Architecture development to incorporate Industry 4.0 solutions to plastics management: Circular Economy

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Abstract

The problems caused by plastic waste and the current situation of the sector make it necessary to rethink processes and business models to ensure the sustainability of the sector. The need to develop a circular economy in the plastics industry and the actions this entails have already been identified in the literature, together with analyses of how these needs might be met through the use of technologies and enablers of Industry 4.0. The objective of the research project reported here was the preliminary design of a plastic waste management network that integrates the technologies and concepts of Industry 4.0 and the principles of the circular economy. For this purpose, the Industrial Internet Reference Architecture (IIRA) methodology was used to cover all stages of the life cycle of plastic products. A model combining the use of Industrial Internet of Things (IIoT) and Artificial Intelligence (AI) technologies to optimize plastic waste management is presented here as a sustainable technological and economical alternative with the potential to improve environmental, social and corporate governance for greater sustainability of the plastics industry. The holistic methodology adopted enabled the development of a versatile, adaptable and scalable architecture that will be of interest to public and private actors in the plastics value chain.

Keywords: Circular economy · Industrial internet of things · Plastics · Sustainable waste management.

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1 Introduction:

Global waste generation is increasing to such an extent that sustainable waste management has been rendered almost impossible. Traditional solutions such as landfill storage and incineration entail significant risks and are neither socially nor environmentally sustainable [1]. Given the crucial role of efficient and sustainable waste management within any circular economy, new technological solutions and industrial policies are urgently needed to facilitate and promote more sustainable options for waste management. Among the different types of waste resulting from human activity, plastic waste demands special attention. Already the main source of marine litter and, some 53 million metric tons of plastic waste per year are expected to pollute the oceans by 2030 [2]. Litter dispersed in the marine environment has a transboundary character and thus constitutes a major and growing global problem. Plastic waste alone accounts for 80–85% of this marine litter, of which 50% comprises single-use plastics and 27% comprises fishing-related products. Reducing such marine litter is a key aim of UN Sustainable Development Goals (SDGs) [3]. Any solution to the global problem of plastic waste will entail comprehensive efforts across multiple fields, including the following actions: reducing plastic waste at source; eliminating existing waste in the marine environment; reducing the use of plastic packaging; awareness-raising and education; applying the principles of the circular economy in seeking alternative uses for waste; and the design and implementation of public policies that support and facilitate all these actions [4].

It is now widely recognized, for example, that new Industry 4.0 approaches need to be developed and implemented in the field of waste management, including new systems that could be used in treatment plants to increase efficiency in waste treatment. These approaches include proposed systems for waste-sorting using robotic technologies, ‘smart containers’ with sensors for material detection and level measurement, methods for detection and sorting that make use of digital image analysis, as well as new business models [5]. In order to achieve a circular economy of plastics, however, it is first necessary to define a strategic vision for transforming today's challenges into future opportunities that involve all the agents along the plastics value chain. This is crucial to ensure that the envisioned paradigm shift includes a decisive role for society, academia, private companies, and public administrations, thereby ensuring a more sustainable solution.

The circular economy has been presented as a solution to two key problems: (i) reducing the amount of plastic waste; and (ii) ensuring the availability of raw materials for the production of new products through recycling. For these solutions to be realised, it is essential to develop tools that facilitate the management of plastic waste. The aim of this research was to design a reference architecture for an Industrial Internet of Things (IIoT) platform capable of processing data from key stakeholders at each stage of the life cycle of a plastic product.

2 Materials and methods:

For the development of this research and analysis of the results, the following three different methodologies were used to enable an optimal approach and implementation for each section: (1) Study of life cycle stages; (2) IIRA; and (3) Metrics.

2.1 Study of life cycle stages

In accordance with the objectives of this study, we applied a methodology based on life cycle analysis (LCA) in accordance with ISO 14040:2006 [6] and ISO 14044:2006 [7] to examine the different stages of the life cycle of a plastic product and to ascertain the role of the stakeholders involved throughout the value chain. Given the aim of developing a general and qualitative solution to plastic waste, this study did not involve phases 2 and 3 of the LCA, i.e. the inventory analysis and impact assessment stages, but focussed instead on the first phase of the LCA in order to identify the stages of the life cycle according to a cradle-to-cradle model [8]. In such models, the product is recycled or reused and employed as raw material at the end of its useful life, thereby closing the material loop.

2.2 Industrial Internet Reference Architecture (IIRA)

The information was also structured according to the four viewpoints that make up the Industrial Internet Reference Architecture (IIRA)

[9], outlined as follows: Business viewpoint, Usage viewpoint, Functional viewpoint and Implementation viewpoint.

2.3 Metrics

Finally, the selected indicators were evaluated qualitatively. A quantification was estimated on a scale of 1–-4 based on a qualitative evaluation (1: very negative impact; 2: negative impact; 3: positive impact; 4: very positive impact). The values obtained for each indicator were then normalized according to the number of dimensions affected. Once the normalized values have had been obtained, they were added together to obtain an overall value between 0 and 1. This gives overall value thus indicates result of the degree of contribution associated with each suggestion proposal for the plastics sector.

3 Results and discussion

We propose a plastic waste management network that integrates the principles of the circular economy with enablers of Industry 4.0 and the viewpoints of the Industrial Internet Consortium. The central node of this proposed network is a data analysis platform offering various end-user services related to plastic waste management. The platform should be useful to improve decision-making and to optimize the different stages of waste collection and management. Open-source based tools are proposed in accordance with the objective of minimizing costs without affecting the quality of the service offered. The way the tool should work is illustrated in Fig. 1.

As illustrated in Fig. 1, the solution involves the following steps:

A.- Gathering information from sensors. The fill-level of waste containers and waste retention networks is monitored using IIoT sensors, i.e., ultrasonic level-measurement sensors, long-distance communications using LoRa, data transmission between sensors and broker using MQTT, and applications for sensor networks using protocols such as ZigBeePRO, WirelessHART, ISA100.11a or WIA-PA [10]. For sensor communications and M2M in general, Bluetooth Smart, MQTT or LoRa protocols can be used to communicate with the gateway. In turn, stakeholders can address the platform via MQTT [11] with the open-source Eclipse Mosquitto software. The PubSub pattern of this protocol is tailored for situations in which it is not guaranteed that all devices will be connected to the network at the same time, meaning it can be used to easily establish many-to-many communications.

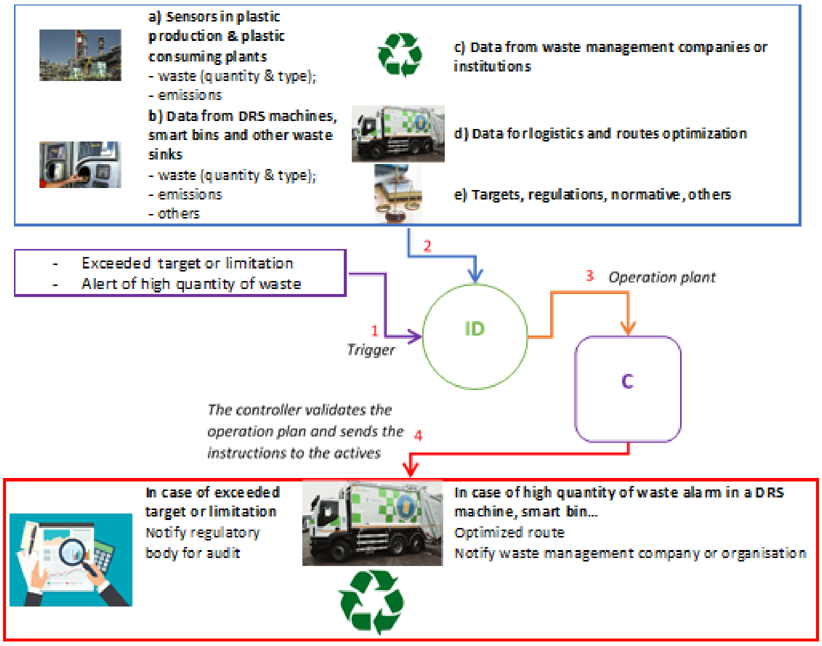

Fig. 1. IIRA Usage Viewpoint (ID: Intelligence director; C: Controller)

Source: The authors, based on data from the Industrial Internet Consortium (IIC 2019)

B.- Providing information to the database. For communications with the context broker, production performance management protocol (PPMP) can be used. This protocol guarantees interoperability among different types of devices and software. It is a flexible protocol that does not present compatibility problems. Data storage is an essential enabler for this type of application, MongoDB is an open-source NoSQL database system that stores BSON data structures with a dynamic schema, making for easier and faster integration of data in certain applications.

C.- Data analysis and visualization through dashboards and reports. Within the proposed system, the fill-level of smart bins or deposit return system (DRS) machines in each area would be analysed to determine the number of containers needed in each location and to optimize the logistics of the waste-management service. Moreover, algorithms may be developed to determine which routes to take and when to act in order to achieve optimal waste collection on the basis of the fill-level of different containers and forecasts of this level in the future, combined with real-time data on geography and traffic conditions. Selecting data transmission in small blocks of minutes is preferred in order to minimize the cost of the tool. The Apache tool called 'Hadoop' would be used. For open-source data visualization, Grafana could be a good option to integrate with FIWARE.

D.- Reporting results to stakeholders. All relevant information would be communicated to each stakeholder, taking account of their various interests and using whichever formats provide the most added value for the stakeholders in each case. The implementation of the system described above is illustrated in Fig. 2.

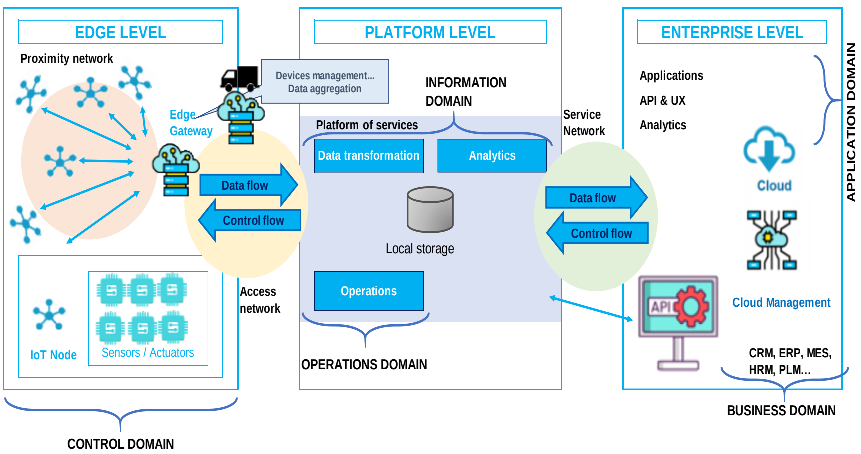

Fig. 2. IIRA Implementation viewpoint (3-tier architecture)

Source: The authors, based on data from the Industrial Internet Consortium, (2019)

The proposed solution presents a versatile model for networks of companies interested in the management of plastic products. The results obtained after the analysis are shown in Fig. 3.

Thus obtaining the result as a percentage for each dimension:

- Economic vector: 22 / (8 x 4) = 0.69 / Positive impact.
- Environmental vector: 23 / (6 x 4) = 0.96 / Very positive impact.
- Social vector: 21 / (6 x 4) = 0.88 / Very positive impact.

Indicators	Classification			Dimension		
	Ec.V	**En.V**	**So.V**	**Ec.V**	**En.V**	**So.V**
Initial investment	**X**			**2**		
Return on investment, ROI	**X**			**2**		
Payback, PB	**X**			**2**		
Energy consumption	**X**	**X**		**4**	**4**	
Maintenance cost	**X**			**2**		
Benefits for companies	**X**			**4**		
Jobs generated	**X**		**X**	**3**		**3**
Jobs eliminated	**X**		**X**	**3**		**3**
Carbon footprint		**X**	**X**		**3**	**3**
Amount of waste reduced		**X**	**X**		**4**	**4**
Percentage of waste recycled		**X**			**4**	
Percentage of waste incinerated		**X**			**4**	
Percentage of waste in landfills		**X**			**4**	
Benefits for citizens			**X**			**4**
Time saved for citizens			**X**			**4**
TOTAL	**8**	**6**	**6**	**22**	**23**	**21**

Fig. 3. Indicators for the results analysis

Source: The authors

4 Conclusions

The three most pressing problems in the management of the plastics sector are (1) the overproduction of material, (2) the accumulation of waste, and (3) the large carbon footprint. The management network architecture proposed offers three possible solutions to these problems. First, the application of circular economy models based on extending the life of products with preventive maintenance based on sensors and product monitoring. Second, a product-as-a-service approach in which the company offers the security of a service and is responsible for preventive and corrective maintenance. In this model, a win-win situation is achieved by extending the useful life of the product, which in turn improves the service offered and increases customer satisfaction. In addition, at the end of a product's useful life, the company itself can take the waste to reuse or recycle some of its parts and deliver a new product to the customer. Third, ecodesign and reuse of materials to facilitate the waste management stages is essential to mitigate current overproduction of plastic and reduce the intensity of material used. A system is also proposed based on the monitoring and sensorization of products and the systems to which they are subjected during their life cycle. This is done with the aim of generating an exchange of knowledge among the stakeholders of the plastic value chain. This exchange should enable an improvement in the efficiency of current waste management. DRS models and smart containers are proposed to improve the recovery of single-use products.

The proposed solution constitutes a versatile architecture for the implementation of a plastics management system. The model can be used for the control of plastic flows within towns and cities or communities at public level or in collaboration with networks of private companies. The results of this research can help improve plastic waste management planning as well as plastic waste recycling.

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