AGENT-BASED MODELLING FOR ASSESSING THE ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY OF PSS

Veronica Arioli
Roberto Sala
Fabiana Pirola
Giuditta Pezzotta
Department of Production, Information and Management Engineering
University of Bergamo
Viale Marconi 5, 24044 Dalmine (BG), Italy
E-mail: veronica.arioli@unibg.it

KEYWORDS
Agent-Based Modelling, Product-Service System (PSS), Sustainability, Assessment.

ABSTRACT

Manufacturing companies are marketing business offerings to customers based on integrated product and service packages – Product-Service Systems (PSS) to remain competitive. While PSS offerings allow foreseeing economical benefits for customers and manufacturers, the sustainability assessment of PSS has not been extensively studied in the literature. While it is recognized that sustainability can be evaluated under the three dimensions of the Triple Bottom Line (TBL) – i.e., economic, environmental, and social – existing assessment methods usually concentrate on only one, neglecting the interplay with the other two. Thus, a more comprehensive method for evaluating PSS sustainability is required. This paper proposes the use of Agent-Based Modelling (ABM) as a method for jointly assessing the economic and environmental sustainability of PSS offerings. The social dimension is not considered since the research about the impacts of PSS offering is still at its beginning, as a consequence of the difficulties in finding common social sustainability indicators. The proposed approach overcomes the limitations of traditional sustainability assessment methods by allowing for dealing with the stochastic nature of reality, testing multiple scenarios, and understanding the impacts of PSS solutions on the economic and environmental sustainability in the long-term perspective.

INTRODUCTION

Manufacturing companies are turning to Product-Service Systems (PSS) to remain competitive in an ever-changing market. PSS refers to an integrated offering of products and services sold together as a single combination to customers (Mont 2002). This approach can provide customers with a more comprehensive solution in response to their needs generating additional revenue for manufacturers and fostering customer loyalty. PSS is described in the literature as a solution that may reduce environmental impact by closing material cycles through End-of-Life services, reducing consumption by offering alternative scenarios of product use, and offering integrated system solutions, mainly including maintenance and repairs activities, to improve operational efficiency (Resta et al. 2009). Indeed, maintenance service which represents one of the most important activities during a product lifecycle in today's industrial context, has a large potential in pursuit of sustainable goals (Franciosi et al. 2020).

While PSS offerings can benefit both customers and manufacturers in pursuing sustainability objectives, their sustainability assessment has yet to be extensively studied in the literature. Although different quantitative methods for sustainability assessment, such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Total Cost of Ownership (TCO), have been proposed to evaluate environmental and economic sustainability, they typically focus on only one dimension of the Triple Bottom Line (TBL) framework, neglecting the interplay between the other dimensions. As a result, a comprehensive method for the sustainability assessment of PSS is necessary to understand better the potential impacts of these offerings on the TBL is needed to find an assessment method that allows for evaluating economic and environmental sustainability comprehensively.

This paper seeks to address this research gap by analyzing different quantitative methods for jointly assessing the sustainability of PSS offerings in the economic and environmental dimensions. Specifically, the authors propose the use of Agent-Based Modelling (ABM) as a suitable method. ABM simulation is a method that involves modeling the behavior of individual agents in a virtual environment. By simulating the behaviour of these agents, it is possible to model the potential impacts of PSS offerings on the TBL, including their economic, and environmental sustainability dimensions. For the above-mentioned sustainability implications, this study mainly covers maintenance-related PSS offerings.
Overall, this paper highlights the need for a comprehensive method for assessing the sustainability of PSS offerings and proposes ABM simulation as a

Communications of the ECMS, Volume 37, Issue 1,
Proceedings, ©ECMS Enrico Vicario, Romeo Bandinelli,
Virginia Fani, Michele Mastroianni (Editors) 2023
ISBN: 978-3-937436-80-7/978-3-937436-79-1 (CD) ISSN 2522-2414

method. By adopting a holistic view of sustainability assessment, manufacturers can better understand the potential impacts of the PSS offerings on the TBL and make informed decisions supporting both business and sustainability objectives.

The following Section proposes an analysis of the literature on the existing quantitative methods for the sustainability assessment of PSS solutions, specifically the ones considering the economic and environmental dimensions of the TBL, and the selection of the most suitable for the paper's goal. Following, a detailed description of the proposed method is inserted (Simulation Model), as well as an illustrative example of its application. Then, the proposed method is discussed by highlighting its advantages and weaknesses, in the discussion section. Finally, the authors provide the conclusion and future developments of the work.

LITERATURE ANALYSIS

Considering understanding the sustainability of a PSS solution, the first step to identify a method for the sustainability assessment is examining the existing literature on methods for this purpose inside the PSS context. In the area of sustainability assessment, two main approaches exist – qualitative and quantitative. The search for methods was mainly focused on the analysis of the quantitative approaches capable of providing a quantitative assessment of the sustainability impacts. Qualitative approaches were excluded since they do not objectively evaluate the impacts. As shown in the following, assessment methods for sustainability in the PSS context are based mainly on one single sustainability indicator. Different authors focus on the environmental perspective and proposed LCA method for comparing traditional business models to PSS ones (Kjaer et al. 2018; Martin et al. 2021; Resta et al. 2009), mainly focusing on use-oriented PSS (Tukker 2004). The authors mentioned above agree on the fact that current LCA guidelines are product-focused and do not deal explicitly with the characteristics of PSS. Moreover, in the scientific literature, only a few case studies related to the application of LCA in the PSS context exist. (Lindahl et al. 2014; Vogtlander et al. 2002; Zhang et al. 2018) propose the combination of LCA and Life Cycle Costing (LCC) methods for calculating the environmental and economic costs of different PSS offerings. However, once again, few examples of real application of the combined methods are present in the literature thus suggesting that the success of the proposed method cannot be proved. Moreover, these approaches ignore the randomness of the product behaviour, especially in the use phase, which influences the service delivery (maintenance).

The literature also suggests simulation as sustainability assessment method. (Lee et al. 2012) proposes using System Dynamics simulation in combination with a TBL framework as method to provide a comprehensive assessment method including the three TBL dimensions. Nevertheless, this method is best suited for high-level strategic purposes. Moreover, it focuses on highlighting the interplay between traditional product sales and PSS sales and their influence on the TBL, thus neglecting the possibility of comparing different PSS solutions. Rondini et al. (2017) propose hybrid simulation including Discrete Event Simulation (DES) and Agent-Based Modelling suggesting that simulation techniques can potentially help to gather the dynamics of a PSS provision process while considering also the sustainability dimension. Differently from SD, DES is a process-centric approach and support medium and medium-low abstraction-level, while ABM, which is used to model agent's behaviours, can vary from very detailed to high level of abstraction, allowing for higher flexibility of modelling purposes (Weimer et al. 2016). Therefore, it was selected as suitable method in this study. According to the literature, simulation has certain advantages in representing complex systems, such as PSS, since it allows describing the behaviour uncertainties using stochastic variables. Moreover, it enables to model many scenarios and analyze the impact of the different configurations in the long-term period. Therefore, simulation is a powerful decision-supporting method (Chalal et al. 2015).

Based on this literature analysis, the authors decided to explore the potential of simulation, and in particular the ABM approach to simulate the behaviour of PSS solutions and, meanwhile, assess their economic and environmental impacts, with the ultimate goal of supporting decisions of the involved stakeholders toward sustainability.

SIMULATION MODEL

In this work, the authors propose an Agent-Based simulation model to evaluate the economic and environmental effects generated by various PSS solutions that companies provide to their clients. The economic and environmental effects of PSS are associated with a single customer since PSS adoption is correlated with customer preferences, which are now geared toward more sustainable solutions.

The PSS solutions involved in the analysis were presented as agents which undergo different states as their product-related services (e.g., distribution, installation, maintenance, etc.) proposed to the customer in combination with the product sale during the downstream stages of the product life cycle. Due to significant role in reducing the economic and environmental impacts of a product or system of maintenance (Franciosi et al. 2020), and the differences in the nature, costs, time needed and potential results of the various maintenance services (Trojan and Marçal 2017), the agents were divided into three types, corresponding to the main maintenance strategies (i.e., Corrective, Preventive, and Condition-Based agent type). By doing this, it was possible to deal with the stochasticity and time factors of the service delivery and thus evaluate more accurately the different economic and environmental impacts related to the specific PSS solutions.

The goal of the proposed method is to support the single customer selection of the PSS which is the most sustainable in economic and environmental terms. Thus, the three agent types were compared in a single view based on the sustainability outputs and the customer's perspective was chosen for their computations. The economic dimension was represented by the *Total Cost of Ownership* (TCO) since it allows overseeing not only the explicit costs of the acquisition of a product/service (e.g., the purchasing cost) but also the implicit ones (e.g., use, maintenance, and EoL costs) (Ellram 1993). LCC and TCO are two similar cost methodologies whose goal is to calculate the expenses of an acquired good or service on a long-term horizon. As a matter of fact, in literature, there is no clear separation between the two concepts, but some authors identify the difference in the fact that in LCC the focus is on the costs related to the product itself, while TCO focuses on the activities attributed to owning the product (Saccani et al. 2017), which can be more suitable for evaluating the economic impact of PSS solutions. While considering the environmental perspective, a single sustainability indicator, *Climate Change* (CC), whose measure is the kilogram of CO^2-equivalent emitted into the atmosphere, was used to reflect this dimension. It represents one of the environmental indicators used in the LCA method, which usually relies on multiple indicators. It was selected to have a single sustainability indicator that is easily understood and affects multiple impact categories. Indeed, among the phases of the LCA, there is the LCIA (Life Cycle Impacts Assessment), which is the phase of quantifying (through database data) the impacts of inputs and outputs. The method currently used to carry out this phase is the ReCiPe method, which considers 18 impact categories and three end-points (Martin et al. 2021). Only the CC, which is characterized by the Global Warming Potential factor, has the potential to affect two of the three end-point impact categories (i.e., human health and ecosystems), thus it is the most comprehensive for the assessment of environmental sustainability.
Summarizing, the TCO and the CO^2-equivalent emissions generated by the different PSS offerings are the sustainability indicators for assessing their impacts in the developed method. The point of view for the assessment is the one of the customers thus as a result the computed TCO and CO^2-equivalent emissions of the PSS solutions are associated with the single customer.

Model description

The AnyLogic software was used for building the model. A detailed description of the model is reported in the following. The PSS offers were modeled through state charts modelling the different product-related service components characterizing the post-sale phase. The state charts are consequently characterized by the following states: (i) distribution, (ii) installation, (iii) use, and (iv) End-of-Life (EoL). In particular, the authors focus on the use state.
The three agent types differ in the use phase due to the **maintenance service**, categorized and described as follows (Trojan and Marçal 2017):

- *Corrective maintenance*. This kind of maintenance occurs when a failure on a customer's product occurs. It is triggered by the customer and, depending on the criticality of the product, it must be performed immediately, or it can be delayed.
- *Preventive maintenance*. It is sorted and performed by time-based fixed intervals and aims to prevent equipment breakdown by repair or components exchange.
- *Condition-Based maintenance*. This is merely preventive maintenance but depends on the actual condition of the product. It implies that the product's health status is continuously monitored, and if threshold values are exceeded, maintenance is performed before the product breakdown occurs. It requires technologies for acquiring and processing product data in real-time, making it more advanced than traditional corrective and preventive maintenance services.

According to Tukker (2004), maintenance services are product-related services. However, in accordance with the nature of the interaction between the customer and the purchaser, the payment formula can differ, resulting in different PSS offerings. Corrective maintenance is a pure transactional service, while preventive and condition-based are typically offered inside maintenance contracts (Gaiardelli et al. 2014). The other services (distribution, installation, and EoL) can be considered pure transactional or included in contracts, allowing for diversifying the PSS offerings. However, in this model, they were considered transactional.

Figure 1 shows the three state charts related to the three agent types. It is possible to observe that the state charts differ in the use phase, as above-mentioned. The initial point of the state chart equals the product sales, which forms the customer's installation base. The first state is represented by the "distribution" where the product is delivered to the customer location. As soon as the distribution service ends, the agent is ready for the "installation", the second state modeled in the state chart. After being installed, the agent moves into the "use" state which is a composite state containing the "usage", "failure" stage, and "maintenance" service.

- In the Corrective agent type (a), the agent switches from "usage" to "failure" when a failure, which

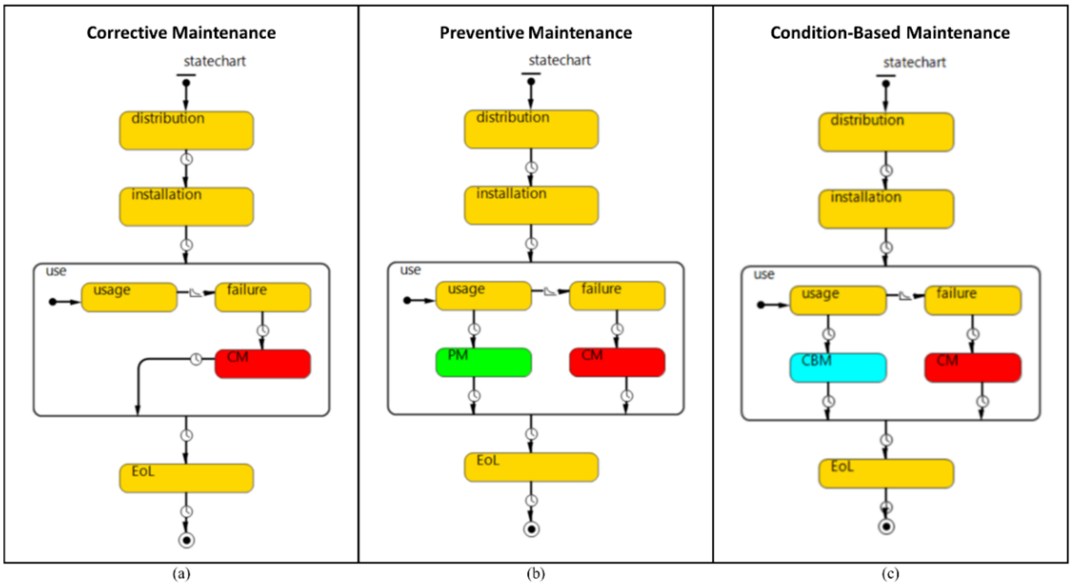

Figure 1: State Charts of the three Agent Types involved in the Model

depends on the product failure rate, happens. Then, based on the urgency of the corrective intervention (urgency hours), the agent moves into the Corrective Maintenance (CM) state. After a time period that equals the time for performing the corrective intervention, the agent returns to the "usage" state.

- In the Preventive agent type (b), the agent can switch from "usage" to two states: "failure" and "PM" (Preventive Maintenance). As previously, the "failure" state is triggered by the product's failure rate, which is drastically reduced concerning the corrective case because by doing preventive operations, the probability of the product breakdown is reduced. In this case, the agent carries the same steps of the Corrective. Meanwhile, based on the preventive maintenance schedule defined in the maintenance contract, the agent moves into the "PM" state.
  Then, following a time period that equals the time for performing the preventive intervention, the agent returns to the "usage" state.
- The Condition-Based agent type (c) "use" state is very similar to the Preventive one, with the only difference related to the schedule of the interventions. In this case, the switch to "CBM" (Condition-Based Maintenance) is triggered by the condition of the product itself: when it is close to the limit values for breakdown, the CBM intervention takes place. Thus, a different failure rate was utilized for this state transition. As before, the agent returns to the "use stage" after the time necessary for completing the maintenance intervention.

The agent shifts to the ultimate state of the state chart, which is represented by the "EoL" services, after a period of time corresponding to the typical operational lifespan of the product. The agent then goes to the endpoint.

By utilizing the state charts, it was possible to display the different services associated with the product and thus clearly represent its post-sale service opportunities. Each state also served for the TCO and CO^2 emissions computations, becoming the phases for the Cost Breakdown Structure characterizing the TCO computation and the inventory for the environmental assessment. The costs components are the following: (i) distribution cost, which includes the transport of the product to the place of use; (ii) installation cost, including the cost for installation activities and the cost of End-of-Life treatment for the generated waste (i.e., packaging); (iii) maintenance costs, which vary among the different maintenance category, and include the cost of spare parts and EoL treatment of generated waste; and (iv) the cost of EoL service, which can cover de-installation of the product, substitution or modernization solutions costs (such as retrofit), collection and transport costs, and EoL waste treatment. The total cost of ownership was then calculated by adding the purchasing cost, which is the product's sale price. Similarly, the environmental effects were measured by determining the variables and conversion factors for calculating the kg of CO^2-equivalent and using the same components of the cost structure. Specifically, the authors used the UK Government Conversion Factors for greenhouse gas (GHG) reporting database. All this data was inserted into the model through parameters, variables, and related functions for the TCO and CO^2 emissions computation. As a result, each contributing state recalls the functions for TCO and kg of CO^2-equivalent.

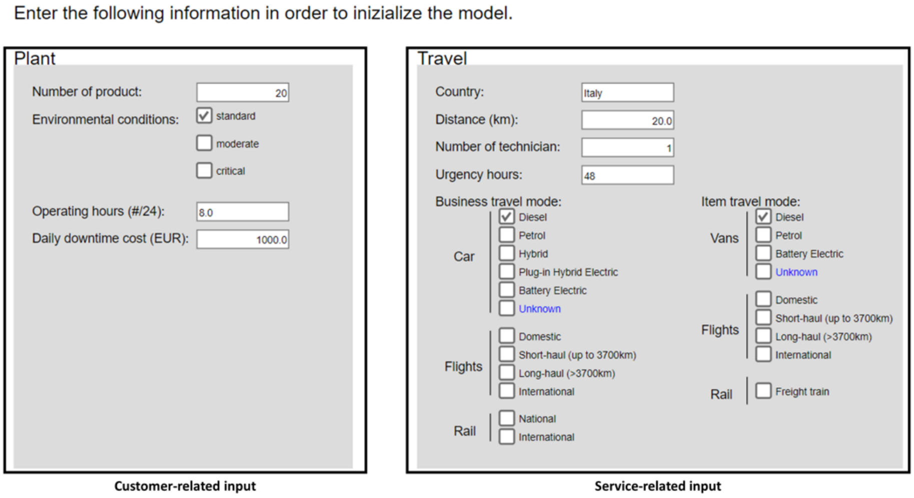

Figure 2: Initializing Inputs of the Model

Since the model aims to support the customer selection of the most sustainable PSS by looking at its generated impacts, it was developed considering the possibility of personalization of inputs. This is useful for aligning the model to the customer context and testing multiple scenarios. Recalling that the capacity to test many "what-if" situations is one of the main advantages of simulation, the built model allows the user to create different scenarios immediately at the start of the simulation run. Indeed, a set of control parameters included in the model that affects the agent behaviours and the sustainability output computations can be inserted before conducting the simulation by the utilizer itself. Figure 2 reports the parameters mentioned above. The parameters were divided as follows:

- Costumer-related inputs. They depend on the customer context and include the installation base, the operating hours of the place of use of the product, its external/environmental conditions, and the daily downtime cost.
- Service-related inputs. They are instead related to the service delivery, specifically the distance between purchaser-client, the urgency hours for the repair, the number of technicians, the travel mode of technician, and items.

Execution results

Academic experts verified the proposed model and to illustrate its applicability, an illustrative case is presented.

In light of the paper's goal, the simulation model was adopted to assess the PSS solutions' sustainability considering the customer's point of view in charge of selecting the most economic and environmentally friendly. In particular, data on the TCO and CO2 emissions associated with three distinct PSS solutions – which vary from one another due to the various maintenance approaches – was gathered for the sustainability assessment. Hereafter an example of the results obtained from a scenario analysis is reported.

The initializing inputs for the following illustrative example are the ones inserted in Figure 2. The product under consideration has a 20-year operating life expectancy. Its failure rate follows a Weibull distribution, while the preventive maintenance contract includes a preventive maintenance intervention every year.

In Figure 3, the yearly distributions of the customer costs for each PSS solution are reported. At time 0, the costs reflect the purchasing cost of the product; then as the year increases, it is possible to observe how the costs differ for each of the PSS solutions. When integrated product and preventive maintenance (PSS 2) is offered, the expenses start rising linearly since the very beginning of the product operational life because they are based on a fixed recurring fee. On the contrary, PSS 1 (Corrective), where corrective maintenance is included as a transactional service, expenses only rise when the product breaks in years 11 and 12. As a result, the PSS 1 solution is the most expensive for the client at the end of the operational product life. Lastly, although it demands a higher initial investment, the PSS 3 (Condition-Based) option is the most financially viable. The point is reached at year 9 concerning PSS2 and at year 11 with PSS1. Similarly, Figure 4 reports the year distributions of the Kg of CO2-equivalent for each PSS offering. Differently than before, PSS 2 offering produces more CO^2 emissions than the other solutions, suggesting that, from an environmental point of view, the one-year-based preventive maintenance schedule is unsustainable. Also, PSS 1 generates a high impact on CO^2 emissions. Once again, PSS 3 is the most suitable for reducing the environmental impact in the long-term period corresponding to the operational lifespan of the product.

Changing the input parameters related to the customer context and the service makes it possible to play with different scenarios. They are not included here due to space constraints.

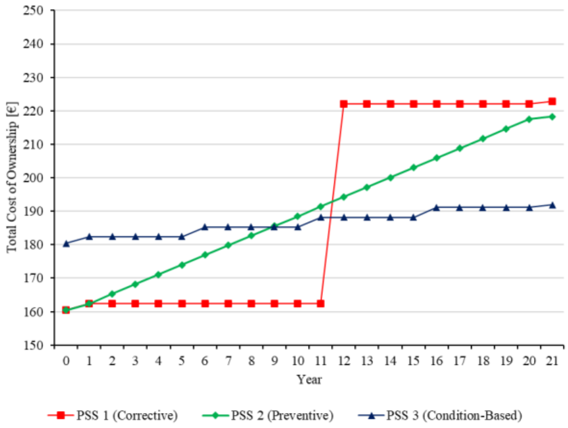

Figure 3: Total Costs of Ownership of the different PSS Solutions

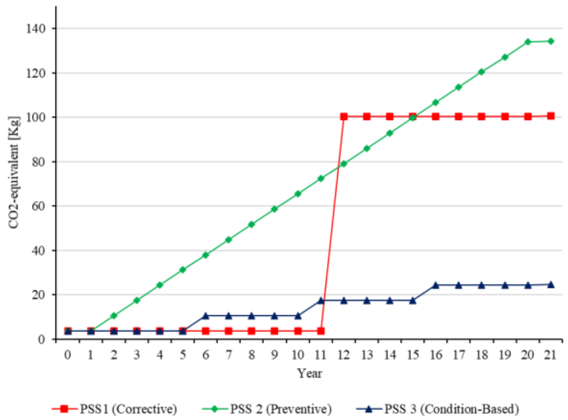

Figure 4: CO^2 Emissions of the different PSS Solutions

It is worth recalling that the model is still in its verification stage; thus, the following steps will address its validation with real-world data.

DISCUSSION

The proposed approach reports the quantitative assessment of the economic and environmental sustainability of different PSS solutions showing the potential of simulation and, specifically, Agent-based modelling in providing support toward sustainable decisions.

Compared to the traditional sustainability assessment methods used in the PSS-related literature, this simulation approach has multiple advantages. First of all, the simulation allows for dealing with the stochastic nature of systems. Therefore, it is useful when PSS involves stochastic processes or systems, such as providing maintenance services (i.e., the timing and nature of maintenance events may be stochastic, depending on factors such as equipment usage, wear and tear, and environmental conditions). By including the computation of the TCO and CO^2 emissions inside the simulation model, the quantitative assessment methods typically used for quantifying the sustainability impacts of products and services that are deterministic can now consider randomness and probability. Moreover, the ABM allows for modeling individual behaviours in a better and simplified way. Therefore, considering the PSS offering as a single entity with its behaviour makes it possible to obtain a more accurate indication of its economic and environmental impacts. Lastly, the approach allows for testing scenarios and understanding the impacts from the long-term perspective.

The proposed method provides a comprehensive sustainability assessment by looking simultaneously at the economic and environmental dimensions. Thus, it is possible to depict the trade-off between the two dimensions for each PSS solution and support decisions. The illustrative example shows that the third option is the PSS offering with minor impacts on both sustainability dimensions. The PSS offer based on preventive maintenance is less expensive for the client, but due to the way it is delivered, it is not environmentally sustainable because it produces higher CO^2-equivalent emissions. Changing its design could mitigate these effects. The first PSS option is the most expensive since a breakdown has already occurred and repair work is required during the maintenance intervention. Moreover, it has high CO^2-equivalent emissions, which makes it unsustainable. It follows that the practical contribution of the proposed method has several implications. On the one hand, it raises client awareness of the financial costs associated with a single PSS solution and the associated CO^2-equivalent emissions. On the other side, the purchaser may leverage it internally for marketing purposes, influencing customers to choose sustainable PSS and thus increasing the PSS adoption rate. Also, it might be employed internally to evaluate the sustainability of new PSS concepts, thus supporting the early stages of PSS design. All these considerations trigger further studies in this direction and will be explored in future studies.

The main limitations of the proposed method involve the data collection. A good knowledge of the product (e.g., failure rate, operational life) and the service provision is required to establish the system's correct behavior. Moreover, the modeler has to gather all the cost components of the PSS offer which requires time and effort. Differently, for the CO^2 emissions computation, it is crucial to have a robust database. For the implemented model, the authors used the UK Government Conversion Factors for greenhouse gas (GHG) reporting database, but it will be integrated with the database used in LCA software in future developments. The quality of the results strongly relies on the availability of such data. Thus, a multidisciplinary team including simulation expertise, product and service managers, sales manager, and expertise in sustainability topics would be required to validate the proposed method. Moreover, it is worth mentioning that the study does not provide a comparison of the Agent-Based Modelling with other approaches that would require future research.

CONCLUSION AND FUTURE DEVELOPMENTS

Nowadays, an increasing number of manufacturing companies are shifting from traditional product sales to the delivery of PSS to adhere to sustainability objectives. However, it is important to assess their TBL impacts quantitatively to promote sustainable PSS solutions.

The proposed approach using Agent-Based Modeling provides a valuable tool for assessing different PSS solutions' economic and environmental sustainability. The simulation approach overcomes the limitations of traditional sustainability assessment methods by allowing for dealing with stochastic nature, testing scenarios, and understanding the impacts from the long-term perspective. Moreover, the approach provides a comprehensive sustainability assessment by simultaneously considering economic and environmental dimensions and helps identify trade-offs between the two. However, the success of the approach depends on the availability of reliable data, which requires a multidisciplinary team with simulation expertise, product and service managers, sales managers, and sustainability experts. Despite these limitations, the proposed method offers a promising avenue for supporting sustainable decisions in the PSS context. Future developments will address the validation of the proposed model within a case study.

REFERENCES

Chalal, M., Boucher, X., Marques, G., 2015. "Decision support system for servitization of industrial SMEs: a modelling and simulation approach." *Journal of Decision Systems* 24, 355–382.

Ellram, L.M., 1993. "A Framework for Total Cost of Ownership." *The International Journal of Logistics Management* 4, 49–60.

Franciosi, C., Voisin, A., Miranda, S., Riemma, S., Iung, B., 2020. "Measuring maintenance impacts on sustainability of manufacturing industries: from a systematic literature review to a framework proposal." *Journal of Cleaner Production* 260, 121065.

Gaiardelli, P., Resta, B., Martinez, V., Pinto, R., Albores, P., 2014. "A classification model for product-service offerings". *Journal of Cleaner Production* 66, 507–519.

Kjaer, L.L., Pigosso, D.C.A., McAloone, T.C., Birkved, M., 2018. "Guidelines for evaluating the environmental performance of Product/Service-Systems through life cycle assessment." *Journal of Cleaner Production*.

Lee, S., Geum, Y., Lee, H., Park, Y., 2012. "Dynamic and multidimensional measurement of product-service system (PSS) sustainability: A triple bottom line (TBL)-based system dynamics approach." *Journal of Cleaner Production* 32, 173–182.

Lindahl, M., Sundin, E., Sakao, T., 2014. "Environmental and economic benefits of Integrated Product Service Offerings quantified with real business cases." *Journal of Cleaner Production* 64, 288–296.

Martin, M., Heiska, M., Björklund, A., 2021. "Environmental assessment of a product-service system for renting electric-powered tools". *Journal of Cleaner Production* 281.

Mont, O.K., 2002. "Clarifying the concept of product-service system." *Journal of Cleaner Production* 10, 237–245.

Resta, B., Gaiardelli, P., Pezzotta, G., 2009. "Sustainability in the auto repair industry: A life cycle assessment application." *International Journal of Product Lifecycle Management* 4, 146–165.

Rondini, A., Tornese, F., Gnoni, M.G., Pezzotta, G., Pinto, R., 2017. "Hybrid simulation modelling as a supporting tool for sustainable product service systems: a critical analysis." *International Journal of Production Research* 55, 6932–6945.

Saccani, N., Perona, M., Bacchetti, A., 2017. "The total cost of ownership of durable consumer goods: A conceptual model and an empirical application." *International Journal of Production Economics* 183, 1–13.

Trojan, F., Marçal, R.F.M., 2017. "Proposal of Maintenance-types Classification to Clarify Maintenance Concepts in Production and Operations Management". *Journal of Business Economics* 8, 560–572.

Tukker, A., 2004. "Eight types of product-service system: Eight ways to sustainability? Experiences from suspronet." *Business Strategy and the Environment* 13, 246–260.

Vogtlander, J., Bijma, A., Brezet, H., 2002. "Communicating the eco-efficiency of products and services by means of the eco-costs/value model." *Journal of Cleaner Production*.

Weimer, C.W., Miller, J.O., Hill, R.R., 2016. "Agent-based modeling: An introduction and primer". In *2016 Winter Simulation Conference (WSC)*. IEEE, Washington, DC, USA, 65–79.

Zhang, W., Guo, J., Gu, F., Gu, X., 2018. "Coupling life cycle assessment and life cycle costing as an evaluation tool for developing product service system of high energy-consuming equipment." *Journal of Cleaner Production* 183, 1043–1053.