities.

**Key words:** circular economy, hybrid modelling, industrial symbiosis, multiple criteria decision analysis, olive mill wastewater, simulation

## HIGHLIGHTS

- A framework to model the participation dynamics of symbiosis formation.
- The framework leverages the strengths of multiple simulation techniques and MCDA.
- The framework supports performance evaluation at individual and symbiosis levels.
- A case study on olive mill wastewater treatment demonstrates the implementation of the framework.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

Industrial processes often strive for resource optimisation within the water cycle, aligning with circular economy (CE) principles and environmental sustainability. Industrial symbiosis (InSym) is key to achieving this goal by facilitating the circular exchange of water, energy, and materials between geographically proximate businesses. This collective approach leverages proximity to generate synergistic benefits (Chertow 2000).

The ULTIMATE project (https://ultimatewater.eu/) views wastewater as a reusable resource and a carrier of valuable energy and components. It promotes CE practices and fosters partnerships between water users, service providers, and local authorities through InSym implementation across diverse industries. While InSym's potential to close the water cycle is undeniable, its adoption presents unique decision-making challenges compared to traditional models due to mainly the collective way of running business cooperatively, which leads to complex considerations of stakeholders during planning and implementation. The unique challenges are often presented as, for instance, different types of industries and interests of the stakeholders involved, complex and dynamic interrelationships affecting participation, sustainability of business models resulting from all-party win-win prerequisite (Herczeg *et al.* 2018), and new business model unable to follow commercial experience to foresee obstacles. Furthermore, these issues exist at operational, tactical, and strategic levels, which reflect the difficulty of applying one single approach to address the decision-making holistically. Fakhimi *et al.* (2016) reviewed modelling and simulation approaches for sustainability analysis and concluded that the combined application of simulation techniques such as discrete-event simulation (DES) and system dynamics (also referred to as hybrid simulation) enables a multi-dimensional assessment of triple-bottom-line (TBL) metrics associated with sustainable operations management. Such a hybrid approach has been used in healthcare (Zulkepli 2012) and collaborative freight transportation (Bae *et al.* 2022).

While Operations Research (OR) offers a plethora of techniques, methods and tools for decision support (Mustafee & Katsaliaki 2020), single OR approaches like mathematical modelling or computer simulation struggle to capture the intricacies of InSym, which is characterised by non-linear, dynamic behaviours and diverse stakeholders. A hybrid modelling approach, integrating OR techniques like MCDA with simulation approaches like DES, Agent-based Simulation (ABS) and System Dynamic (SD), proves more effective in comprehensively representing the dynamic complexities of an evolving system of interest (Mustafee *et al.* 2020; Mustafee & Fakhimi 2024), such as InSym, which often demonstrates the characteristics of complex adaptive systems (Chertow & Ehrenfeld 2012).

This study presents a hybrid modelling approach for the water cycle within the InSym framework, addressing InSym's unique decision challenges to achieve CE. The application of the modelling framework (Chen *et al.* 2025) is demonstrated through a case study from Israel related to olive mills, where it is used to analyse a proposed InSym solution for a real-word challenge – the treatment of olive mill wastewater (OMW), one of the most challenging wastewater types for treatment.

A short review of the OR literature for modelling InSym is presented next (Section 1.1). This is followed by a discussion on the dilemma of OMW treatment (Section 1.2), which also contextualises the case study. Section 1.3 then guides the readers through the remainder of the paper.

### 1.1. Literature review

Several studies have applied OR approaches in the context of InSym decision-making. In a recent study by Yazıcı *et al.* (2022), various OR techniques used in InSym decision problems were examined and categorised into four groups: exact methods, heuristic methods, multi-criteria decision analysis (MCDA), and simulation. The authors highlighted that approximately half of the reviewed papers utilised simulation methods to support decision-making, making it the most prevalent application. Furthermore, MCDA was widely employed to determine priority values of criteria impacting the InSym network, rank alternatives, design InSym networks, and evaluate the effects of InSym applications on performance. The study by Demartini *et al.* (2022) summarised nine commonly used approaches for modelling InSym. These approaches included two simulation approaches (*ABS* and *SD*), in addition to *Input-Output model, Lifecycle Assessment (LCA), Material Flow Analysis (MFA), Network Analysis, Mixed Integer Linear Programming, DEcision-MAking Trial and Evaluation Laboratory (DEMATEL),* and *Ecological Network Analysis*. Notably, these nine approaches align with the four categories mentioned in Yazıcı *et al.* (2022) and extend beyond the simulation category. Demartini *et al.* (2022) identified ABS as the most widely applied approach, gaining popularity in recent years. It has also been integrated with LCA, MFA, and other techniques, underscoring the use of hybrid modelling methods combining multiple OR techniques.

ABS models of InSym are limited in their potential to predict the influence of social activities and networking on the system (Ghali *et al.* 2017). Furthermore, existing models typically assume perfect sharing of by-product information related to potential synergies, which is seldom the case in real-world scenarios. Ghali *et al.* (2017) proposed a novel model that represents social embeddedness using a set of dependent variables to address these limitations. These variables describe the evolution of trust, reputation, and knowledge sharing within various social dynamics and structures, highlighting their significance in influencing the development of InSym.

Lawal *et al.* (2021) categorised tools developed for InSym as primarily focussing on process integration or mathematical optimisation (MO); both approaches tend to focus on resource aspects of InSym, such as reclamation, exchange, and utilisation. The study highlighted that process integration tools for InSym design and planning have mostly operated in isolation and thus concentrated on individual resources, e.g., heat, water, carbon, waste and power. Similarly, MO applications exhibit the same pattern.

Our literature review has shown that there have been a limited number of studies on deploying OR tools and techniques for modelling InSym decision-making. This is especially true if we consider studies incorporating geographic proximity as a significant component of the modelling work. Furthermore, decision-making problems can arise at 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. The literature primarily focused on either quantifying life cycle assessments (LCAs) or accounting for environmental impacts (Aparisi 2010; Cecelja *et al.* 2015). Additionally, the literature would gain from using OR methods (including simulation) to evaluate performance at individual and symbiotic levels while considering the dynamics of the InSym participants (both *potential adopters* who may join the InSym solution or *existing users* who may evaluate whether to remain or to exit the InSym based on dynamical evaluation of the KPIs). These gaps have motivated us to discuss the opportunity for a decision-making tool to assess InSym strategies.

### 1.2. The dilemma of OMW treatment

Olive oil is considered beneficial to health and is in increasing demand worldwide. A 2022 report by the International Olive Council (IOC) shows that European Union countries account for two-thirds (66%) of the world's olive oil production (IOC 2022). However, disposing OMW is a significant environmental challenge in Mediterranean regions (30 $\mathrm{Mm}^3$ of OMW per year are produced globally; Tosti *et al.* 2013). Further, the treatment of OMW is fraught with challenges for the industry; for the governments, there are environmental implications to consider.

The olive mill industry, which produces olive oil, table olives, and related products, consumes substantial amounts of water and generates significant wastewater, especially during the olive harvesting season. This OMW has a high biological and chemical oxygen demand, high concentrations of oils and greases, high salinity, and high phenolic compounds, making its treatment very costly (Roig *et al.* 2006; De Marco *et al.* 2007; Hanifi & El Hadrami 2008; Amaral *et al.* 2008; Hanafi *et al.* 2013). These industries often operate on a small to medium scale and face challenges in managing their wastewater due to seasonal fluctuations in production and discharge. Establishing advanced treatment facilities capable of handling these seasonal discharges is both financially burdensome and operationally challenging. Mandating these businesses to set up treatment facilities may lead to financial difficulties, threatening the financial sustainability of the businesses. This situation presents a significant dilemma for the government.

Consequently, a common practice for disposing of OMW has been discharging it onto the soil (i.e., field spray practice), with varying levels of control to limit its potential negative effects on soil and groundwater (Saadi *et al.* 2007; Tamimi *et al.* 2016). However, the dispersion of olive mills across agricultural regions makes it difficult for authorities to effectively monitor field spray and wastewater discharge, especially given the seasonal fluctuations in production and discharge volumes. This situation has led some mills to resort to illegal discharge practices into the sewer system, causing local sewage treatment plants to collapse and pose significant environmental risks. In most olive oil-producing countries in the Mediterranean region, water resources are relatively scarce, making the reuse of treated water crucial for irrigation. The collapse of municipal wastewater treatment plants (WWTPs) due to the inhibition of microbial growth and activity and the clogging of filtration stages is costly to repair and severely affects the supply of recycled water. Additionally, the high water demands of olive mill operations contribute to the potential illegal exploitation of groundwater resources in these areas.

Our case study is from Israel. Israel is among the top 15 olive oil-producing countries that collectively contribute to 96% of global olive oil production (Council 2019). According to the Israeli government, the country has approximately 140 active oil presses, with 90 located in the northern region. The olive oil production process generates up to 80,000 $m^3$ of waste annually (SIEGEL-ITZKOVICH 2022). This waste has led to frequent clogs and occasional breakdowns in WWTPs. The current practice of field spraying has proven ineffective in mitigating these issues.

The study sought to investigate the potential for hybrid modelling and simulation to inform policy that applies InSym collective strategy. It also shows the novelty and potential of practical contributions in the planning of the combined application of centralised and decentralised treatment. The decision-making approach could be used by local authorities, private sectors, or environmental agencies to make better decisions regarding resource reuse and wastewater treatment.

### 1.3. Outline of the paper

Following the introduction section, Section 2 discusses the unique characteristics of InSym and relevant modelling methods. This subsequently leads to the proposed hybrid framework for modelling InSym in the context of the water cycle, a discussion of the main framework components and a flowchart to aid framework implementation. Section 3 showcases the practical application of the proposed framework through a case study focusing on Israeli olive oil manufacturing industries. This section explores the adoption of an InSym solution as a potential policy involving the logistics of wastewater transport between symbiosis WWTP and olive oil businesses. Section 4 presents the results obtained through experimentation, comparing various scenarios and their potential outcomes. Finally, Section 5 concludes the paper by summarising the key findings and discussing the broader applications of the framework in modelling InSym systems for the water cycle. This section also acknowledges the limitations of the current research and proposes potential avenues for future work.

## 2. METHODS

InSym presents unique challenges for decision-making compared to traditional business models. Its distinctive features are (a) stakeholder diversity, (b) complex and non-linear interrelationships, (c) participation dynamics, (d) sustainability of business models, and (e) benefits that are dependent on the scale of InSym and with a long-term perspective. Modelling these features necessitates a tailored framework that supports multiple OR approaches, which is discussed next. For the reader's benefit, the discussion also lists papers that will provide further information on the modelling methods.

### 2.1. Modelling of stakeholder diversity

Stakeholders within an InSym network may have varying perspectives, based on their specific conditions and demands, on system performance and KPIs, requiring consideration of diverse viewpoints. The use of **MCDA** is an appropriate modelling method as it captures diverse perspectives of stakeholders involved in decision-making and accommodates varying viewpoints on system performance over time. For more details on the MCDA technique, please see the following articles by (Belton & Stewart 2002; Greco *et al.* 2016).

### 2.2. Modelling of complex and non-linear interrelationships

InSym involves an intricate web of interrelationships between various impact factors, characterised by dynamics, non-linearity, and variability. **System dynamics (SD)** is effective in handling the intricate, interactive relationships among impact factors within the symbiotic business model, particularly in dynamic contexts where these relationships vary over time. For more details, please see articles by (Karnopp *et al.* 1990; Coyle 1997).

### 2.3. Modelling of participation dynamics of InSym users

The number of InSym participants may evolve through time. Businesses, for example, may initially join InSym for reported efficiencies but later withdraw due to changing circumstances, impacting the broader system. Similarly, potential adopters could join if existing users report efficiency and economic gains. **ABS** can model the diverse behaviours of the potential adopters and the current InSym participants (user agents). The interactions between the user agents and the 'InSym provider agent' will determine the participation dynamics and lead to the system's evolution through simulated time (North & Macal 2007; Macal 2016).

### 2.4. Modelling of sustainability of both the individual business models and the collective inSym business model

Business model sustainability is not just the requisite of the individual symbiosis adopters, but the InSym solution also needs to sustain the collective business model. **DES** can be used to model and optimise InSym processes, identify bottlenecks, and perform experimentation to help businesses adapt to new operational paradigms and business models. For further information on DES, please refer to (Robinson 2005; Leemis & Park 2006).

### 2.5. Modelling of scale-dependent benefits with a long-term perspective

The extent of InSym adoption significantly impacts its economic and environmental benefits, influencing profits, waste reduction, and its overall attractiveness to new participants (Demartini *et al.* 2020). InSym also often requires a long-term commitment from participants to realise its potential. **Hybrid simulation** is an appropriate methodology to capture the relevant KPIs through the overarching model's DES, ABS, or SD sub-components, respectively. Further, experiments can be executed decades into the future, thus supporting the long-term InSym perspective.

Our proposed framework for modelling InSym consists of three interconnected components: symbiosis operation (SO), symbiosis performance evaluation (SPE) and symbiosis participation dynamics (SPD). Figure 1 illustrates the components and their interrelationships, providing a comprehensive picture of the framework elements.

- **SO**: This component focuses on simulating the actual operations within the InSym system. It leverages event-based logic similar to DES to model continuous processes, particularly employing DES-based fluid flow modelling for water resource analysis and optimisation.

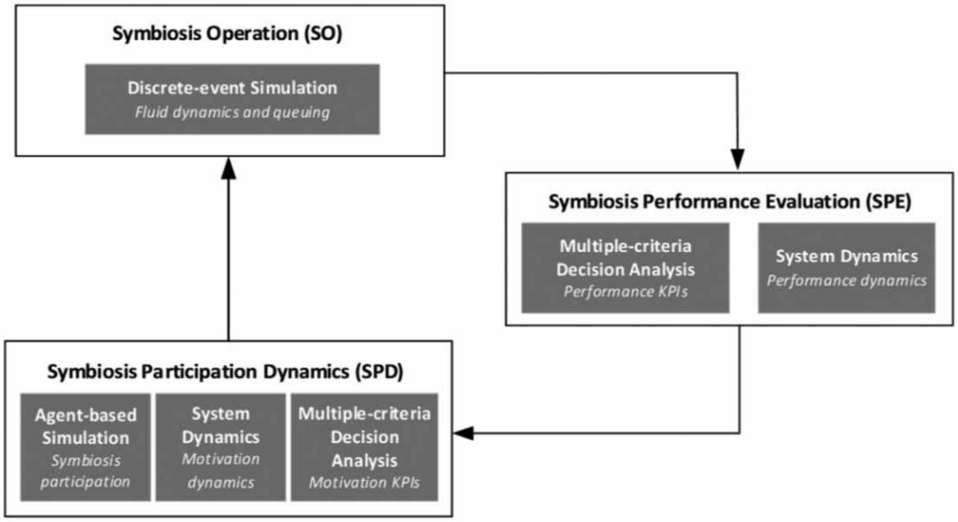
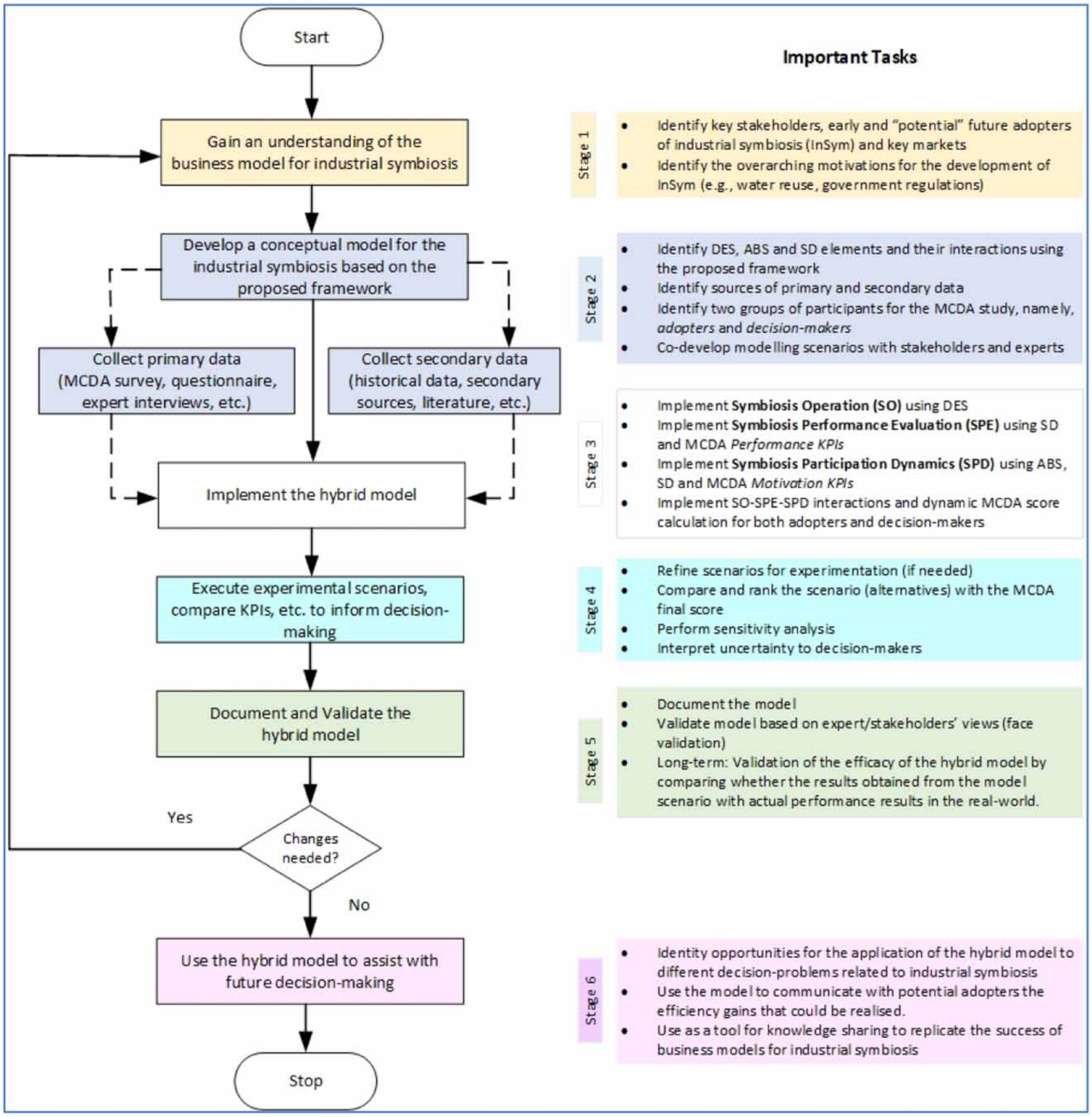


**Figure 1** | The relations between the components of the hybrid modelling framework.

- **SPE**: This component, inspired by MCDA, utilises these MCDA-derived KPIs in conjunction with SD to evaluate the overall performance of the InSym system.
- **SPD**: This component utilises a combination of MCDA, ABS, and SD to model the dynamic nature of business participation within the InSym network. ABS models participating businesses and shared resources (e.g., transport vehicles, water treatment facilities) as agents, allowing in-depth analysis of the InSym business model. SD calculates the motivational dynamics driving participation within the proposed framework. Finally, MCDA identifies key factors influencing a business entity's decision to join the system.

Our proposed hybrid modelling and simulation (Fakhimi & Mustafee 2024) framework empowers informed decision-making for potential adopters, current InSym users, and InSym facility operators by integrating diverse modelling techniques into a unified hybrid model. Figure 2 provides a comprehensive flowchart for implementing this framework using simulation software like AnyLogic. The figure includes a list of key tasks within each stage.



Stage 1
- Identify key stakeholders, early and "potential" future adopters of industrial symbiosis (InSym) and key markets
- Identify the overarching motivations for the development of InSym (e.g., water reuse, government regulations)

Stage 2
- Identify DES, ABS and SD elements and their interactions using the proposed framework
- Identify sources of primary and secondary data
- Identify two groups of participants for the MCDA study, namely, *adopters* and *decision-makers*
- Co-develop modelling scenarios with stakeholders and experts

Stage 3
- Implement **Symbiosis Operation (SO)** using DES
- Implement **Symbiosis Performance Evaluation (SPE)** using SD and MCDA *Performance KPIs*
- Implement **Symbiosis Participation Dynamics (SPD)** using ABS, SD and MCDA *Motivation KPIs*
- Implement SO-SPE-SPD interactions and dynamic MCDA score calculation for both adopters and decision-makers

Stage 4
- Refine scenarios for experimentation (if needed)
- Compare and rank the scenario (alternatives) with the MCDA final score
- Perform sensitivity analysis
- Interpret uncertainty to decision-makers

Stage 5
- Document the model
- Validate model based on expert/stakeholders' views (face validation)
- Long-term: Validation of the efficacy of the hybrid model by comparing whether the results obtained from the model scenario with actual performance results in the real-world.

Stage 6
- Identity opportunities for the application of the hybrid model to different decision-problems related to industrial symbiosis
- Use the model to communicate with potential adopters the efficiency gains that could be realised.
- Use as a tool for knowledge sharing to replicate the success of business models for industrial symbiosis

**Figure 2** | Flowchart to aid the implementation of the proposed framework.

- Stage 1 – **Understanding the business model**: Identify key stakeholders and their motivations for the proposed symbiosis. Define motivation KPIs (of SPD) and performance KPIs (of SPE) (as depicted in Figure 1).
- Stage 2 – **Conceptual modelling**: Develop a conceptual model considering primary and secondary data sources. Integrate DES, SD, and ABS elements based on the specific case study. Conduct MCDA analysis to determine weights and scores for motivation KPIs (of SPD) and performance KPIs (of SPE). Utilise expert opinions or literature values if survey responses are insufficient. Stakeholder co-development of the model and scenarios is optional but highly encouraged.
- Stage 3 – **Implementation of hybrid model**: Build the hybrid model following the SO, SPE, and SPD elements, incorporating the defined modelling techniques (as illustrated in Figure 1). This iterative process requires both the conceptual model and primary/secondary data.
- Stage 4 – **Develop scenarios for experimentation**: Outline and rank experimental scenarios based on dynamic MCDA final scores (of SPE) calculated during runtime. Stakeholder co-development is encouraged.
- Stage 5 – **Documentation and validation**: Utilise frameworks like STRESS to thoroughly document and validate the hybrid model's logic, inputs, and outputs, facilitating stakeholder feedback. Conduct long-term validation tests to compare model predictions with real-world InSym adopter behaviour and synergies over time, guiding model adjustments through a feedback loop.
- Stage 6 – **Explore opportunities for reusing the hybrid model**: Consider reusing the developed InSym hybrid model or its components for other industrial symbiosis contexts, maximising time and resource efficiency.

In Section 3, we will further explain the methodology of the modelling framework by demonstrating the implementation of its six stages in a real-case context. This will help readers understand the hybrid simulation method.

## 3. FRAMEWORK IMPLEMENTATION: THE ISRAELI OMW CASE STUDY

This section presents the implementation of the proposed framework for the Israeli OMW case study in the ULTIMATE project. This section discusses the development of the hybrid model through the six stages of the proposed framework (Figure 2 above).

### 3.1. Stage 1: understanding the business model

Olive mills have significant opportunities to extract additional value from their wastewater treatment processes. Reusing treated water can help alleviate local water shortages; extracting valuable compounds, such as antioxidants, offers the potential for additional revenue generation (valorisation of wastewater); biogas produced during OMW treatment can also generate revenue. These financial benefits can be better realised through InSym, which allows economies of scale and is advantageous in the reclamation of resources.

The olive mill case study provides a context for exploring InSym and transforming wastewater into a valuable resource. An Advanced Anaerobic Technology (AAT) is applied, proposed by a research partner of the ULTIMATE project, is an innovative solution for treating OMW before the municipal WWTP process. It is currently being tested using a pilot facility built at Karmiel WWTP by our project partner (*Karmiel* is the name of a town in northern Israel). This approach incorporates advanced wastewater treatment technology and extraction of value-added compounds (VACs), alongside biogas production, which can adapt to seasonal demand fluctuations, fostering InSym and mutual benefits for local olive mills and local authorities. The proposed approach is also suitable for a distributed collective WWTP system, which involves multiple symbiosis (collective) WWTPs serving smaller areas (only for treating OMW). As current practice still relies on field spray by tankers, and existing sewer networks cannot be used to transport OMW to the symbiosis WWTP, we proposed to use tankers to transport the wastewater to the symbiosis WWTP that is equipped with a storage reservoir, VAC extraction facility, and AAT treatment facility.

However, compared with the current field spray practice, the proposed collective WWTP is expected to cause additional costs to olive mills in transporting wastewater due to longer transport distances and better audit conditions. Besides, it also requires a higher service capacity of tanker transport to collect all wastewater (note that, in the case of field spray implementation, wastewater is not fully collected), as olive mills usually do not have a storage tank that can store wastewater for longer than a few days. The increased transport costs and the tanker service capacity will affect olive business owners' willingness to comply with the proposed collective treatment policy. The local government provides transport subsidies to aid the practice of field spray; thus, it is expected that similar subsidies may also be provided to the proposed collective treatment policy. However, in the long term, the subsidy may gradually decrease.

With limited historical data and experience in this new collective policy, investing in the proposed InSym WWTPs and transport subsidy becomes a decision challenge for local government, particularly since it involves interactive and dynamic factors, including transport distance (due to the fixed number and location of WWTPs), subsidy duration, the number of adopters, and tanker capacity.

A simulation-based decision support tool could thus help explore different scenarios and address some of these uncertainties, thereby aiding in developing robust InSym business models. Towards this, the application of the proposed hybrid framework enables simulation-based experimentation to identify opportunities for the InSym collective treatment among olive mills in Karmiel, serving as an analytical tool for the decision-maker (i.e., local government), addressing key questions related to investment strategies (e.g., the distribution level of collective WWTPs), optimal timing for investments (e.g., subsidy), operational efficiencies (e.g., tanker capacity), and factors influencing service profitability in the evolving collective strategy and InSym context.

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

Figure 3 presents the conceptual model. There are two main levels: the global level and the local level. The three main elements of the conceptual framework (SO, SPE, and SPD; refer to Figure 1) are arranged at the local and/or global levels. 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 66 olive mill businesses, tankers, and symbiosis WWTPs, are also arranged as agents locally or globally. The individual performance, mainly from the operation (simulated by individual DES model of olive mill agent), reflects on the system performance.

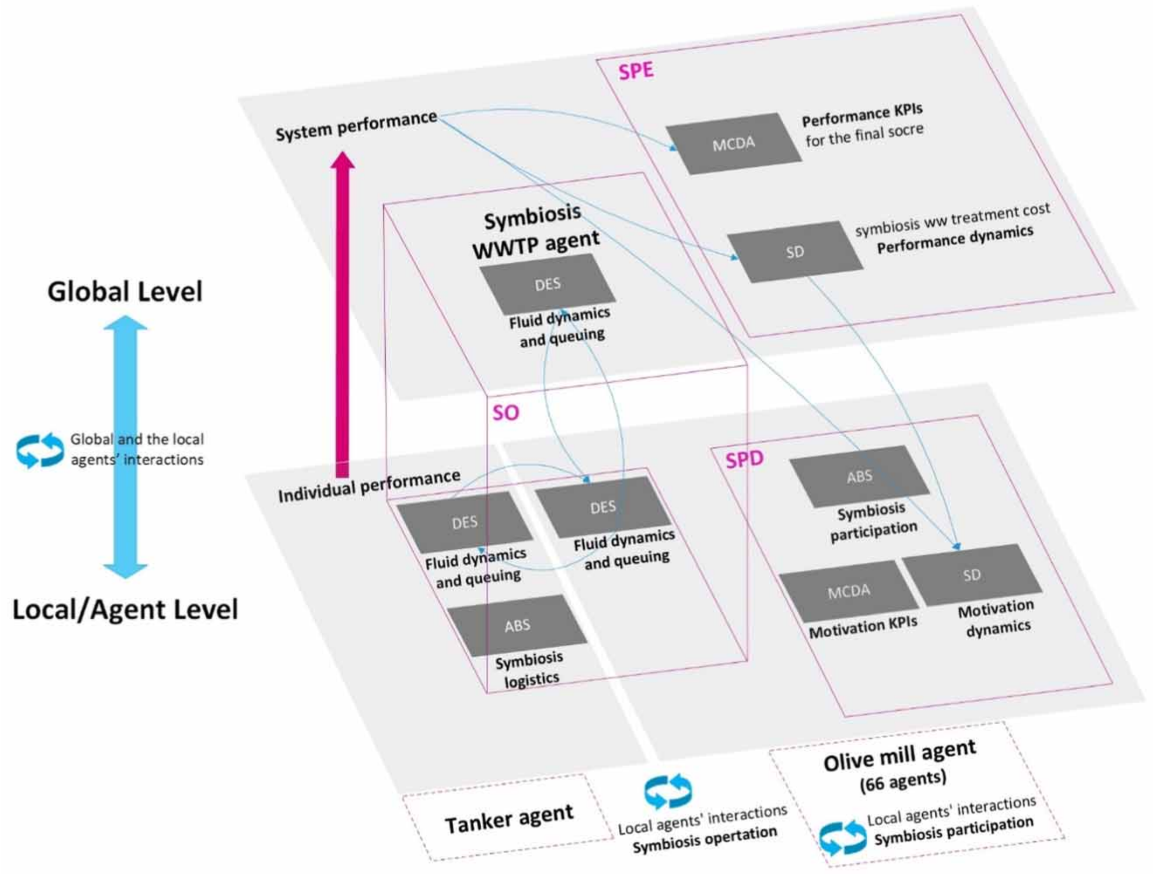


**Figure 3** | Conceptual model of the olive mill case study.

The system performance affects not only the annual final score of MCDA and symbiosis treatment cost rate (per $m^3$) of SD in SPE, but also conversely affects 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 performance KPIs are related to decision-making; hence, their weights are primary data from the decision-makers (Table 1, i.e., $WC_i$ and $SC_i$ of the final score Equation (2) in Section 3.3). In our case study, the data is acquired through consultation with the project partner responsible for implementing the pilot AAT treatment at Karmiel. The data is acquired through discussions at the Community of Practice (COP) and meetings with local authorities.

The SD module in SPE (global level, Figure 3) deals with the change in the wastewater treatment cost, as the unit cost varies with the treated volume. Some system performance indicators, such as the change in the number of adopters, also affect the motivation KPIs of the SD module of SPD in olive mill agents. The SD and MCDA modules for motivation KPIs (SPD in olive mill agents) will constantly update accordingly, resulting in an updated willingness level for the ABS module to assess its participation status. The motivation KPIs are listed in Table 2. The participation assessment goes yearly through the simulation period, leading to a yearly change in the number of adopters.

The DES module within the olive mill agents (Figure 3) simulates processes of wastewater discharge, either to the sewer or the tankers. The DES module in tanker agent deals with wastewater transport, whereas in symbiosis WWTP agent, the DES module deals with basic VAC extraction, wastewater treatment, and biogas production (i.e., processing of wastewater before it enters the municipal WWTP process). The agent interactions can occur among olive mill agents, and between tanker agents and olive mill agents. In this case study, the olive mill agents interact through the SD module of SPD, which is related to participation dynamics. The interaction between tanker agents and olive mill agents is not only wastewater collection and transport (through the DES modules of SO and the ABS module of SO), but also the tanker's collection performance that will conversely affect the willingness to adopt (through the SD module of SPD). The tanker's collection performance is primarily affected by transport capacities.

### 3.2.1. Primary and secondary data

The data used for the model are derived from multiple sources. Secondary data, estimated from the information provided by the local authority and the project partner experimenting with the pilot AAT treatment, was used to parameterise variables

**Table 1** | The performance KPIs and MCDA weighting for overall performance (symbiosis performance evaluation or SPE)

| Descriptions of KPI | Weight | Consideration dimension |
|---|---|---|
| Financial performance | 50 | Financial dimension, including the total benefits and costs |
| Adoption rate (of olive mills) | 30 | Business participation dimension. The percentage of olive mill businesses who are complying the collective policy |
| Tanker performance (collection rate) | 20 | The service capacity dimension to collect wastewater from olive mills |

**Table 2** | The motivation KPIs for symbiosis participation (symbiosis participation dynamics or SPD)

| Motivation KPIs | Aspects | Related Variables or Parameters |
|---|---|---|
| Financial burden | Operational; Financial | The volume of treated wastewater (global level) Transport cost (agent level) |
| Peer influence | Social | The number of adopters (global level) |
| Environment protection | Operational; Strategical | The number of adopters (global level) The volume of treated wastewater (global level) |
| Resource utilisation | Operational; Environmental | Treated rate (agent level) Treated rate- symbiosis (global level) |
| Operational efforts | Operational | None |
| Penalty avoidance | Legal | The number of adopters (global level) Treated rate (agent level) |

related to business and operational parameters of the olive mill and WWTP service, including OMW volume and financial parameters for symbiosis WWTP.

An MCDA survey was conducted to support the SPD element of the framework in addressing participation dynamics. We firstly identified the motivation KPIs that can represent the decision-making factors in adopting the collective treatment policy and the idea of InSym. The MCDA survey then was designed to elicit the weights and scores (i.e., $WC_i$ and $SC_i$ of the willingness level Equation (1) in Section 3.3) towards the six motivation KPIs. The six KPIs for the case study are as follows:

(1) **Penalty avoidance (PA)**: Motivation to adopt the collective treatment policy to avoid legal penalties.
(2) **Financial burden (FB)**: Motivation to reduce the FB caused by transporting wastewater to the disposal reservoir of symbiosis WWTP.
(3) **Resource utilisation (RU):** Motivation to enhance RU by increasing the reclamation of recycled water, VACs, and biogas from the symbiosis WWTP, as well as ensuring the continuous reclamation of recycled water from municipal WWTPs without operational failures.
(4) **Environment protection (EP):** Motivation to comply with the policy for EP.
(5) **Peer influence (PI)**: Motivation to adopt the policy due to the recommendation from other adopters or/and the number of adopters.
(6) **Operational efforts (OEs)**: The concerns of extra OE needed and disturbance caused by complying with the policy.

The KPIs and the SPD MCDA questionnaire design were validated by consulting olive mill professionals and our project partner (Supplementary material, Appendix A, MCDA survey). Our survey aligned with the framework 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 participating in InSym solutions differ among stakeholders.

To capture data (motivation KPIs) for the framework's SPD element, we conducted the MCDA survey in 2023. The survey targeted 66 olive mill companies who were potential adopters of InSym. However, due to the 2023 Gaza conflict, we could not obtain sufficient data despite several attempts. Thus, based on discussions with stakeholders and consultation with olive mill professionals, we decided to use the limited primary data related to participation and assigned them to 66 olive mill companies. We acknowledge this as a limitation of the study.

### 3.3. Stage 3: implementation of hybrid model

The hybrid model utilises three main types of agents: symbiosis WWTP, olive mill business, and tanker agents.

- Symbiosis WWTP agent: There are multiple instances of the WWTP agent type. The number of WWTPs is dynamic in the hybrid modelling, which depends on the government's investment scenarios, e.g., the distribution level of collective WWTPs. The agent includes a DES module that performs the symbiosis (i.e., collective treatment) comprising wastewater treatment, VAC extraction, and biogas production.
- Olive mill business agents: There are 66 olive mill agents (one for each company located within a 20-km zone centred on the existing municipal WWTP as the study area). For each olive mill instance, there is also a DES module that models the individual wastewater discharging process for the business operation. An AnyLogic database is linked to the olive mill agents and records data for individual parameters. The parameters are used to initialise the agents, e.g., location in latitude and longitude.
- Tanker agent type: The success and sustainability of the proposed collective treatment solution rely on adequate transport service to collect and transport the wastewater to the symbiosis WWTP. As it is difficult to estimate the service capacity at this stage, we still seek to develop the hybrid model to analyse how the tanker capacity affects the operational scenarios tested. We will test the performance of a fleet of 66 tankers/agents, with a baseline scenario guaranteeing full-service capacity for wastewater collection using only 66 large tankers (17 $m^3$ each). We will then assess the impact of incorporating a variable proportion of smaller tankers (3 $m^3$) into the total fleet of 66. These two sizes are currently applied in local field spray practice.

The implementation of the model consists of four main tasks (of Figure 3):

#### 3.3.1. Implementation of SO using DES:

Since the SO spans three distinct settings – two at the local level and one at the global level – DES, primarily used for operational processes, is applied across all three. For the case study, the local level includes DES for each olive mill agent

(Figure 4(a)) and DES for the tanker agents (Figure 4(b)). The symbiosis WWTP agents operate at the global level (Figure 4(c)). These three DES modules utilise the Fluid library of AnyLogic (AnyLogic 2023), which employs tanks, pipes, and valves to model processes such as wastewater transport, treatment, VAC extraction, and biogas production.

The model applies the same DES process to each olive mill business (i.e., DES module, Figure 4(a)), while allowing for variability in performance. For instance, businesses produce varying amounts of wastewater. Those producing more wastewater require more frequent tanker collections to manage all the wastewater produced. When tanker service is unavailable, wastewater from non-adopters or adopters will be discharged untreated into the sewer system (potentially leading to failure of municipal WWTP).

Figure 4(c) illustrates the wastewater treatment, VAC extraction process, and biogas production, followed by the transport process in Figure 4(b).

### 3.3.2. Implementation of SPD using ABS, SD, and MCDA (motivation KPIs):

Figure 5(a) shows that the hybrid model calculates SPD through the interactions of the two SD modules within the model. While SPD operates within each olive mill agent to determine its participation status (i.e., SPD is integrated into each olive mill agent at the local level), it also interacts with the SD module of SPE to influence the global symbiosis treatment cost (part ofSPE). The SD module (of SPD) of the olive mill agent includes five of the six motivation KPIs from the MCDA KPIs. The number of motivation KPIs utilising the SD module varies depending on whether the change in an individual KPI involves time and/or complex causal relationships. The dynamic evolution of these KPIs, combined with the MCDA weights obtained

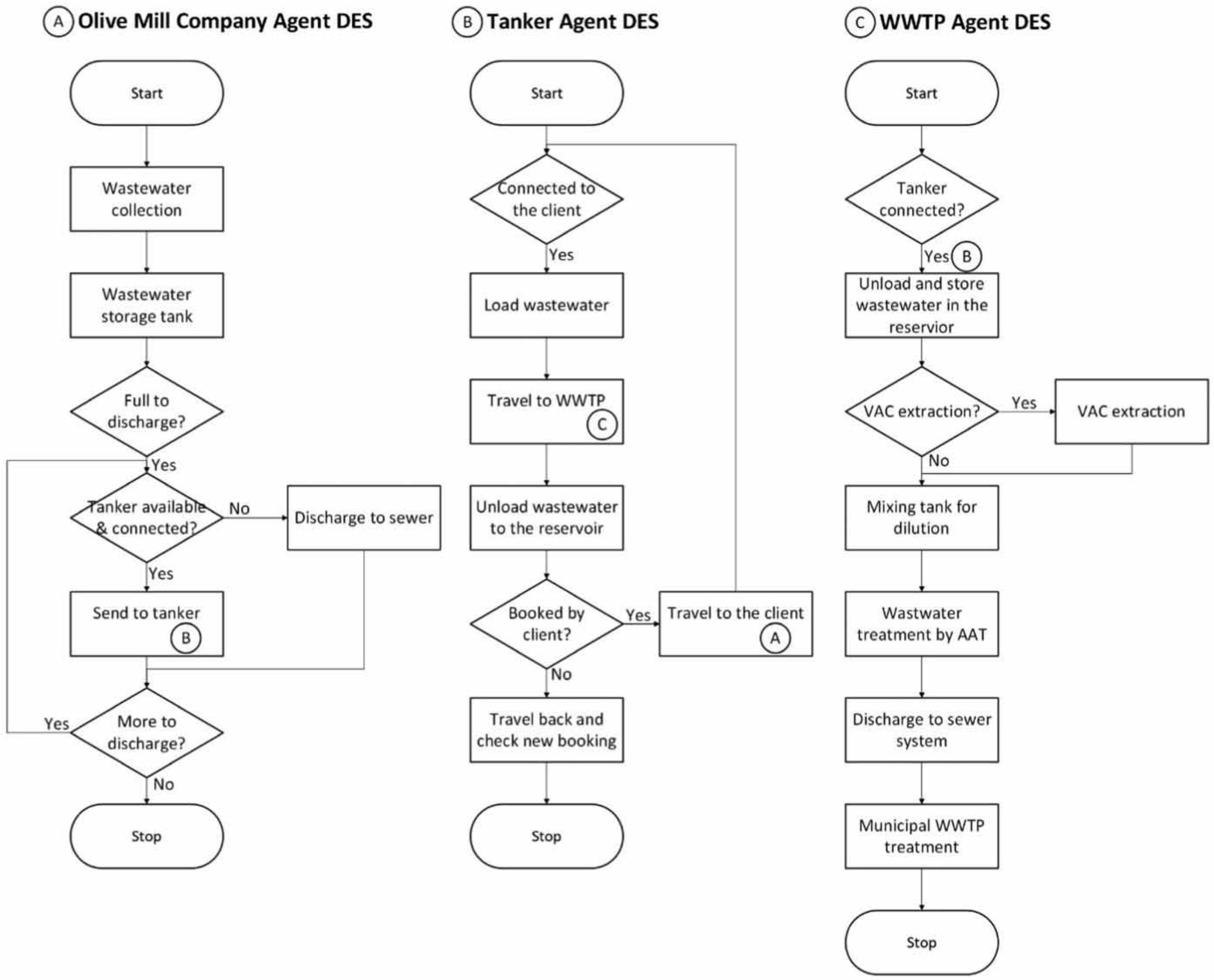


**Figure 4** | DES module for water utilisation process in the local olive mill agent (a), local tanker agent (b), and global WWTP agent (c).

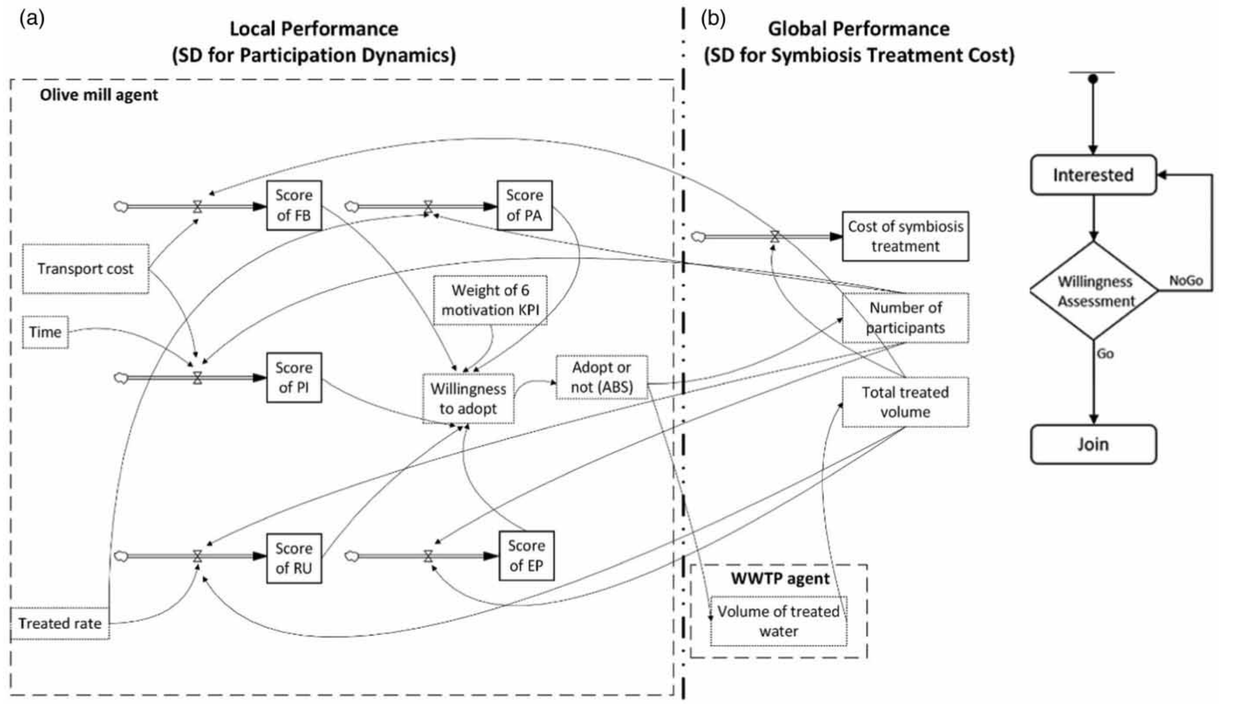


**Figure 5** | (a) SD module at the local level (olive mill agent) and global/symbiosis level (WWTP agent). (b) The adoption status of the ABM module in the olive mill agent varies based on the result of the agent's SD module.

from the questionnaire survey, affects the 'willingness to adopt' (i.e., willingness to comply with the collective treatment policy). The willingness level can be calculated using the following Equation (1):

$$\mathrm{WL} = \sum_{i=1}^{i=6} \mathrm{WC}i * \mathrm{SC}i\ /6 \tag{1}$$

Here, WL is the willingness level between 0 and 1 (100%), $\mathrm{WC}_1$, $\mathrm{WC}_2$, $\mathrm{WC}_3$, … $\mathrm{WC}_6$ are the weight of six performance criteria (motivation KPIs) between 0 and 1 (100%), $\mathrm{SC}_1$, $\mathrm{SC}_2$, $\mathrm{SC}_3$, … $\mathrm{SC}_6$ are the score of six motivation KPI between 1 and 5 (dynamically performed by the SD module) that is designed as a scale for facilitating initial motivation KPI scoring in the questionnaire survey (please see Section 3.2 regarding data collection).

The 'willingness to adopt' is then handled by an ABS module within the olive mill agent. This module uses a threshold (e.g., 3) to determine the participation status: whether to join/adopt (if $\mathrm{WL} >= 3$) or not (if $\mathrm{WL} < 3$), as shown in Figure 5(b). If an olive mill agent decides to join, it sends a request to book the tanker service, increasing the total volume of wastewater treated by the symbiosis WWTP agent at the global level. This change in volume subsequently affects the symbiosis treatment cost via the global SD module (of SPE), which in turn influences the SD module of participation dynamics (SPD).

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

The SPE encompasses two types of performance: the performance of the symbiosis WWTP and the performance of individual olive mill companies. As depicted on the right side of Figure 5(a), the modelling framework ensures that individual businesses and symbiosis operations remain healthy and mutually beneficial. If either aspect fails, the symbiosis and the businesses involved cannot sustain themselves.

The performance of the symbiosis WWTP is evaluated using indicators derived from its own DES module. Changes in symbiosis performance dynamically affect global-level performance-related values. For example, an increased volume of treated wastewater can lead to a lower treatment cost. This dynamic is managed by an SD module (SPE) at the global level.

Conversely, the performance of individual olive mill businesses is assessed through their respective DES modules and presented via global statistics indicators. Since performance indicators from the global and local levels may not follow the same trends in different simulation scenarios, a single indicator is required to rank these scenarios. Additionally, decision-making stakeholders often have divergent views on what constitutes good performance for the symbiosis. To address this, the MCDA approach is applied at the global level, using performance KPIs as MCDA scores and weights derived from a survey of decision-makers (e.g., local authorities in this case study). A final score is calculated for ranking purposes.

In this case study, the decision-makers represent the symbiosis WWTPs, but in other applications of the modelling framework, the decision-makers could primarily consist of symbiosis adopters. The composition of decision-making stakeholders can range from a simple group of potential adopter businesses to a more complex group, including potential adopters, local authorities, treatment providers, and other investors. It is important to note that even within a group of decision-makers who are also adopters, individuals may have differing views on the interests of the symbiosis versus their own business interests. Therefore, a separate set of KPIs (performance KPIs) is needed, distinct from the motivation KPIs.

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

$$\mathrm{SF} = \sum_{T=1}^{T=j} \mathrm{WC}i,\, Tj * \mathrm{SC}i,\, Tj\ /100 \tag{2}$$

where SF is the final score of the scenario experimented, $\mathrm{WC}_1$, $\mathrm{WC}_2$, $\mathrm{WC}_3$, … $\mathrm{WC}_n$ are the weight of $n$ performance criteria (performance KPIs) between 0 and 100, $\mathrm{SC}_1$, $\mathrm{SC}_2$, $\mathrm{SC}_3$, … $\mathrm{SC}_n$ 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 (please see Section 3.2 the paragraph prior to Table 1).

However, the modelling framework 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 the pursuit of different priorities at different stages, e.g., statutory priority, such as the introduction of zero-emission at certain year, and market share expansion at a later stage. However, we only apply a fixed weighting in this case study.

### 3.3.4. Implementation of SO–SPE–SPD interactions

The interactions between SO, SPE, and SPD are the core features designed for the modelling framework, reflecting the crucial aspects of real-world InSym: operation, performance, and participation dynamics. Each element also facilitates interactions between local and global levels through different combinations of agents, ABS, DES, SD, and MCDA modules, as outlined in the implementation stages.

As shown in Figure 5 and Figure 6(a), these interactions include:

- The interaction between olive mill agents at the local level and symbiosis WWTP agents at the global level.
- The interaction between the DES of olive mills at the local level and the DES of tanker agents at the local level.
- The interaction between SD modules within local olive mill agents and SD modules at the global level.
- The application of participation MCDA within local olive mill agents and performance MCDA at the global level.
- The modelling framework addresses the complexity of InSym by comprehensively performing reciprocal and synergistic relations between individual businesses and the symbiotic system (e.g., operation, facility, business model, and even market).

We applied the modelling framework to build a hybrid model using the AnyLogic platform (version 8.7.9). The simulation period spans 20 years, from January 1, 2023, to December 31, 2042. The simulation procedure and the interactions among SO, SPE, and SPD operate on an annual loop basis until the end of the simulation period. After manually setting up parameters for the tested scenario and the weights of MCDA KPIs for SPE (as mentioned in Section 3.2 Table 1), the simulation of InSym operation (SO) begins with the first year.

At the end of each year, the KPIs for SPE are updated, simultaneously affecting the evolution of the SPD module, while continuing the SO for the following year. At the start of each year, individual businesses can change their participation status, such as shifting from potential adopters (not adopting the collective treatment policy) to symbiosis adopters (adopting

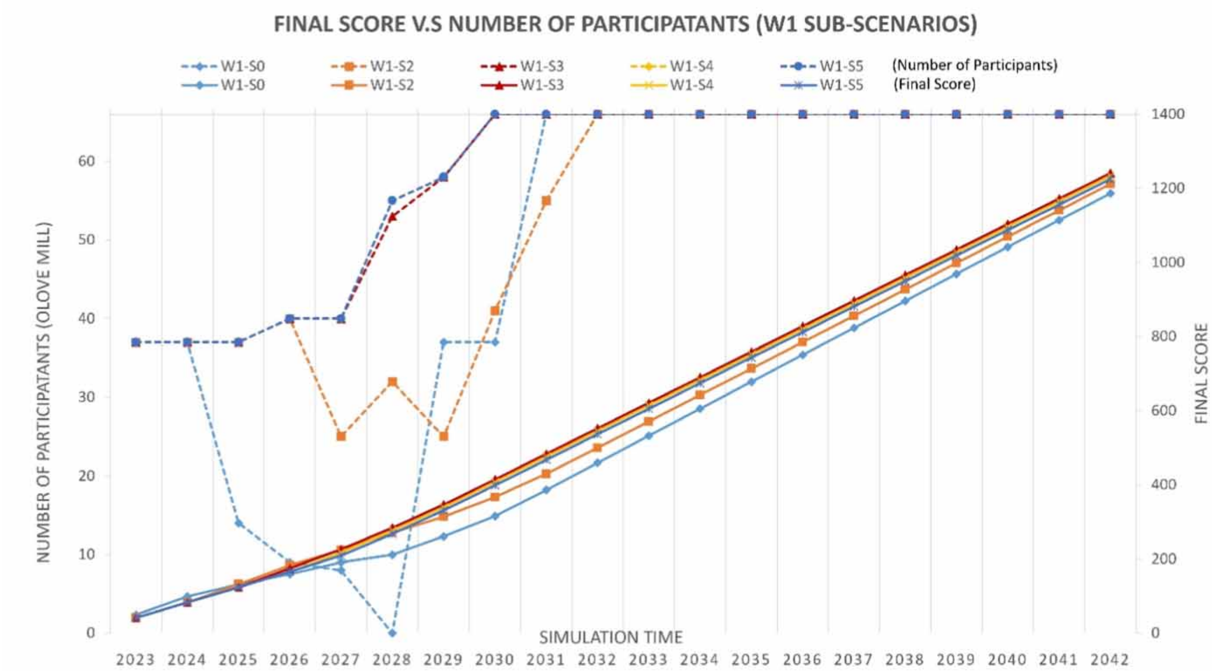


**Figure 6** | Final score comparison among five W1 sub-scenarios.

the proposed policy). This change is guided by the SPD module, influenced by annual changes in SPE and any changes in SO at the individual agent level during the previous year. Additionally, criteria weighting for performance MCDA (SPE) can be adjusted at the start of each year based on changes in annual performance (SPE) or other conditions specific to the InSym context, such as different priorities planned for different periods. However, we only apply a fixed weighting in this case study.

### 3.4. Stage 4: scenarios for experimentation

The primary focus of the scenarios for experimentation is to evaluate the performance of symbiosis under different operational conditions from the local authority's perspective. Towards this, two sets of scenarios, each comprising several sub-scenarios, are tested (Table 3).

The first scenario analyses different investment patterns, including subsidy duration and the number of symbiosis WWTPs. The scenario group consists of two main scenario types: permutations from two factors of operational conditions. One factor is to explore whether to apply centralised or distributed symbiosis WWTPs (i.e., the number of symbiosis WWTPs), which affects the transportation distance and the costs; the latter is a concern for the olive mill businesses and determines whether or not they comply with the proposed policy.

The second factor is to test the duration of transport subsidies to aid the practice of field spray. Due to limited government funds for such subsidies, initial compliance is expected to be strongly encouraged, especially in the early stages before monitoring and legal enforcement become fully effective. Thus, to take into account the local government's potential financial capacity for subsidies for a period of five years only, we capped the subsidies at five years in sub-scenarios related to the first set of scenarios.

As for the second set of scenarios, transport capacity is the main factor to be tested as it is highly uncertain and dynamically affects the willingness of compliance and financial performance. Although we can hardly estimate the transport service capacity at this stage, we still want to address the significance and dynamics of this critical factor through hybrid modelling so that the decision-maker (the local government) will consider it in its planning.

### 3.5. Stage 5: documentation and validation

We presented the model to various stakeholders through individual meetings, facilitating a comprehensive validation process. Additionally, expert feedback was actively sought to guide further model development and refinement through iterative

**Table 3** | Thirteen scenarios for experimentation

| Scenario name | Description | Note |
|---|---|---|
| Set 1 | To identify the best subsidy scenario from the W1 group (1 centralised symbiosis WWTP) and W4 group (4 distributed symbiosis WWTPs) | W: WWTP S: Subsidy Year |
| W1-S0 | One centralised WWTP, 0-year subsidy | WWTP A, which is the existing WWTP |
| W1-S2 | One centralised WWTP, 2-year subsidy | |
| W1-S3 | One centralised WWTP, 3-year subsidy | Best sub-scenario |
| W1-S4 | One centralised WWTP, 4-year subsidy | |
| W1-S5 | One centralised WWTP, 5-year subsidy | |
| W4-S0 | Four distributed WWTPs, 0-year subsidy | WWTP B, C, D, E |
| W4-S2 | Four distributed WWTPs, 2-year subsidy | |
| W4-S3 | Four distributed WWTPs, 3-year subsidy | Best sub-scenario |
| W4-S4 | Four distributed WWTPs, 4-year subsidy | |
| W4-S5 | Four distributed WWTPs, 5-year subsidy | |
| Set 2 | Based on the best scenario from Set 1, to test different tanker capacities with W4-S3 (best) scenario | |
| W4-S3 (L:66) | Baseline for Set 1 and 2, with 66 large tankers | 66 large tankers to guarantee full collection |
| W4-S3 (L:22, S:44) | 22 large tankers & 44 small tankers | Still 66 tankers in total |
| W4-S3 (S:66) | 66 small tankers | Still 66 tankers in total |

improvements. Documentation is in the form of deliverables to the European Commission and research papers. We have also used the *Strengthening the Reporting of Empirical Simulation Studies (STRESS)* guidelines (Monks *et al.* 2019) to document the model. In future, we will also perform extended validation tests to assess how well the model's predictions align with the actual behaviours and interactions of InSym adopters over time. The insights gained can be used to refine the model through an iterative feedback process, ensuring its accuracy and adaptability.

### 3.6. Stage 6: explore opportunities for reusing the hybrid model

The ULTIMATE project includes three InSym case studies. Future work will investigate the potential for reusing components of the current model within other case studies, thereby saving time and maximising the value of the existing code base of the model.

## 4. RESULTS AND DISCUSSION

As a successful InSym relies on long-term commitment of participating industries and a financially viable model, likewise, the proposed collective treatment policy requires these two criteria to succeed. However, they are likely to be affected by many factors, which jointly interact to form various scenarios. Therefore, we conducted a 20-year experiment (2023–2042) to capture diverse scenarios, ensuring it is long enough to achieve full participation from all 66 olive mill businesses at least once for all scenarios.

Table 4 (Appendix B) presents the simulation results for 13 chosen scenarios, including the weightings used for the final score in the performance MCDA (SPE, refer to Table 1). It is important to note that while the model allows for testing various MCDA weightings throughout the simulation, we used a single fixed weighting chosen by the local authority, the case study's decision-maker, to best reflect their priorities.

The model uses a final score as the primary performance indicator for comparing different scenarios. This score is derived from three contributing factors: *financial performance* (criterion #1), the *adoption rate* of the 66 olive mills (criterion #2), and *tanker performance* (collection rate, criterion #3) – all detailed in Table 1. Since these criteria are interconnected, we designed two sets of scenario experiments to understand how critical factors like the number of WWTPs (affecting transport distance), transport cost subsidy, and tanker capacity affect the overall effectiveness of collective OMW treatment. The first set disregards the impact of criterion #3 by fixing tanker performance at full capacity (100% collection rate) to establish a baseline. The second set will then explore scenarios with varying tanker capacities.

### 4.1. Set 1 – experiments to identify the best subsidy scenario from the W1 group (1 centralised WWTP) and W4 group (4 distributed WWTPs)

Set 1 compares two main scenario types: **W** (number of WWTPs) and **S** (subsidy duration), to identify the most advantageous policy regarding subsidy length. We analyse ten **WS** scenarios categorised into two groups based on the number of WWTPs. The number of WWTPs (W) directly affects transport distance, which is a critical factor. **W1** scenarios involve only one advanced WWTP treating OMW before entering the existing municipal system (centralised model). **W4** scenarios utilise four distributed WWTPs with advanced treatment facilities, resulting in shorter transport distances.

Figure 6 illustrates the overall performance (final score) for the W1 group scenarios. **W1-S3** (three-year subsidy) consistently leads in score across most years. While W1-S3 performs slightly lower in participant numbers than **W1-S4** and **W1-S5** (these lines overlap in Figure 6), it significantly outperforms **W1-S0** and **W1-S2**. This suggests that a three-year subsidy effectively encourages businesses to participate in the collective treatment plan, preventing the loss of adopters. Extending the subsidy beyond three years does not significantly improve *participation* (criterion #2) or *financial performance* (criterion #1). Figure 7 shows that longer subsidies (four and five years) lead to worse financial performance due to the increased subsidy burden.

The W4 group, utilising four distributed WWTPs, also exhibits a trend favouring a three-year subsidy (**W4-S3**) – refer to Figure 8. Like the W1 group, **W4-S4** and **W4-S5** (overlapping lines in Figure 8) show slightly higher participation than **W4-S3**. However, W4-S3 still significantly outperforms scenarios without a subsidy (**W4-S0**) or with a two-year subsidy (**W4-S2**). This suggests, once again, that a three-year subsidy effectively encourages businesses to participate, preventing a loss of adopters.

As seen in Figures 6 and 8, comparing the W1 and W4 groups reveals interesting information. In scenarios with no subsidies or shorter subsidy periods (0 and 2 years), the loss of adopters in the W1 group (**W1-S0** and **W1-S2**) is more dramatic than in the W4 group (**W4-S0** and **W4-S2**). This indicates that when faced with longer transport distances due to fewer symbiosis WWTPs (resulting in higher transport costs), olive businesses are more likely to opt out of the programme

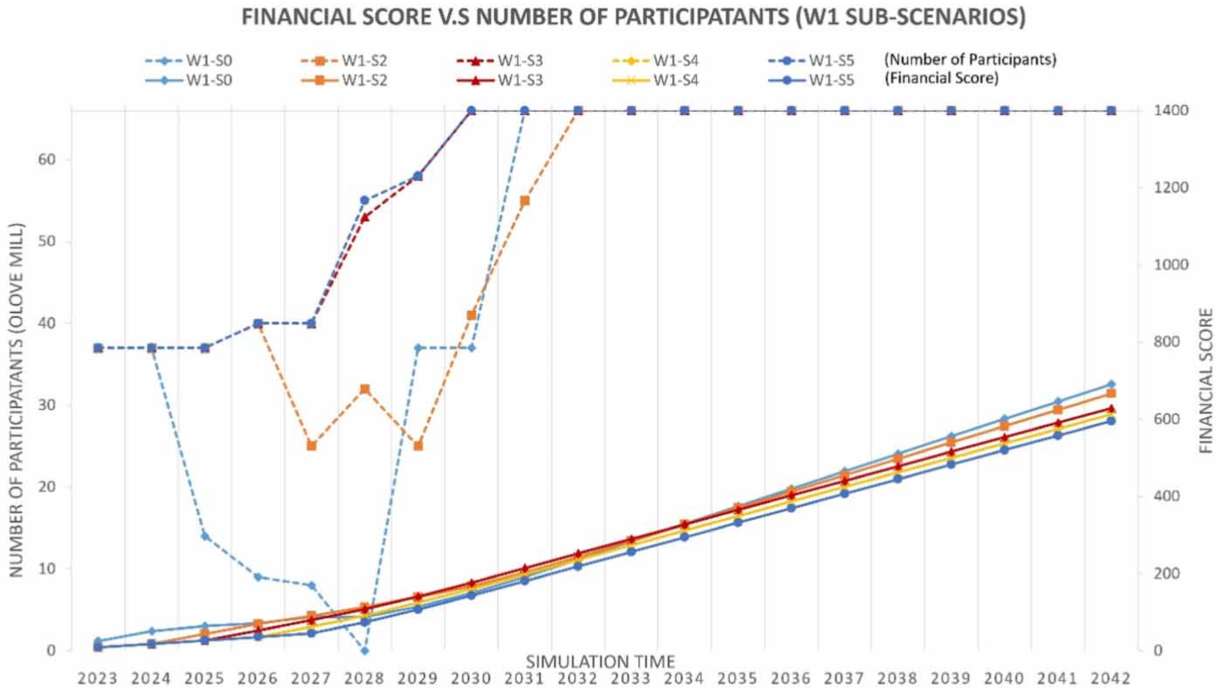


**Figure 7** | Financial score comparison among five W1 sub-scenarios.

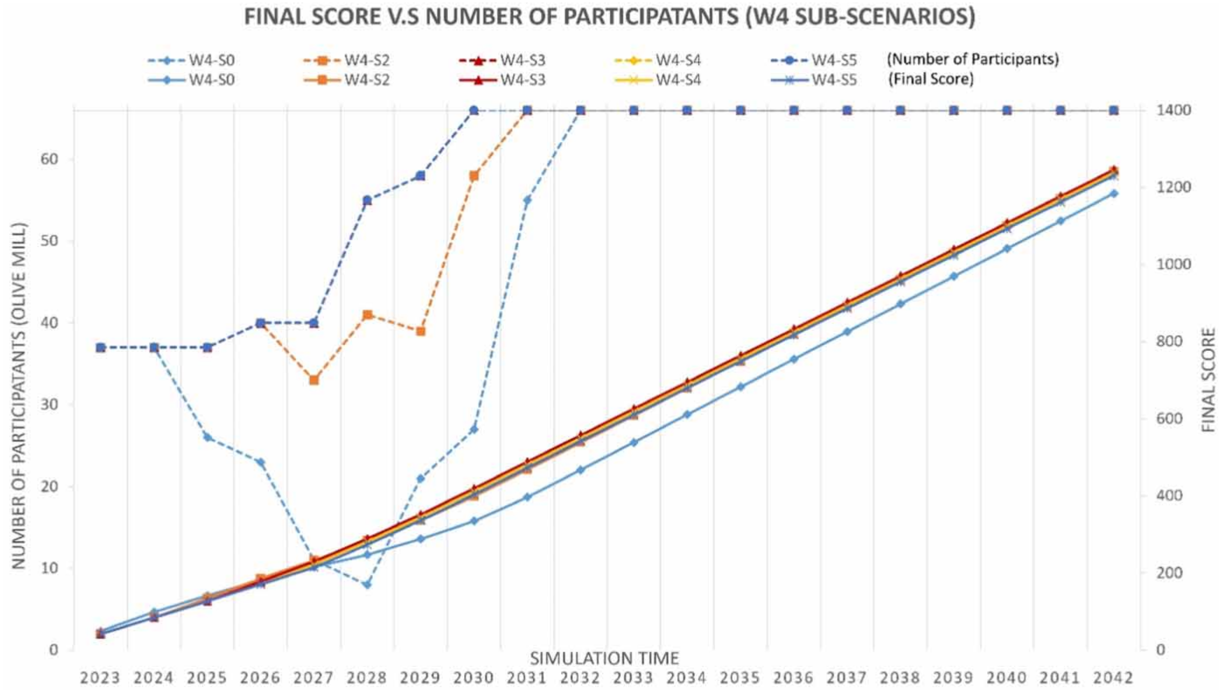


**Figure 8** | Final score comparison among five W4 sub-scenarios.

if the subsidy is too short. Thus, if the local authority decides not to offer a subsidy (W1-S0 vs. W4-S0), the four distributed WWTPs in the W4 scenario led to significantly better participation and a higher overall score. However, if a subsidy is provided, a duration of three years or more can effectively bridge the gap in participation caused by the difference in WWTP numbers (and, consequently, transport distances).

We chose to test W4 scenarios (four distributed WWTPs) in Set 1 for two main reasons:

- **Coverage:** The existing WWTP (A) covers an area of approximately 20 km, encompassing all 66 olive mill businesses in the study area. Four distributed WWTPs were strategically planned to better serve these businesses based on their locations.
- **Dilution requirements:** The proposed advanced OMW treatment process requires diluting OMW with municipal sewage at approximately 1:96 ratio. With fewer WWTPs (e.g., two or three), obtaining sufficient municipal sewage for dilution might be challenging. Investigating sewer network locations and sewage volume would be necessary to determine the optimal number of symbiosis WWTPs. However, obtaining this data was beyond the scope of this study.

Therefore, based on the available information and the dilution requirement, four symbiosis WWTPs (W4) were considered the most appropriate option for this scenario. It's important to note that while the results show minimal difference between W1 and W4 with a three-year subsidy, scenarios with two or three WWTPs could still be explored in Set 1 if practical sewer network conditions make them more advantageous.

### 4.2. Set 2: experiments to test varied tanker capacities based on the best 3-year subsidy policy from Set 1

Building on the optimal scenario W4-S3 identified in Set 1, we further explored how tanker capacity (criterion #3) affects the performance of the collective treatment policy. Estimating the exact tanker capacity required is challenging and beyond the scope of this study. Transitioning existing field spray tanker services to this new collective system requires comprehensive investigations and adjustments within the transport industry. However, the model effectively highlights the significance of tanker capacity for a successful and sustainable policy in practice.

Insufficient tanker capacity could lead to situations where even participating businesses experience illegal discharge due to missed collections. This would result in penalties for the business and potentially discourage them from *continuing participation* (criterion #2), ultimately impacting *financial performance* (criterion #1). Conversely, changes in the number of participating businesses (criterion #2) also affect the required *tanker capacity* (criterion #3). This two-way interaction is evident in Figure 9, although the relationship between participation and optimal tanker capacity is not always linear.

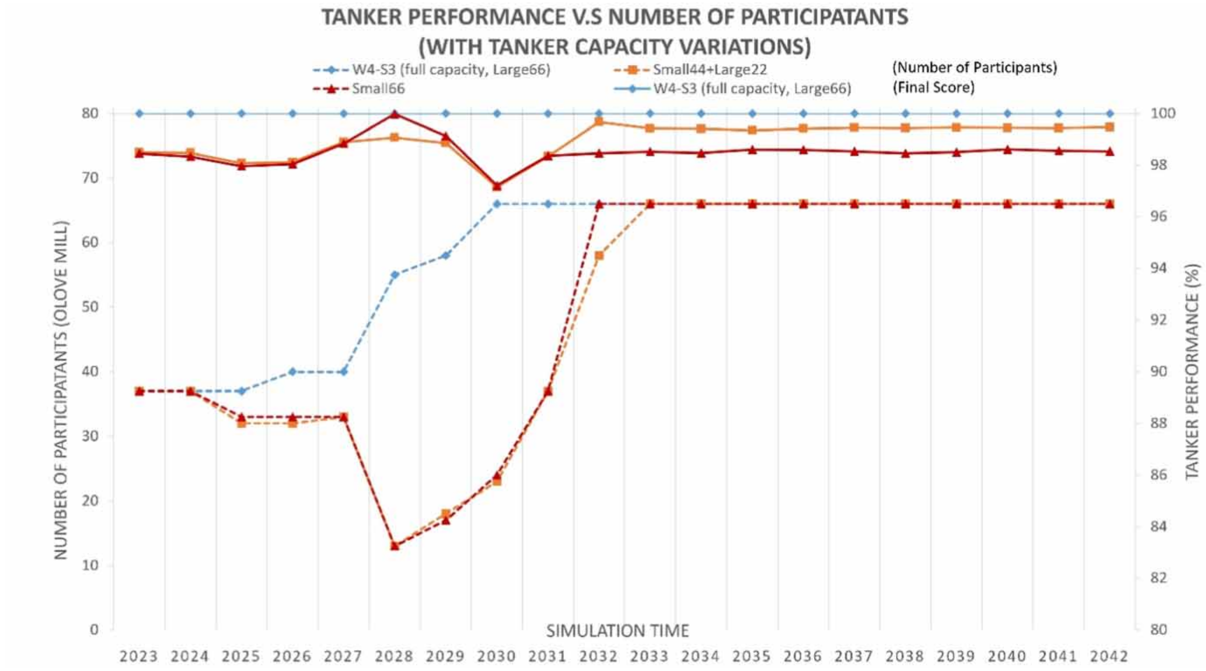


**Figure 9** | Mutual effect between tanker performance and the number of adopters.

As mentioned earlier, Set 1 utilised 66 large tankers (100% collection rate) as the baseline, considering the 66 olive mills in the study area. Finding the minimum number of large tankers through modelling would not be practical. In reality, the transport industry likely utilises a mix of tanker sizes, with more small tankers (3 $m^3$) and fewer large tankers (17 $m^3$). Set 2 investigates the impact of this mixed-fleet scenario.

Figure 10 demonstrates that even with the same total number of tankers (66), reducing the number of large tankers reduces participant numbers. This is because small tankers cannot satisfy the collection demands (i.e., the storage tank at olive mills

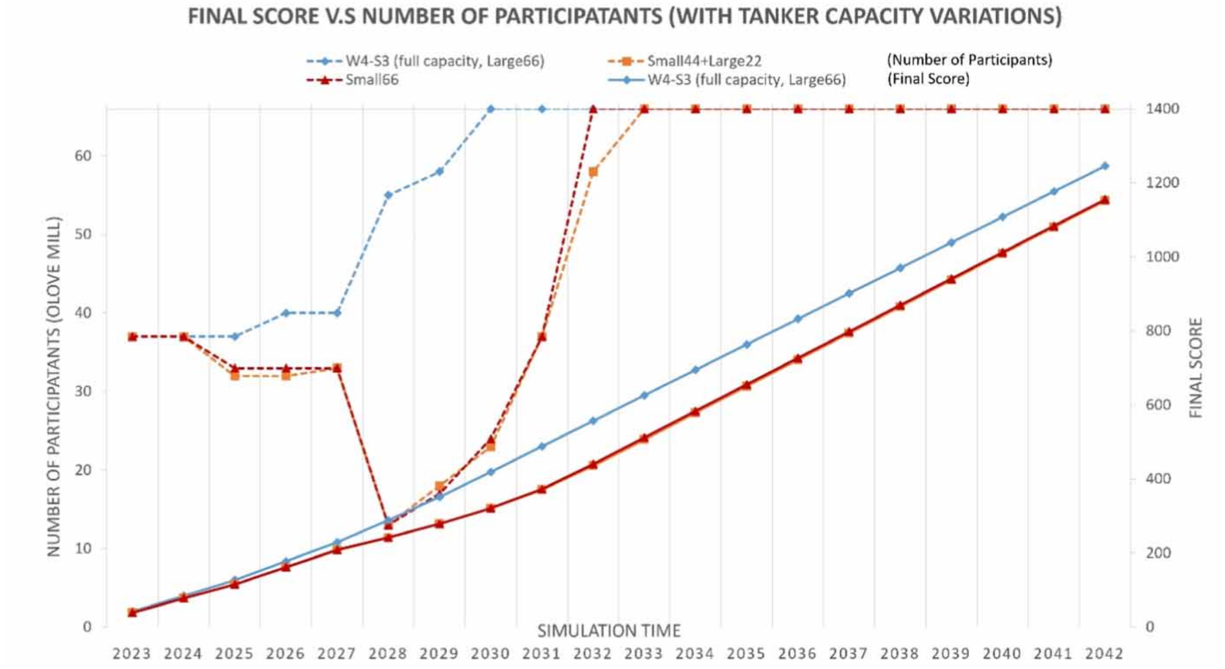


**Figure 10** | Final score comparison among three tanker capacity scenarios.

may be full before the next collection), leading to illegal discharge (failure of compliance) and negatively affecting olive mills' adoption towards the policy. This decline in participation has a more substantial negative impact on the overall score (final score) compared to the effects observed with varied subsidies or distributed WWTPs (Figures 6 and 8). The responsibility for the difficulty of implementing the policy (due to inadequate transport capacity) falls on the government (policy designers) and the transport industry, not the olive mills. However, the transport costs (including subsidies) are the responsibility of the olive mills.

Figure 11 delves into how a mix of tanker capacity (i.e., large and small tankers) affects individual olive mill businesses. It reveals a significant impact on the rate of illegal discharge and the duration of business participation (adoption period). Interestingly, the scenario with 44 small and 22 large tankers performs very similarly to that with only 66 small tankers. While the mix of 44 and 22 tankers better reflects the likely real-world distribution of tanker sizes within the transport industry, having only one-third of the service provided by large tankers is still insufficient to mitigate the negative consequences of inadequate capacity. Inadequate transport capacity, resulting in more uncollected wastewater under the policy, leads to an interlinked and interactive issue between illegal discharge and policy adoption. Increased illegal discharge due to uncollected wastewater may cause adopters to abandon the policy, while a decrease in the number of adopters can, in turn, lead to more illegal discharge.

Figure 12 explores how the illegal discharge rate (wastewater) for individual businesses is affected by tanker capacity. The blue dots represent the discharge rate with 66 large tankers (full capacity), while the grey and orange dots show the discharge rates with reduced tanker capacity scenarios.

The figure reveals two key trends:

- **Impact of production volume:** When tanker capacity is reduced, businesses with higher wastewater production (yellow dots) experience a more significant increase in discharge rates (difference between blue and grey/orange dots), suggesting larger olive mills are more susceptible to the negative effects of insufficient collection.
- **Impact of adoption timing:** Early adopters (the first 37 businesses who adopt at the beginning) generally show a smaller difference in discharge rates between full capacity (blue) and reduced capacity scenarios (grey/orange) compared to late adopters with similar production levels (yellow dots). This suggests that late adopters are more likely to abandon the programme (turn into non-adopters) if faced with insufficient transport capacity, resulting in a higher increase in their illegal discharge rates.

Concerning the legislation aspect, Doula *et al.* (2017) have proposed the following recommendations to address the challenges of OMW treatment that forms a dilemma between constraints/requirements and supports:

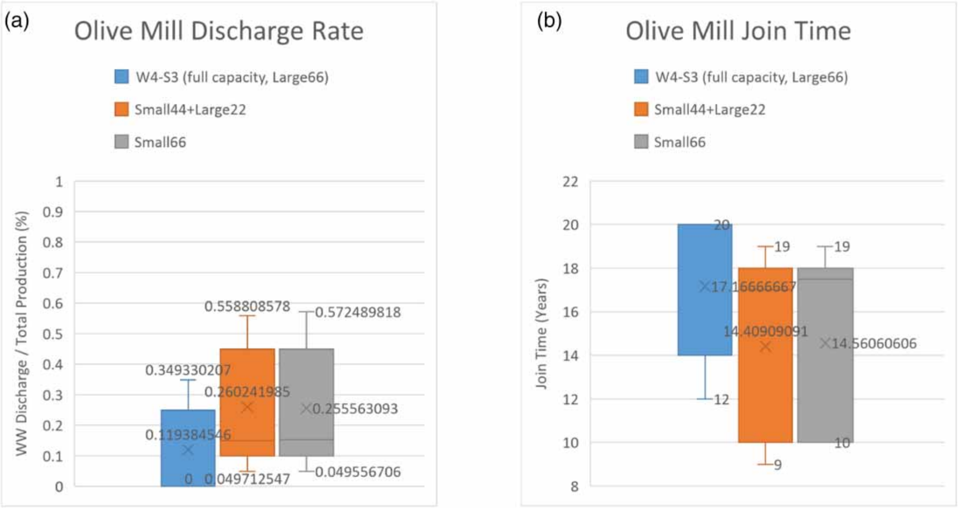


**Figure 11** | (a) The effects of varied tanker capacity on discharge rates and (b) the effects of varied tanker capacity adoption duration of the 66 olive businesses.

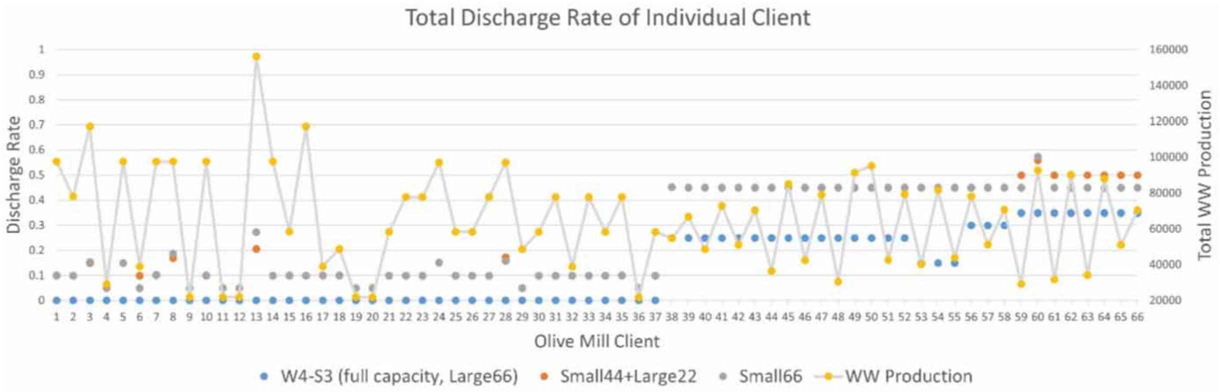


**Figure 12** | The effect of varied tanker capacity on the discharge rate of 66 olive businesses.

- Olive mills should be classified based on their production volume or waste generation. This allows for targeted regulations. High-capacity mills could implement on-site treatment systems, while smaller facilities could treat their waste collectively. This reduces individual costs and simplifies treatment.
- National laws could allow smaller mills to treat their wastewater alongside municipal waste. This leverages existing infrastructure for suitable cases.
- Laws should encourage initiatives for municipalities to build treatment facilities. Regional agreements between mill owners, municipalities, and other stakeholders could be facilitated as this promotes resource sharing and potentially creates a biomass source for energy production or other uses.
- Legislation should promote the establishment of collective treatment plants for OMW. This approach is particularly suitable for regions with high mill concentrations and facilitates efficient, large-scale treatment.

Through the above recommendations, we observe that our simulation findings for the proposed InSym solution/policy echo the paradigm underlying these recommendations. Moreover, our findings highlight critical factors that must be addressed to overcome the challenges of implementing the paradigm due to scattered locations of small-scale olive mills in relation to municipal centralised treatment system, seasonal wastewater discharge, and high organic loading: Initial financial support (e.g., government subsidy) is crucial and justified to alleviate the burden of OMW treatment and ensure participation/compliance. Operational logistics challenges, including the level of distributed treatment facilities, i.e., transport distance, as well as the dynamics from the third party, e.g., tanker capacity, could hinder compliance and potentially jeopardise the policy's success. These factors must be resolved alongside investments in advanced distributed treatment facilities under the proposed collective policy. CE will then be achieved to benefit the InSym system through the reclamation and reuse of resources.

As the implementation of the model involves several uncertain factors, such as business participation, transport capacity, and government subsidies, effectively addressing these uncertainties within the model is crucial. We suggest incorporating probabilistic or sensitivity analyses into the proposed framework to account for these uncertainties. For instance, the willingness to adopt (represented by the MCDA score) and its associated weights from the survey across individual businesses reflect a high degree of subjectivity, which introduces 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 and replicating each scenario according to the confidence interval of Monte Carlo analysis, we can observe how final scores are influenced by varying levels of uncertainty. This approach can provide valuable insights into the robustness and reliability of the model.

## 5. CONCLUSIONS

The proposed hybrid modelling framework for InSym decision-making and its implementation demonstrates the ability of the hybrid model to address critical factors related to the proposed collective treatment solution, including the distribution level of symbiosis WWTPs, WWTP site selection, subsidy strategy, transport capacity, and the potential for expansion of olive mills.

Those factors are dynamic and uncertain and are often interlinked. The modelling also reveals its advantageous application at strategic, tactical, and operational levels, which can serve as a practical planning tool for designing a distributed WWTP system.

Our detailed analysis of InSym WWTP in the context of case study offers valuable insights for decision-makers. These insights shed light on the performance and viability of various operational scenarios within the complex and dynamic context of collective policy related to InSym and wastewater treatment. This information equips local authorities with knowledge of conflicting considerations among stakeholders (i.e., adopter businesses vs. government), to make informed investment and strategic planning decisions for the proposed solution to achieve the common goal of sustainable operation of olive oil WWTP. It demonstrates its effectiveness in tackling unique decision-making challenges within the industrial symbiosis concept and its broad applicability involving distributed strategy (as mentioned in the Introduction section), which can be difficult to assess using traditional empirical methods or OR/simulation approaches that only apply one technique. Thus, our hybrid modelling study makes a novel contribution to the field of InSym decision-making by deploying a hybrid simulation that combines ABS, DES and SD simulation techniques with MCDA.

## ACKNOWLEDGEMENTS

The authors would like to thank the olive mill businesses and local authorities in the study area who were involved in the research. They provided valuable data and inputs for the modelling and symbiosis development. We thank our project partners, Prof Isam Sabbah and Dr Nedal Massalha at the Galilee Society, for providing relevant olive mill data and helping us conduct the MCDA (SPD) survey.

## FUNDING

The study is part of and funded by the ongoing EC Horizon 2020 ULTIMATE project (GA 869318), which aims to demonstrate circular economy solutions for the whole value chain and to strengthen synergies between industries and water utilities.

## AUTHOR CONTRIBUTIONS

O.C. contributed to conceptualisation, investigation, formal analysis, writing – original draft. N.M. contributed to funding acquisition, conceptualisation, investigation, methodology, writing – original draft and review, supervision. B.E. and M.K. contributed to investigation, writing – review. L.V. contributed to funding acquisition, project administration, writing – review. A.C. contributed to funding acquisition, investigation, writing – review, supervision. S.D. and D.S. supervised the study.

## DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

## REFERENCES

Amaral, C., Lucas, M. S., Coutinho, J., Crespí, A. L., Do Rosário Anjos, M. & Pais, C. (2008) Microbiological and physicochemical characterization of olive mill wastewaters from a continuous olive mill in Northeastern Portugal. *Bioresource Technology*, **99**, 7215-7223.

AnyLogic 2023 *AnyLogic Fluid Library* [Online]. Chicago: The AnyLogic Company. Available: https://www.anylogic.com/features/libraries/fluid-library/ [Accessed 23.02.2025 2025].

Aparisi, T. A. D. (2010) *Social Aspects of Industrial Symbiosis Networks*. London, UK: University College London.

Bae, K.-H., Mustafee, N., Lazarova-Molnar, S. & Zheng, L. (2022) Hybrid modeling of collaborative freight transportation planning using agent-based simulation, auction-based mechanisms, and optimization, *Simulation*, **98**, 753–771.

Belton, V. & Stewart, T. (2002) *Multiple Criteria Decision Analysis: an Integrated Approach*. Boston: Springer Science & Business Media.

Cecelja, F., Raafat, T., Trokanas, N., Innes, S., Smith, M., Yang, A., Zorgios, Y., Korkofygas, A. & Kokossis, A. (2015) e-Symbiosis: technology-enabled support for industrial symbiosis targeting small and medium enterprises and innovation, *Journal of Cleaner Production*, **98**, 336–352.

Chen, O., Mustafee, N., Evans, B., Khoury, M., Vamvakeridou-Lyroudia, L., Chen, A., Djordjević, S. & Savić, D. (2025) New business models for the circular economy of water: a hybrid simulation study of a mobile rental wastewater treatment service, *Journal of Cleaner Production*, 145041.

Chertow, M. R. (2000) Industrial symbiosis: literature and taxonomy, *Annual Review of Energy and the Environment*, **25**, 313–337.

Chertow, M. & Ehrenfeld, J. (2012) Organizing self-organizing systems: Toward a theory of industrial symbiosis, *Journal of Industrial Ecology*, **16**, 13–27.

Council, I. O. O. (2019) International Olive Oil Council.

Coyle, R. G. (1997) System dynamics modelling: a practical approach, *Journal of the Operational Research Society*, **48**, 544–544.

De Marco, E., Savarese, M., Paduano, A. & Sacchi, R. (2007) Characterization and fractionation of phenolic compounds extracted from olive oil mill wastewaters, *Food Chemistry*, **104**, 858–867.

Demartini, M., Bertani, F., Passano, G. & Tonelli, F. (2020) 'A Hybrid Simulation Model to Analyse and Assess Industrial Sustainability Business Models: the Use of Industrial Symbiosis', *International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing*. New York, NY, USA: Springer, pp. 473–482.

Demartini, M., Tonelli, F. & Govindan, K. (2022) An investigation into modelling approaches for industrial symbiosis: a literature review and research agenda, *Cleaner Logistics and Supply Chain*, **3**, 100020.

Doula, M. K., Moreno-Ortego, J. L., Tinivella, F., Inglezakis, V. J., Sarris, A. & Komnitsas, K. (2017) Olive mill waste: Recent advances for the sustainable development of olive oil industry. *Olive Mill Waste*, pp. 29–56.

Fakhimi, M. & Mustafee, N. (2024) *Hybrid Modeling and Simulation: Conceptualizations, Methods and Applications*. Cham, Switzerland: Springer Nature.

Fakhimi, M., Mustafee, N. & Stergioulas, L. K. (2016) An investigation into modeling and simulation approaches for sustainable operations management, *Simulation*, **92**, 907–919.

Ghali, M. R., Frayret, J.-M. & Ahabchane, C. (2017) Agent-based model of self-organized industrial symbiosis, *Journal of Cleaner Production*, **161**, 452–465.

Greco, S., Figueira, J. & Ehrgott, M. (2016) *Multiple Criteria Decision Analysis*. New York, NY, USA: Springer.

Hanifi, S. & El Hadrami, I. (2008) Phytotoxicity and fertilising potential of olive mill wastewaters for maize cultivation, *Agronomy for Sustainable Development*, **28**, 313–319.

Hanafi, F., Mountadar, M., Etahiri, S., Fekhaoui, M. & Assobhei, O. (2013) Biodegradation of toxic compounds in olive mill wastewater by a newly isolated potent strain: aspergillus Niger van tieghem, *Journal of Water Resource and Protection*, **5** (8), 7.

Herczeg, G., Akkerman, R. & Hauschild, M. Z. (2018) Supply chain collaboration in industrial symbiosis networks, *Journal of Cleaner Production*, **171**, 1058–1067.

IOC (2022) World Olive Oil Figures [Online]. IOC. Available: https://www.internationaloliveoil.org/the-world-of-olive-oil/ [Accessed 23.02.2025 2025].

Karnopp, D., Margolis, D. L. & Rosenberg, R. C. (1990) *System Dynamics*. New York, NY, USA: Wiley.

Lawal, M., Alwi, S. R. W., Manan, Z. A. & Ho, W. S. (2021) Industrial symbiosis tools – A review, *Journal of Cleaner Production*, **280**, 124327.

Leemis, L. M. & Park, S. K. (2006) *Discrete-event Simulation: A First Course*. Upper Saddle River, NJ, USA: Pearson Prentice Hall.

Macal, C. M. (2016) Everything you need to know about agent-based modelling and simulation, *Journal of Simulation*, **10**, 144–156.

Monks, T., Currie, C. S., Onggo, B. S., Robinson, S., Kunc, M. & Taylor, S. J. (2019) Strengthening the reporting of empirical simulation studies: introducing the STRESS guidelines, *Journal of Simulation*, **13**, 55–67.

Mustafee, N. & Katsaliaki, K. (2020) Classification of the existing knowledge base of OR/MS research and practice (1990–2019) using a proposed classification scheme, *Computers & Operations Research*, **118**, 104920.

Mustafee, N. & Fakhimi, M. (2024) Towards an Integrative Taxonomical Framework for Hybrid Simulation and Hybrid Modelling. In: Mustafee, N. & Fakhimi, M. (eds) *Hybrid Modeling and Simulation: Conceptualizations, Methods and Applications*. Cham, Switzerland: Springer.

Mustafee, N., Harper, A. & Onggo, B. S. (2020) 'Hybrid modelling and simulation (M&S): driving innovation in the theory and practice of M&S', *2020 Winter Simulation Conference (wsc)*. New York, NY, USA: IEEE, pp. 3140–3151.

North, M. J. & Macal, C. M. (2007) *Managing Business Complexity: Discovering Strategic Solutions with Agent-Based Modeling and Simulation*. New York, NY, USA: Oxford University Press.

Robinson, S. (2005) Discrete-event simulation: from the pioneers to the present, what next?, *Journal of the Operational Research Society*, **56**, 619–629.

Roig, A., Cayuela, M. L. & Sánchez-Monedero, M. (2006) An overview on olive mill wastes and their valorisation methods, *Waste Management*, **26**, 960–969.

Saadi, I., Laor, Y., Raviv, M. & Medina, S. (2007) Land spreading of olive mill wastewater: effects on soil microbial activity and potential phytotoxicity, *Chemosphere*, **66**, 75–83.

Siegel-Itzkovich, J. (2022) Environmental Protection Ministry Cracks Down on Olive-oil Press Waste. *Jerusalem Post*. Available: https://www.jpost.com/environment-and-climate-change/article-720562 [Accessed 23.02.2025].

Suzanne, É. (2021) *Production Planning for Industrial Symbiosis*. Lyon, France: University de Lyon.

Tamimi, N., Diehl, D., Njoum, M., Marei, A. & Schaumann, G. E. (2016) Effects of olive mill wastewater disposal on soil: interaction mechanisms during different seasons, *Journal of Hydrology and Hydromechanics*, **64**, 176–195.

Tosti, S., Accetta, C., Fabbricino, M., Sansovini, M. & Pontoni, L. (2013) Reforming of olive mill wastewater through a Pd-membrane reactor, *International Journal of Hydrogen Energy*, **38**, 10252–10259.

Yazıcı, E., Alakaş, H. M. & Eren, T. (2022) Analysis of operations research methods for decision problems in the industrial symbiosis: a literature review, *Environmental Science and Pollution Research*, **29**, 70658–70673.

Zulkepli, J. (2012) *A Theoretical Framework for Hybrid Simulation in Modelling Complex Patient Pathways*. PhD Theses, London, UK: Brunel University Brunel Business School.

First received 15 June 2024; accepted in revised form 20 January 2025. Available online 17 February 2025