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Short communication

Industry 4.0 sustainable supply chains: An application of an IoT enabled scrap metal management solution

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ABSTRACT

The fourth industrial revolution and the digitisation of supply chains have led companies to realize that the adoption of Industry 4.0/Internet of Things (IoT) solutions creates opportunities for more sustainable management. The sustainable management of scrap metal is a challenging task for all the organisations that participate in the supply chain and especially for scrap metal producers and waste management companies. Although metals are considered to be infinitely recycled, scrap metal management is often inefficient due to several factors including collection processes, communication and marketplace limitations, which have significant environmental and economic impacts. The purpose of this paper is to provide evidence of the impact of an IoT solution on the sustainable supply chain management (SSCM) performance. A case study from a scrap metal producer that operates in the lift industry and a waste management company is presented, in order to illustrate how the deployment of a state-of-the-art industry 4.0 solution has the potential to improve sustainability both in the firm level and in the supply chain level. Direct benefits of the introduced solution are the automation of monitoring and negotiation procedures for the produced scrap metal. Indirectly, the proposed solution is beneficial in terms of CO_2 emissions' reduction, resources availability and response time optimization. The results validate the framework for assessing SSCM for Industry 4.0 developed by Manavalan and Jayakrishna (2019) and demonstrate that Industry 4.0 solutions have the potential to improve, among others, the economic, environmental and social sustainability in supply chain management. The present study contributes to the literature by bridging the gap between theoretical developments and real-world cases in the fields of industry 4.0 and SSCM. Managerial implications, limitations and future research opportunities are also provided.

1. Introduction

In the last decade, a significant growth on sustainable supply chain management (SSCM) and industry 4.0 research has been observed. Big data analytics, Internet-of-Things (IoT), deep learning, simulation and forecasting techniques are used to address the contemporary needs of supply chains such as flexibility, increased productivity, less waste, optimization of resources inside and outside a factory and more sustainable production processes. With pressures from various stakeholders such as consumers andkm investors, sustainability has become a key business issue and companies are prompt to develop more sustainable practices within their organizational level but also across their supply chains. Yadav et al. (2020) have developed and tested a framework that links SSCM challenges with its solution measures. The findings of their study, revealed that managerial and organisational challenges are the key factors for the adoption of SSCM failures, while the lack of financial, technical and human resources restrict sustainability. Koberg and Longoni (2019), found that SSCM configurations (open, third party and closed) and SSCM governance mechanisms (e.g. supplier assessment and collaboration) are key components of

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global SSCM. The digitalization of processes in the manufacturing and business sectors and the application of solutions that deploy smarter equipment are expected to have positive impacts in the manufacturing productivity, resource efficiency and waste reduction (Tortorella and Fettermann, 2018). Recent studies have shown that *"manufacturing companies need to speed up in shifting the focus towards sustainability and make use of technology like 'Internet of Things' (IoT) to meet the organization's goal"* (Manavalan and Jayakrishna, 2019, p. 25).

To this end, industry 4.0 solutions are identified as key enablers for the development of SSCM.

The proposed work in this paper is part of the European project COMPOSITION,[1] which aims to develop an Integrated Information Management System (IIMS) to optimize operations in both internal production processes level and supply chain processes level. The developed solution, is deployed at KLEEMANN HELLAS SA, one of the major lift companies in the European and global market, with a distribution network to more than 100 countries and at ELDIA S.A., an industry leader in waste management and recycling in Greece. For KLEEMANN, which produces more than 1.000 tons of scrap metal annually, scrap metal management represents one of the most critical industrial processes. For ELDIA, which provides rational solutions for all waste management issues, the reduction of the volume of waste ending up at landfills, the adoption of modern methods and technologies that maximise the utilisation of materials deriving from waste sorting and the utilisation of recyclable materials with significant financial gains for enterprises are the core company principles. Both companies are committed to the adoption of environmentally friendly practices by using resources efficiently and managing wastes effectively. Digital transformations such as the installation of sensors and the development of IoT specific software-algorithms are driven by the need for more efficient waste management. The developed solution provides fill level monitoring, notifications, and an online ecosystem for automated negotiations between scrap metal producers and waste management services suppliers in order to improve the efficiency of waste collection and creates business opportunities in the scrap metal marketplace. As Reck and Graedel (2012, p. 690) underline, "*the most beneficial actions that could improve recycling rates are increased collection rates of discarded products, improved design for recycling, and the enhanced deployment of modern recycling methodology"*.

While previous research on SSCM and Industry 4.0 has offered valuable results, the literature is still limited and further exploration is required on the investigation of the sustainability impacts of Industry 4.0 (Ghobakhloo, 2019). The study of Carter et al. (2019), has also highlighted the need to better address the validity of existing SSCM models. Therefore, the objective of this paper is to evaluate the developed solution against SSCM for industry 4.0 criteria and provide real world results. More specifically, the present study focuses on the utilisation of an industry 4.0 solution for scrap metal management and investigates the role of IoT in SSCM. This work is considered a technical report that summarises the results of the application of the developed technology in the two companies, whereas the detailed description of software and hardware developments are not in the scope of this paper. However, a brief overview of the deployed technologies is available in this paper in order to introduce all the necessary means to the reader for enabling better and deeper understanding of the introduced concept.

The remainder of this paper is organized as follows. In section 2, a literature review is provided followed by the presentation of the proposed solution and its application to the scrap metal producer and the waste management company. The results and discussion are presented in Section 4. Finally, in the conclusions section, managerial implications, limitations and future research opportunities are provided.

2. Literature review

As already noted in the introduction, a rising interest in the area of SSCM and industry 4.0 is evident. The recent study of Manavalan and Jayakrishna (2019) confirms this observation by showing a growing, but still limited trend in SSCM research and Industry 4.0/IoT. From 8 papers published in 2009, 128 papers are published in 2018 (Manavalan and Jayakrishna, 2019). This demonstrates that this research field is still in its initial stages. Various industry 4.0 and IoT solutions have been designed to support decision-making in manufacturing operations and procedures. Manavalan and Jayakrishna (2019) highlight the necessity of focusing on sustainability by utilizing state of the art technologies such as 'Internet of Things' (IoT) to meet customers' requirements and organisations' goals as well as the aggressive change in market dynamics. In this section, a brief overview of SSCM and SSCM and industry 4.0 applications is presented.

2.1. The concept of sustainable supply chain management

A large body of literature has recently focused on the topic of Sustainable Supply Chain Management (SSCM) (Carter et al., 2019; Mardani et al., 2020; Rajeev et al., 2017). Globalisation allows processes to be dispersed around the world linking all supply chain members, from suppliers to end customers, through information sharing and flows of material and capital (Seuring and Müller, 2008). Seuring and Müller (2008, p. 1700), define SSCM as *"the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e. economic, environmental and social, into account which are derived from customer and stakeholder requirements*." Hence, SSCM focuses on the equal consideration of the environmental, economic and social dimension of sustainability (Elkington, 1997) and the management and coordination of all business operations within a firm and the cooperation of all supply chain partners. A framework, based on Elkington's Triple Bottom Line approach, has been developed by Carter and Rogers (2008), and shows that the intersection of environmental, economic and social performance creates sustainability. In addition, special attention is given to legitimacy issues of various stakeholders, including employees, suppliers, customers, Non-Governmental-Organisations (NGOs) etc., whose requirements are related to supply chain's activities (Mueller et al., 2009).

2.2. Sustainable supply chain management and industry 4.0 applications

Several factors that influence either positively or negatively the adoption of SSCM have been identified in the literature. For example, cost savings associated with operational and material efficiencies (Chkanikova and Mont, 2015) and increased resource utilisation (Giunipero et al., 2012) are two of the main SSCM enablers. Information sharing is another important factor that enables SSCM (Faisal, 2010; Grimm et al., 2014; Wittstruck and Teuteberg, 2012), while forecasting accuracy, which reduces or prevents waste production is also a key supply chain factor for SSCM (Mena et al., 2014; Mastos and Gotzamani, 2018). On the other hand, pressures from stakeholders such as regulatory bodies, Non-

[1] https://www.composition-project.eu/.

Governmental Organisations (NGOs), community organisations, suppliers, customers, global competition, lack of adaptability and delayed market entry have prompted companies to reconsider the balance of environmental, social and economic issues in their operations (Hassini et al., 2012). Indeed, the complex and dynamic nature of these factors may increase supply chain uncertainty (Atzori et al., 2010; Giusto et al., 2010). To overcome these challenges, Industry 4.0 applications have been developed in order to transform supply chains and create digital networks (Atzori et al., 2010; Giusto et al., 2010). For example, in the smart city domain, a few studies have proposed smart waste collection management solutions using Internet-of-Things (IoT) (Navghane et al., 2016; Shyam et al., 2017). From an industrial point of view, IoT is leveraged to measure bins' fill level while simultaneously proposing optimal routes for scrap metal bins' transportation within a factory (Vafeiadis et al., 2019a). Furthermore, an integrated IoT-Industry 4.0 sensor-based solution for predictive maintenance is deployed in a lift manufacturer, to provide remote real-time condition monitoring of equipment (Vafeiadis et al., 2018). In the shipbuilding sector, Ramirez-Peña et al. (2019) have investigated the sustainability facets of the shipbuilding supply chain from an Industry 4.0 perspective. In their study twelve key enabling Industry 4.0 technologies (Internet of Things, Artificial Intelligence, Big Data, Autonomous Robots, Cybersecurity etc.) are connected with 4 supply chain paradigms (Lean, Agile, Resilience and Green) in order to define how the shipbuilding supply chain should look like. Yadav et al. (2020) have developed a SSCM framework that identifies the supply chain challenges and solution measures related to industry 4.0 and circular economy and tested its applicability in the automotive sector. Their findings showed that the adoption of 6 R's (recycle, reuse, reduce, refuse, rethink and repair), the environmental product design and life cycle analysis and the digitisation of supply chain are the top ranked solution measures to overcome SSCM challenges (Yadav et al., 2020). Last but not least, studies in the food industry have shown that the application of Internet of Things (IoT) technology in supply chains, enables SSCM adoption and has the potential to reduce waste, costs, emissions and social impacts (Accorsi et al., 2017).

2.3. Scrap metal management and sustainable supply chains

Metal recycling, such as scrap metal which is produced during the manufacturing processes, is considered one of the key sustainability practices (Graedel et al., 2011). Compared to other resources, metals are considered to be inherently recyclable meaning that they can be reused infinitely. This procedure results in the reduction of mining and process in virgin materials which ultimately minimizes energy and water consumption as well as the general environmental degradation of the process (Graedel et al., 2011). Fig. 1 below shows an example of a metal and product life cycle. In this study, the focus is on the new scrap that is produced from the product manufacturer and the handling of it from the waste management company.

Apart from the environmental benefits of scrap metal recycling, there are also strong economic opportunities. For example, in 2015, the U.S. ferrous scrap industry was worth $18.3 billion while in 2014, the U.S. nonferrous scrap reached $32 billion (Leblanck, 2018).

Manavalan and Jayakrishna (2019, p. 936) highlight that *"the basics of sustainability in Industry 4.0 suggest that organisations should realize closed loop life cycles for product.* In order to leverage these environmental and economic opportunities, and to improve scrap metal management procedures industry 4.0 using IoT technologies should be adopted. These technologies can enable the *"interconnection of components, machines, systems, processes and various stakeholders of supply chain to form a digital supply chain network with future Industry 4.0"* (Atanasov et al., 2015; Pfohl et al., 2017). Innovative business models based on state-of -the-art technologies can produce smart products and services in an integrated digital ecosystem (Kölsch et al., 2017). Digital cyber networks act as the focal point, where information from different supply chain members is shared along the entire supply chain (Ivanov et al., 2016; Zuehlke, 2010).

2.4. Research gap and research questions

As already noted in the literature, Industry 4.0/IoT solutions are used in several sectors and have the potential to transform traditional supply chains into sustainable supply chains. Industry 4.0 can make cities, factories and procedures, both in the firm level and the supply chain level more environmentally friendly, safer, and more efficient. Manavalan and Jayakrishna (2019) propose that academicians and practitioners should collaborate in future studies, and focus on the investigation of IoT and Industry 4.0 applications towards SSCM. Despite the fact that there are several Industry 4.0/IoT opportunities available for the development of SSCM, a linkage between theoretical developments and real-world applications is still scarce. The majority of the available frameworks in the literature are conceptual in nature and are not validated by real-world cases. Moreover, industry-specific studies are still limited (Rajeev et al., 2017). In order to shed light on the abovementioned research gap, an Industry 4.0/IoT integrated scrap metal management solution is proposed by this work with the aim to answer the following research questions:

RQ1: How is an IoT solution deployed in a real-world supply chain?

RQ2: How does an IoT solution perform against SSCM for Industry 4.0 criteria in a real-world supply chain?

3. Proposed solution and deployment

In this section an integrated scrap metal management solution, which includes a variety of components is proposed. The core components that enable this solution are briefly presented in this section. Detailed descriptions of different system's components are available in corresponding articles. The different components that collaborate for the execution of the sustainable scrap metal management scenario are:

1. IoT fill level sensors deployed to shop-floor's bins
2. A real-time monitoring system for bins' fill level
3. A notification system that informs the factory stakeholders about production line's bins collection and transportation
4. A data and visual analytics platform for waste management companies to optimize their planning activities
5. An online Ecosystem for automated negotiations between scrap metal producers and waste management companies

The first four components are participating in the firm level activities. The last one is applicable on the supply-chain level. Fig. 2 highlights the tools that are available in the firm level for both the waste producer/manufacturer and the waste management company. As depicted in the figure the collaborative ecosystem acts as broker between the participants.

Prior to the presentation of the main building components of the solution, it is worth to mention that the effective scrap metal management in the manufacturer/scrap metal producer begins even before the production of scrap metal. A predictive maintenance solution, that is analysed in Vafeiadis et al. (2019b) and Vafeiadis et al. (2018), for the polishing machine that produces the

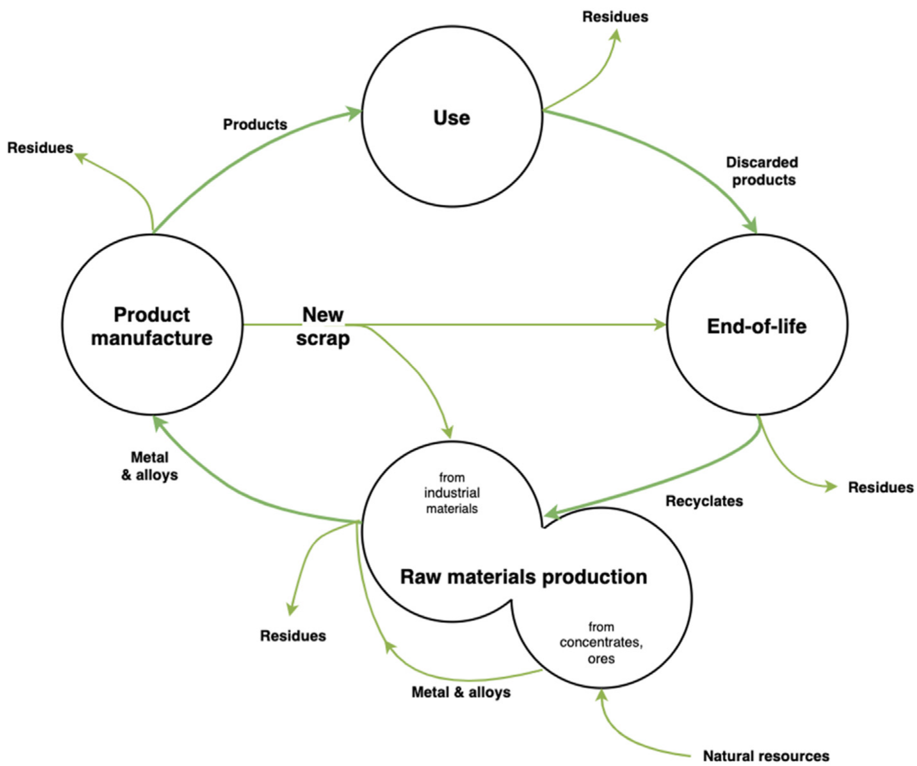

Fig. 1. The life cycle of a metal, consisting of production, product manufacture, use, and end of life. The loss of residues at each stage and the reuse of scrap are indicated (adopted from Meskers, 2008).

scrap metal, as an output of the polishing process, has been designed and deployed. The solution is enabled by vibration sensors deployed in the machine's motors and by a real-time visual and data analytics system. The implemented methodology creates the vibration profile of the machine and defines in real time if abnormal vibrations occur. Therefore, the system's usage enables the maintenance manager to monitor the machine's behaviour and to be visually notified for abnormalities. The provided early malfunction diagnosis minimizes the production of defect products that will be moved to scrap metals.

3.1. IoT fill level sensors

The presented application scenario is enabled by the deployment of IoT fill level sensors for the different type of scrap metal bins. Two types of LoRa[2] enabled fill level sensors were developed and deployed at KLEEMANN's premises (see Fig. 4). The first one is an infrared (IR) VL53L0X sensor[3] used for the smaller indoor bins, which contain scrap metal or other recyclables. The second one, is the HRXL-MaxSonar-WRT MB7380 IP67[4] ultrasonic sensor, which monitors the larger outdoor scrap metal bins. Due to the small size of indoor bins, the usage of IR sensors was considered as the best option as this sensor module is about 15 times cheaper than the ultrasonic one and produces accurate measurements as the distance of the bin's bottom is about 1 m. In opposite, for the large open top containers the adoption of the IR sensors was not feasible as it was not possible for this type of sensor to provide accurate measurement due to the large volume the aforementioned containers cover. Besides the sensing modules, a low power microcontroller, STM53L0[5], is used to control both systems. Moreover, a sx1272MB2xAS[6] LoRa communication module provides wireless communication with the LoRa gateway (Lorank 8). The whole IoT device's system is powered by 4 AA batteries whose life can reach more than two years. The complete deployed system in the two companies and the cloud infrastructure is depicted in Fig. 3.

On the system level, the sensors periodically take raw distance measurements from their position to the surface of the waste heap, which are transmitted wirelessly to the LoRa Gateway. The LoRa Gateway, connected to the internet, relays the measurements to the cloud platform where the distances are translated into percentages, according to the dimensions of each bin. This is the value that is finally monitored by the users.

3.2. Real-time monitoring system

The Real-time Monitoring System has been designed and deployed in order to provide visual representation of the fill level sensors' measurements that have been introduced in the previous section. The system has been developed as a complete web-based tool in order to be available in every device in a factory, by just visiting and logging in to the monitoring web page. An example of the user interface of the monitoring system is available in the following figure:

The user interface is developed by using AngularJS and it is updated every time that receives a new measurement by a fill level sensor (see Fig. 4). The communication between fill level sensors

[2] https://lora-alliance.org/.
[3] https://www.st.com/en/imaging-and-photonics-solutions/vl53l0x.html.
[4] https://www.maxbotix.com/Ultrasonic_Sensors/MB7380.htm.
[5] https://www.soselectronic.com/products/stmicroelectronics/stm53l0-satel-i1-T560253.
[6] https://os.mbed.com/components/SX1272MB2xAS/.

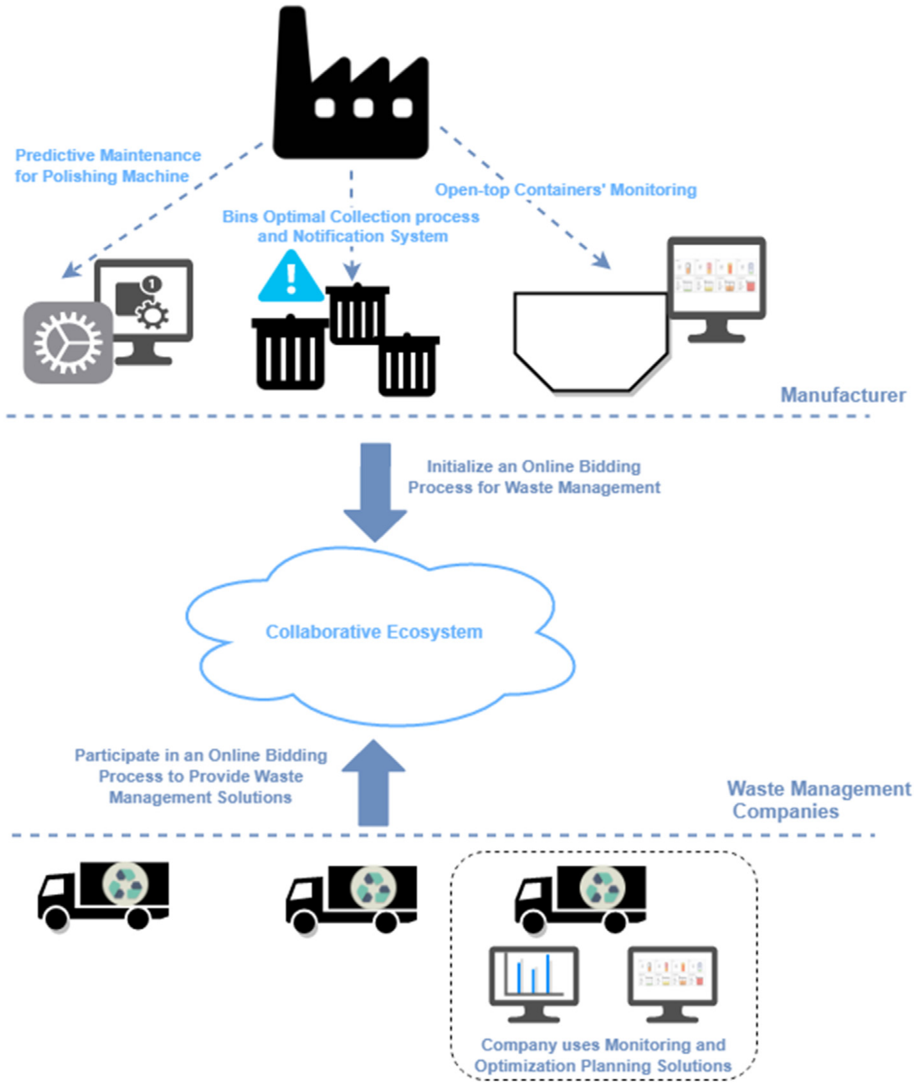

Fig. 2. High level architecture of solution.

and the monitoring system is based on MQTT protocol. The interface informs the user about the current value of the fill level percentage of a bin, about the battery level percentage and about the date (timestamp) of the latest measurement (see Fig. 5). Furthermore, the interface supports different colors representation for bins' fill level. The green color indicates an almost empty bin (fill level less than 50%), the orange color a bin with fill level over 50% and the red color is an almost full bin (fill level over 80%). This feature enables an easier and quicker monitoring by the end user without the need to read the numbers about fill level percentage.

3.3. Notifications system

Alongside with the deployment of the fill level sensors and the corresponding user interface for monitoring, a notification system for the bins' collection has been implemented. The system uses the sensors data and sends a notification every time that a sensors measurement is over a predefined threshold. In the proposed solution, a worker/forklift driver receives a notification in his mobile phone, every time that the fill level value of a bin is over 80%. There are two different options that a user/worker is able to receive a notification. The first is by installing a mobile app that has been designed during the project in order to send alerts for different events in the shopfloor. The second option for a worker to receive notification is by email. A mailing mechanism has been designed only for the bins' collection notification.

In order to provide further cost and time savings, the system does not only notify the user about the bin that should be collected and be transferred outdoors in large open top containers but it also provides him an optimal route for this collection process as well. The modelling of factory maps enabled this functionality. These factory models (gbXML[7]) were able to highlight the positions of indoor scrap metal bins and of the outdoor open top containers. After that, a version of Dijkstra algorithm (Vafeiadis et al., 2019c) has been implemented for these positions and the routes that connect them. By using this algorithm, the notification system was capable to send the positions inside the factory that a worker should visit in order to collect a bin in an optimal way. Two are the main benefits of this process. (a) The scrap metal is transported by following the optimal path in order to reduce transportation time, fuel costs, and CO_2 emissions and (b) the indoor bins are emptied

[7] https://www.gbxml.org/.

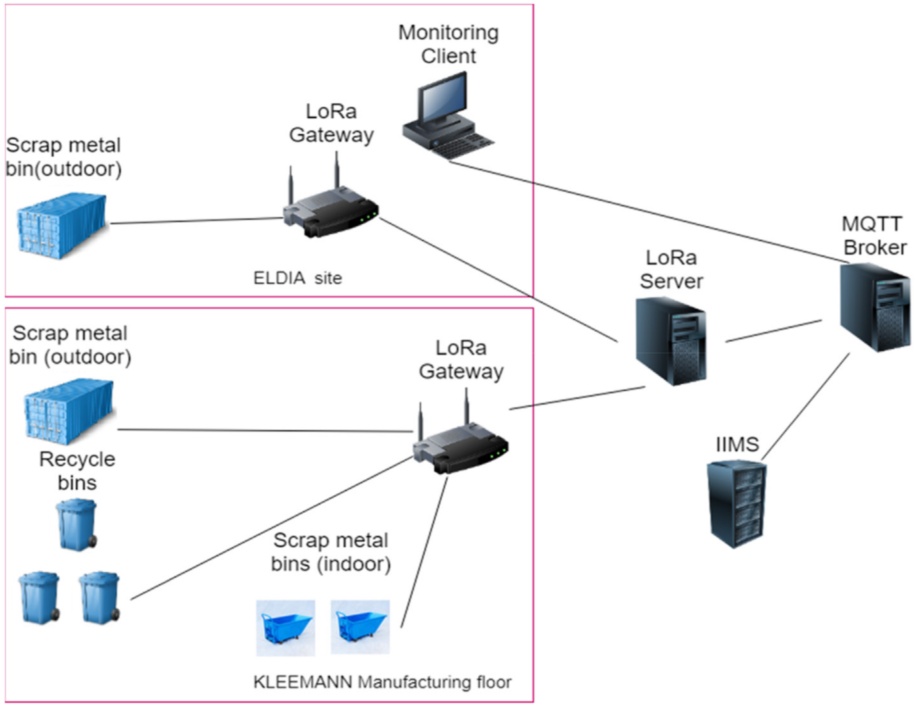

Fig. 3. Architecture of fill level sensors network.

Fig. 4. Indoor (left) and Outdoor (right) Scrap Metal Bins with Deployed Sensors (in red circles). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

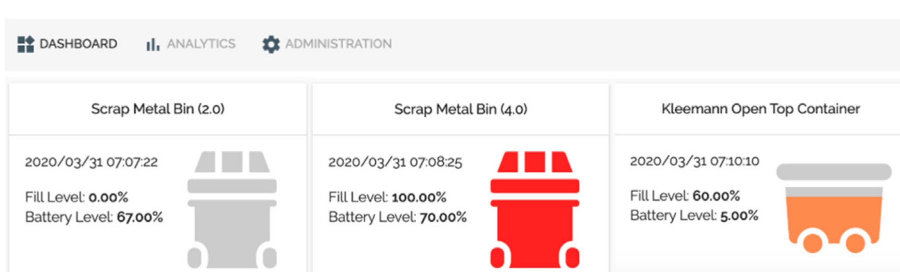

Fig. 5. Fill level monitoring framework.

quickly. The last is of great importance, as full bins cause interruption of production processes. The production process stops until the bins are empty, in order to be able to collect the scraps that are the output of machines' operation.

3.4. Data and visual analytics platform for planning optimization

Besides the sensor installations, monitoring and notification functionalities in the waste producer's side, an online analytics platform that enables effective planning for waste management companies has been implemented and deployed. The platform provides data and visual analytics tools, as it presented in detail in Vafeiadis et al. (2019a). The key features supported by the platform are:

- Monitoring of containers fill level based on IoT sensors. Many of open-top containers in waste producers' facilities is a property of the waste management company, which collects and replaces them with empty ones. The company uses a monitoring framework similar with the one that described above (Fig. 5).
- Analysis of the containers fill level trend based on Slope Statistics Profile. The user is able to select bin/sensor and to monitor the trend of fill level in order to give higher priority to customers with the most aggressive trend in their bins/containers.
- Forecasting about the tonnage of wastes that is going to be transported by a waste management company based on Moving Average and Markov Chain models. For better planning and resource allocation predictions about future transported tonnage per material or per customer are available to waste management company. The user is able to select material, type of visualizations and months ahead for prediction (see Fig. 6).
- Calculator for optimal pair of routes and tonnage that should be transported is also available by the platform. The planning responsible is able to check the proposed list of optimal pairs in order to evaluate its planning. The method is based on Genetic Algorithms.
- Price forecasting for various waste types/materials informs the waste management company for the future prices of various waste types by using a Deep Learning Methodology in historical data of the company.
- Statistical analysis and visualizations for better data exploration and understanding are also supported by the platform.
- Data deployment functionality is also available to the user. The user is able to update historical data by filling an online form provided by platform or by deploying a.csv file coming from the company's ERP system.

3.5. Online negotiations ecosystem

Targeting to the complete automation of scrap metal management, an Online Agent-based Ecosystem (Bonino and Vergori, 2017) has been designed and deployed in the COMPOSITION project. In this Ecosystem every company is represented by a virtual agent. These agents are able to negotiate in real time by participating in online bidding process that is provided by the Ecosystem. The communication of participants is enabled by the agent framework and the negotiations are enabled by a Matchmaking module (Nizamis et al., 2018a, 2018b) which is part of the Ecosystem. The data flow between the key ecosystem components is available in Fig. 7.

Both KLEEMANN and ELDIA have set up their agents in the Ecosystem. Therefore, both of them are available to negotiate about scrap metal and arrange a pick up automatically by using the online bidding process functionality. During this process, the KLEEMANN agent advertises its request to the Ecosystem. The request is about scrap metal management service. The Matchmaking engine of the ecosystem applies semantic matching to the knowledge base of the ecosystem and match the request with the available services and their providers. After that, the agent that represents the scrap metal producer/owner notifies the proposed/matched service providers to provide their offers for this request. The offers are evaluated in real-time by the Matchmaking engine that matches the request with the best available offer. The evaluation process takes into consideration different criteria based on the requester agent's preferences. In order to evaluate an offer for scrap metal management service the Matchmaking engine uses criteria such as the price of the service, the time that the service can be delivered and the rating/reputation of a company/agent in the Ecosystem. By the end of the bidding process, the system suggests the best available offer to KLEEMANN's agent. The purchasing manager, who accepts the suggested offer or examines other available offers, as he is able to explore them through the bidding process UIs, makes the final decision. Finally, the selected waste management company is

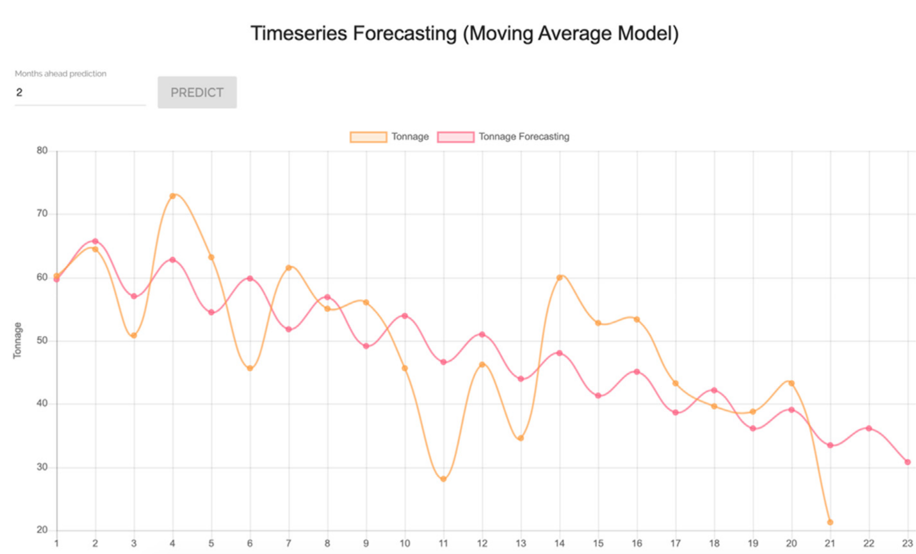

Fig. 6. Data analytics framework - tonnage forecasting.

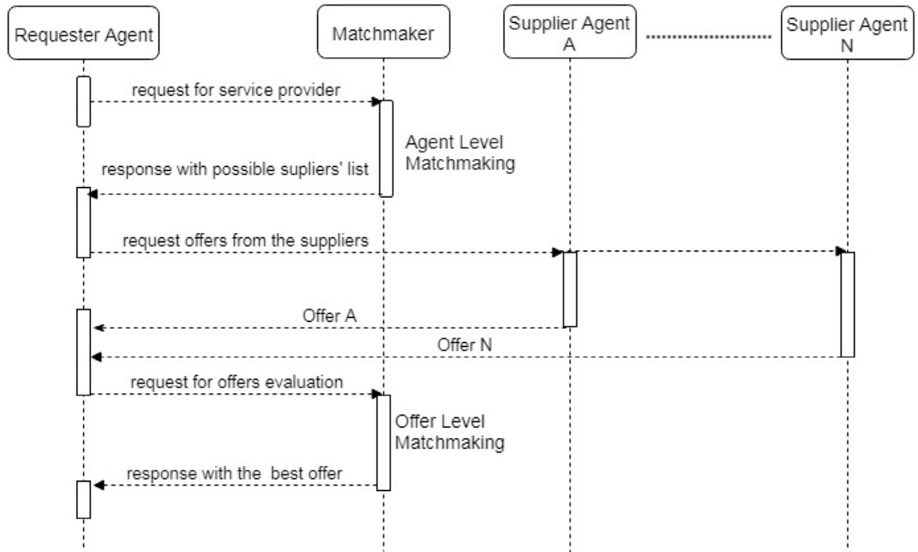

Fig. 7. Ecosystem information data flow (Nizamis et al., 2018a).

informed (the rest of companies are notified as well that they are not selected) by the system and the scrap metal collection process is completed as soon as the scrap metal is collected. The part of bidding process is successfully tested between KLEEMANN, ELDIA and some virtual/dummy agents in a simulated scenario. The use of COMPOSITION Ecosystem and its UIs for the online bidding process were tested and validated from both sides (requester/KLEEMANN and supplier/ELDIA). Moreover, the functionality of matchmaking scenarios and the suggestions of the best available offers were validated through some simple test cases. However, a large-scale use case of a real-world ecosystem with many participants and services is an ongoing activity.

4. Results and discussion

The aim of this paper was to provide evidence of the impact of an IoT solution on the SSCM performance. To shed light on SSCM and industry 4.0 tools, an integrated scrap metal management solution is proposed and its deployment is analysed to address the two research questions: RQ1. How is an IoT solution deployed in a real-world supply chain? and RQ2. How does an IoT solution perform against SSCM for Industry 4.0 criteria in a real-world supply chain? Given that a very small number of previous works has developed and deployed IoT enabled solutions for SSCM, our study contributes to the SSCM and Industry 4.0 literature by validating the proposed solution in real world cases.

To answer the first research question, this study has presented the high-level architecture of the proposed IoT enabled solution by describing the different components used for the sustainable scrap metal management. Firms in the waste management sector or in other sectors that wish to adopt IoT tools for SSCM in the firm level, can utilise the first four components. The online ecosystem that offers automated negotiations between scrap metal producers and waste management companies can be utilised by firms that wish to adopt IoT tools for SSCM in the supply chain level. The study of Manavalan and Jayakrishna (2019) revealed that real-time information sharing can enable the integration between supply chain partners such as suppliers, manufacturers, retailers and customers in Industry 4.0 environments and can offer benefits to the entire supply chain. In line with Manavalan and Jayakrishna (2019), the proposed solution provides a real-time monitoring system that has been designed and deployed in order to provide visual representations of the fill level sensors' measurements. The system has been developed as a complete web-based tool in order to be available in every device in a factory, by just visiting and login to the monitoring web page. On the contrary to the study of Kumar and Shoghli (2018), which suggests that major barriers to the success of IoT technologies into supply chains are the organisation culture (related to the senior management commitment, privacy issues, support mechanisms and education), the installed on-site technology of the proposed solution is well accepted from both companies and so far, it is not affecting day to day operations. This is due to the fact that the users of the system have been informed about the expected benefits of the solution and they have been trained on the use of it. Hence, the organisation culture in this case has acted as a driver to the success of the proposed solution. Furthermore, the user interface of the monitoring system is well received providing most of the necessary information needed for the scrap metal fill level and bidding process (see Figs. 5 and 8).

Drawing upon the application of the proposed solution and in order to answer to the second research question, the results suggest that the development of Industry 4.0 solutions can act as enablers for sustainable supply chain management. The findings can be used to frame SSCM and industry 4.0 relationships on the basis of Manavalan and Jayakrishna' s (2019) framework (Fig. 9). The framework is developed to assess SSCM for Industry 4.0 under five SSCM dimensions namely 1) business based smart operations, 2) technology based smart products, 3) sustainable development, 4) collaboration and 5) management strategy and organization to meet Industry 4.0 requirements. The framework comprises of 18 sustainability criteria and 62 attributes (for more information see Table 14 from Manavalan and Jayakrishna, 2019). The framework is considered one of the first models for assessing SSCM from an Industry 4.0 perspective.

The following table (Table 1), presents the results of this study related to the SSCM in industry 4.0 perspectives, criteria and attributes. The results reported in this study are based on historical and live data provided by KLEEMANN and ELDIA. The data refer to cost of person hours, fuel consumption, time spent in internal and external supply chain processes, scrap metal price per tone and logistics costs.

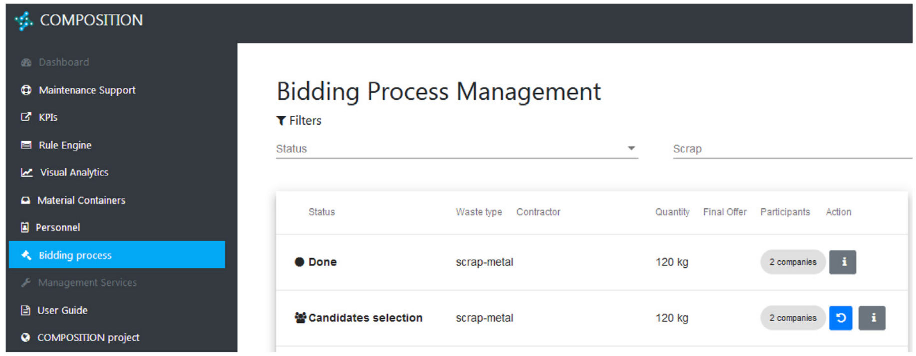

Fig. 8. Bidding process example UI.

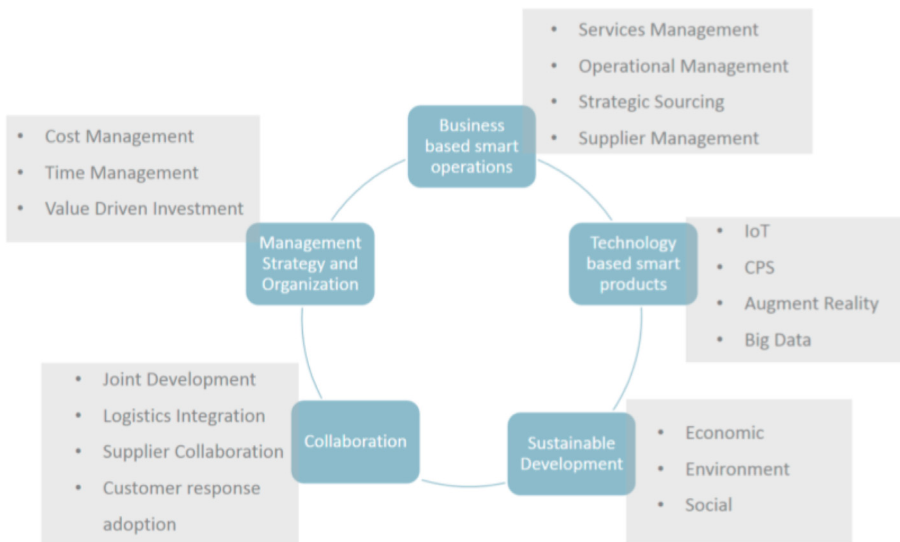

Fig. 9. Framework for assessing SSCM for Industry 4.0.

The overall findings show that 5 out of 5 perspectives, 17 out of 18 criteria and 35 out of 62 attributes have been addressed by the proposed solution. Most of the attributes have been assessed based on a qualitative approach since this project focused on pilot testing rather than large scale experiments. Despite this fact, some quantitative results have been provided by the participating companies.

The results of this study are in line with previous research that indicates that industry 4.0 solutions support organisations in providing more sustainable products (Yadav et al., 2020). Rajeev et al. (2017) have previously suggested that sustainable shipbuilding supply chains that improve economic, energy and environmental aspects can be achieved through the application of industry 4.0 technologies. Focusing on the aspects that lead to sustainable development and sustainable supply chain management, this study provides evidence of improvements on all the three dimensions. Regarding the economic impact of the proposed solution, the existing waste bins have been upgraded to smart waste bins with the use of sensors, thus their life is extended and there is no need for new bins. The environmental benefits of the proposed solution are already evident since in both companies the fuel consumption and CO2 emissions have been reduced as a result of monitoring and forecasting processes. From the social dimension point of view, the proposed solution has improved the quality of work and safety.

5. Conclusions

In line with the research objective and in order to answer the research questions, the present study evaluated the developed IoT enabled scrap metal management solution against SSCM for industry 4.0 criteria. The proposed scrap metal management solution in section three, where the core technical components are presented, answers to the first research question. The framework for assessing SSCM for industry 4.0 developed by Manavalan and Jayakrishna' s (2019) is used as a key starting point for the presentation of the results but also as a guiding framework for assessing the specific case. The results have demonstrated that the implementation of industry 4.0 solutions for scrap metal management enhances the competitive advantage of both waste producers and waste management companies towards sustainable supply chain management. It allows waste producers and waste management companies to monitor their processes in the firm level and the supply chain level in real time and make more efficient decisions. Furthermore, the findings have shown that companies in the waste management sector can benefit from the proposed solution which enables the reduction of non-renewable energy resources and CO2 emissions among others (see Table 1). By applying this framework to the two companies, this study strengthens the empirical evidence of industry 4.0 solutions for developing SSCM and thus contributes to supply chain sustainability through cleaner production processes.

Table 1
Framework for assessing SSCM for industry 4.0 and results of the proposed solution.

Perspectives	Criteria	Attributes	Proposed solution
Business based smart operations	Services Management	Streamline and monitor execution of service	The monitoring and notification system for collection and transportation enables the streamlining and monitoring of the procedure
	Operational Management	Automate routine work/transactions	Online ecosystem for automated negotiations and notification system for waste collection by providing optimal collection information
		Align operations to business needs	Online ecosystem for automated negotiations is based on company needs. Winning bid selection is based on business priorities (price, delivery time etc.)
		Respond to exceptions before business is affected	The data and visual analytics platform used by the waste management company optimizes its planning activities and assists in addressing unexpected conditions (monitoring and forecasting services are available)
		Manage spend and reduce waste	Reaction time is improved by 20% from scrap metal monitoring. 4% reduction of scrap metal due to the predictive maintenance solution
	Strategic sourcing	Maximise realised savings	15% improvements in logistics costs from process monitoring
		Get right suppliers and right materials	In the simulated scenario the composition marketplace has facilitated the bidding process and based on specific pre-defined criteria (type of service, price, supplier's rating, delivery time, payment and delivery terms etc.) the optimal matchmaking has been performed. Right supplier and right material are provided with KLEEMANN acting as a requester and ELDIA as supplier.
		Structure negotiations for quality outcomes	Structured negotiations are enabled by the agent framework and the Matchmaking module
		Enforce appropriate contract verbiage	The evaluation process takes into consideration different criteria based on the requester agent's preferences. In order to evaluate an offer for scrap metal management service the Matchmaking engine uses criteria such as the price (and payment terms) of the service, the time that the service can be delivered and the rating/reputation of a company/agent in the Ecosystem. These clearly defined criteria are terms that could be incorporated in a contract and hence the automation of this procedure enforces specific wording in contracts.
	Supplier Management	Analyse supplier performance	Suppliers' performance can be evaluated based on the rating/reputation tool of the ecosystem.
Technology based smart products	IoT	Monitor entire supply chain network	Monitor supplier-buyer network (extension to the monitoring of the entire supply chain is possible, when more companies join the platform). Furthermore, an extension of the proposed system is under development. It is going to utilise blockchain technology capabilities for track and trace both negotiation and delivery processes.
		Introduce Cyber Security	A security framework is provided for the complete securitization of the COMPOSITION platform components, in terms of authentication, authorization and cyber security of all the communications involved in the different processes. In particular, secure MQTT broker is used for IoT devices and cloud services communication, and a user login page alongside with role management services are provided by the security framework.
		Manage resource and systems	Increased availability of resources (both personnel and fleet) by 10% for KLEEMANN and 25% for ELDIA due to the usage of analytics, monitoring and the optimization tool. ELDIA is able to monitor customers' bins and prepare a more effective collection plan that optimizes the use of resources such as trucks. Planning optimization is further enhanced by using tonnage and price forecasting mechanisms that enable the planning manager to have a clearer sight on the future needs.
	Cyber Physical System (CPS)	Assess the real-time information sharing	The Real-time Monitoring System has been designed and deployed in order to provide visual representation of the fill level sensors' measurements that have been introduced in the previous section. The system has been developed as a complete web-based tool in order to be available in every device in a factory, by just visiting and login to the monitoring web page.
		Self-monitor and control the process	Fill level monitoring within the factory and control of collection process. Moreover, negotiations monitoring is provided through online bidding process as every aspect of the process (participants, offers details, winner information etc.) is stored and is available to the user. Information about pick up arrangement are available as well.
		Predict actions or needs of users	Bins collection automation inside KLEEMANN's production line, and price and tonnage forecasting for ELDIA in order to predict future needs and optimize planning.
		Self-organising production	Through the predictive maintenance offered by the system, the maintenance manager is able to inform the production manager to better organise production schedule.
		Proactive risk alerts based on historical data	The system's usage enables the maintenance manager to monitor the machine's behaviour and to be notified for abnormalities in order to reduce possible breakdowns.
	Big Data	Predictive analytics and forecasting tools	Forecasting about the tonnage of wastes and price forecasting for various waste is provided by the ecosystem. Furthermore, a predictive maintenance solution based on polishing machines' vibrations is available.
Sustainable development	Economic	Financial Stability	Both companies are confident that the proposed IoT solution, along with the ones that are to be deployed in the future, are key factors for leveraging Industry 4.0. The ability of the solution to work with already existing systems enhances productivity and accuracy in the firm level and promotes visibility in the supply chain level. The competitive advantage that is gained through the developed IoT solution along with the above characteristics, are able to create stability in the production line and across the entire supply chain.
		Investment on technological improvements	The results of this study have already triggered both companies to purchase a new fully integrated software that will be connected to the smart bins and offer new functionalities. The existing waste bins have been upgraded to smart waste bins with the use of sensors and the use of COMPOSITION components. Thus, their life is extended since

Table 1 (*continued*)

Perspectives	Criteria	Attributes	Proposed solution
		Retrofitting approach to extend the equipment life before considering new equipment	there is no need for new bins for the next 5 years. In even longer term, the optimized usage of trucks in ELDIA case for waste collection could be defined in terms of trucks life extension and repairing/maintenance costs' reduction.
	Environment	Reduce non-renewable energy resource	8% fuel reduction at KLEEMANN and 15% at ELDIA as a result of monitoring and forecasting. The aforementioned reductions were achieved through the better collection planning in KLEEMANN's premises and ELDIA's supply network respectively.
		Global warming with air pollution	8% CO2 reduction related to fuel consumption at KLEEMANN and 15% at ELDIA
	Social	Enforce health and safety practices	Congestion caused by the collection procedure is eliminated. The employees empty only certain bins and only collect full or almost full bins. The quality of work and safety of employees are improved as the working environment remains cleaner and actions (wastes monitoring, collection and transportation) that can cause injuries are reduced to the minimum.
		Awareness on macro-economics	While a macroeconomic shift regarding employment and productivity is expected and recent studies (Švarcová et al., 2019) show an increasing trend of R&D human resources development (including Industry 4.0 projects), the rapid increase of China may worsen future competitiveness.
Collaboration	Joint Development	Reduction of non-value-added costs	Reduction in time spent on emails/phones due to the ecosystem for automated negotiations but also through the notification system.
	Logistics Integration	Leverage technology & enable information driven decision-making	Both companies are using the developed technology and the data analytics to assist their decision making. Analytics enable the planning optimization over a waste management related supply chain and the Ecosystem online bidding process assists purchasing manager in supplier selection process.
	Supplier Collaboration	Establish collaboration with suppliers using online systems	From the simulated scenario between KLEEMANN and ELDIA, a better interaction with suppliers related to communication channels, prioritisation of real needs and response time is observed. However, large scale interactions are needed to evaluate the online system.
	Customer response adoption	Customer Satisfaction – Cost, Quality, Timeliness	Decrease of collection time, reduction in cycle-times from process monitoring, reduction of order-to-delivery time and shipping costs by 15%The strength of an already good customer relationship is enhanced due to improved service. This is backed up by the response to a customer questionnaire – improved customer satisfaction
Management Strategy and Organization	Cost management	Monitor price-movements of components that impact profitability	Monitoring price is available through price forecasting for various waste types/ materials, which informs the waste management company for the future prices of various waste types by using a deep learning methodology in historical data of the company. Cost savings from process monitoring by 40%
	Time management	Automate expensive data management	Reduction of time by 50% based on the data entry management. Elimination of data entry steps.
		Mobile based communication systems	Earnings of 10%–20% in time especially by avoiding calls and emails.
	Value driven investment	Generate demand for goods and services	New sensors will be installed in 5 large customers, who expressed their interest in participating in the proposed solution.
		Anticipate risks and provide mitigation plans	The simultaneous call for more containers that could be managed is reduced due to the fill level notifications. This reduction is even larger by exploiting the capabilities of fill level trend analysis solution that enables the definition of the most aggressive fill level trends in customer bins in order to get higher priority during planning activity. Price and tonnage forecasting provides valuable information about future prices and transportation requirements of the different types of wastes.

5.1. Managerial implications

Apart from the above-mentioned benefits, this study provides clear managerial implications for companies that deploy or wish to deploy industry 4.0 solutions in order to improve the overall effectiveness of waste management through the connectivity and interaction among supply chain partners. In general, the proposed solution indicates new ways that managers can approach smart waste management procedures leading to SSCM. First, the framework for assessing SSCM for industry 4.0 is validated by real world cases. This can be used as a proof of concept that will encourage managers to adopt Industry 4.0 solutions in order to make better decisions for improving and redesigning their supply chain strategy in a more sustainable way. Second, the results of this study, revealed five key management areas that should receive careful attention in order to improve SSCM with the deployment of industry 4.0 solutions. Business based smart operations, technology based smart products, sustainable development, collaboration, management strategy and organization are the key strategic priorities that should be integrated in order to create more sustainable supply chains. Third, this work has proved the important role of industry 4.0 solutions in the development of sustainable supply chains. The use of IoT technologies that provide remote monitoring have a positive impact on the entire supply chain sustainability, since the resources are managed more efficiently and effectively. By adopting an online ecosystem such the introduced one, the negotiations over supply chain can be automated and time and costs can be reduced. Fourth, managers can use the proposed solution and framework as an assessment tool for benchmarking by evaluating the effectiveness and readiness of industry 4.0 developments to face business competition. Overall, the proposed solution and framework can be regarded as a guiding tool and an opportunity for managers to develop and navigate industry 4.0 solutions and processes towards SSCM, both in the firm-level and the supply-chain level.

5.2. Limitations and future research

Despite the fact that the study has revealed some key benefits for the two companies and offered managerial implications for other firms, there are a number of specific limitations that suggest future research proposals. First, this study is based on a dyadic supply chain relationship between companies located in one country, Greece. Hence, the findings are not necessarily generalisable and transferable to other countries and are not considering the supply chain as a whole. Future studies could investigate the specific solution and framework on larger supply chains and in other sectors worldwide to enable the generalisation of the findings. Most of the authors are already working on a circular economy IoT application in the European waste to energy sector. Furthermore, the reach and the depth of analysis is limited due to the fact that the assessment of SSCM in industry 4.0 is based on the developed technical solution. Therefore, a case study using interviews with the users of the solution could give further insights on SSCM performance with the use of industry 4.0 tools. While the study has addressed some key social criteria the need for providing better insights on the social dimension of supply chains towards the integration of sustainability in supply chains is still dominant (Bubicz et al., 2019). Future studies could investigate the social dimension of IoT/industry 4.0 applications in supply chain management. Finally, from an application point of view, the developed IoT enabled solution is a promising technique for both intra-factory and inter-factory sustainable operations, but further studies and tests are necessary to validate it and make it industrially viable.

CRediT authorship contribution statement

Theofilos D. Mastos: Conceptualization, Validation, Resources, Writing - original draft, Writing - review & editing, Supervision. **Alexandros Nizamis:** Conceptualization, Software, Formal analysis, Data curation, Writing - review & editing, Visualization. **Thanasis Vafeiadis:** Software, Formal analysis, Data curation. **Nikolaos Alexopoulos:** Software, Formal analysis, Data curation. **Christos Ntinas:** Software, Formal analysis, Data curation. **Dimitrios Gkortzis:** Investigation, Validation. **Angelos Papadopoulos:** Investigation, Validation. **Dimosthenis Ioannidis:** Supervision, Project administration, Funding acquisition. **Dimitrios Tzovaras:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

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