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RESEARCH PAPER

An IoT-enabled Decision Support System for Circular Economy Business Model[1]

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Abstract

The traditional linear economy using a take-make-dispose model is resource intensive and has adverse environmental impacts. Circular Economy (CE) which is regenerative and restorative by design is recommended as the business model for resource efficiency. While there is a need for businesses and organizations to switch from linear to circular economy, there are several challenges that needs addressing such as business models and the criticism of CE projects often being small-scale. Technology can be an enabler towards scaling up CE however, the prime challenge is to identify such technologies that can allow predicting, tracking and proactively monitoring product's residual value to motivate businesses to pursue circularity decisions. In this paper, we propose an IoT-enabled Decision Support System for circular economy business model that effectively allows tracking, monitoring and analysing products in real-time with the focus on residual value. The business model is implemented using an ontological model. This model is complemented by a Semantic decision support system. The semantic ontological model, first of its kind, is evaluated for technical compliance. We applied Decision Support System (DSS) and the ontologicalmodelinareal-worldusecaseanddemonstrateviabilityandapplicability of our approach.

KEYWORDS:
Circular Economy, Industry 4.0, Internet of Things, Circular Supply Chain Management, Decision Support Systems, Zero waste, Semantic Technology

1 | INTRODUCTION

The United Nations has forecasted that by 2030, the world will need to double the current resources to catch up with the rate of global production, consumption and population growth[1]. However, if growth could be sustained in a world with finite natural resources remains a prevalent question[5]. According to the European Commission, the two objectives of resource

[1] **Abbreviations:** IoT, Internet of Things; 5G, Fifth Generation Mobile Communications Networks; IMCD, Intelligent Material Circularity Detector; CSC, Circular supply chain; DSS, Decision Support Systems; RDF, Resource Description Framework; OWL, Web Ontology Language; EMF, Ellen MacArthur Foundation; CEBM, Circular Economy Business Model. [1]Ellen MacArthur Foundation (EMF) https://www.ellenmacarthurfoundation.org/

efficiency are sustainable utilisation of natural resources and minimal impact of natural resource extraction[1,2]. These objectives are geared towards addressing waste due to inefficient use of resources. A report, “The New Plastic Economy”[3] by Ellen MacArthur Foundation (EMF)[1] presented at the World Economic Forum (WEF) forecasts that by 2050, there will be more plastics than fish by weight in the ocean if the current habit of waste generation from production and resource consumption is continued. In fact,

scarcity of metals and minerals in manufacturing industry has been described as a ticking time bomb[4]. To address these issues it is required to switch from linear economy (take-make-dispose) model, to Circular Economy (CE) which is a restorative and regenerative model.

CE is "based on the principles of designing out waste; keeping products and materials in use longer, and regenerating natural systems"[7]. It is a deviation from cradle-to-grave (linear) to cradle-to-cradle[2] (circular) design concept, which minimises waste generation, making energy recovery from materials the last option, contrary to the status quo. In this paper, "a product is anything that is manufactured and offered to customers for use, via sale or other access models"[44]. CE is widely being accepted as an alternative model due to its regenerative and restorative design concepts as seen in CE100[3] network created by EMF[7]. CE concept dates as far back as 1970 but has gained ground lately[8] and is considered promising in terms of resource efficiency, safer environment and long-term business profits. One area where CE has been investigated is in the Supply Chain (SC) field. Circular supply chain (CSC) has been proposed for closing the loop[21]. However, in enabling CSC, there are several limitations such as finding and utilizing appropriate enabling technologies[10,11]. These technologies could facilitate adoption of CSC and, consequently support CE business models to leverage the benefits[12] which include efficient resource utilisation, optimised cost benefits, maximum profits, business opportunities and safer environment. One of the criticisms of circular economy is lack of scaling up, however; technology could be an enabler for scaling circular business model.

Technology such as Internet of Things (IoT)[29], Cyber-Physical Systems (CPS)[15,35], Fifth generation mobile networks (5G)[31], Cloud Manufacturing[6,14] and Additive Manufacturing[15], in short Industry 4.0 suite of technologies presents great and effective opportunities to realise resource saving, eco-friendly and sustainable manufacturing[16]. The goal of Industry 4.0 includes higher level of automation, productivity and operational efficiency[18]. The extant research that utilises Industry 4.0 for addressing the requirements for CSC implementation is limited and do not sufficiently address resource flow and efficiency issues in implementing CSC[17, 19].

In particular, our work and contribution to this field in combining CSC and Industry 4.0 focuses on addressing two key challenges of CSC. First, uncertainty of products residual value often leading to the lack of understanding of the value that will be created from CSC. This is a substantial obstacle in business adoption of CE[10, 20]. Second, as pointed out by Mishra et al.[21], the cost of collection, treatment, segregation of products, components and materials is another barrier to adopting and creating value from circular business model. In the face of these challenges, organisations are having difficulty in capturing value by adopting circular economy business model (CEBM). Building Decision Support Systems (DSS) – which are commonly used for “supporting decision making often involving myriad information sources and complex alternatives”[13], is a potential solution to these challenges. We propose a model-driven DSS[4], first of its kind for supporting circularity decisions. To implement our DSS, we propose and utilise a novel CSC model enabled by IoT and 5G, and underpinned by Semantic Web technologies. IoT technology plays a crucial role in our DSS as sensors are utilised to capture and transmit data over IoT networks, which is essential to providing real-time tracking and monitoring of products[30].

Remaining part of the paper is organized as follows; first, we outline the literature review on the need for switching to CE, existing approaches to combine Industry 4.0 and CE, and use of the Semantic Web technologies for building DSS. In section 3, we propose our novel IoT-enabled decision support system for circular economy business model. This section also outlines how Semantic Web technologies are utilised to design and develop a central component of the DSS. In section 4, we present

[2] "The Cradle-to-Cradle framework focuses on design for effectiveness in terms of products with positive impact and reducing the negative impacts of commerce through efficiency". https://www.ellenmacarthurfoundation.org/circular-economy/concept/schools-of-thought

[3] "CE100 is a Network that provides a pre-competitive space to learn, share knowledge, and build new collaborative approaches." https://www.ellenmacarthurfoundation.org/our-work/activities/ce100

[4] “a DSS that operates on some model of reality, in order to optimize or simulate outcomes of decisions based on data provided”[13]

an experimental study with a real-world use case, and data sets to demonstrate the value-add offered by our model and the DSS. Finally, we conclude the paper with our findings and insights for the future work.

2RELEVANT LITERATURE

2.1 The need to Switch from Linear to Circular Economy

The status quo of business model today is described as linear where manufacturers extract raw materials, make products for consumers who will dispose them after use[7]. This traditional take-make-dispose model not only creates waste but could be hazardous to the environment, energy-consuming and resource-intense[2]. Unfortunately, we live in a world where resources are

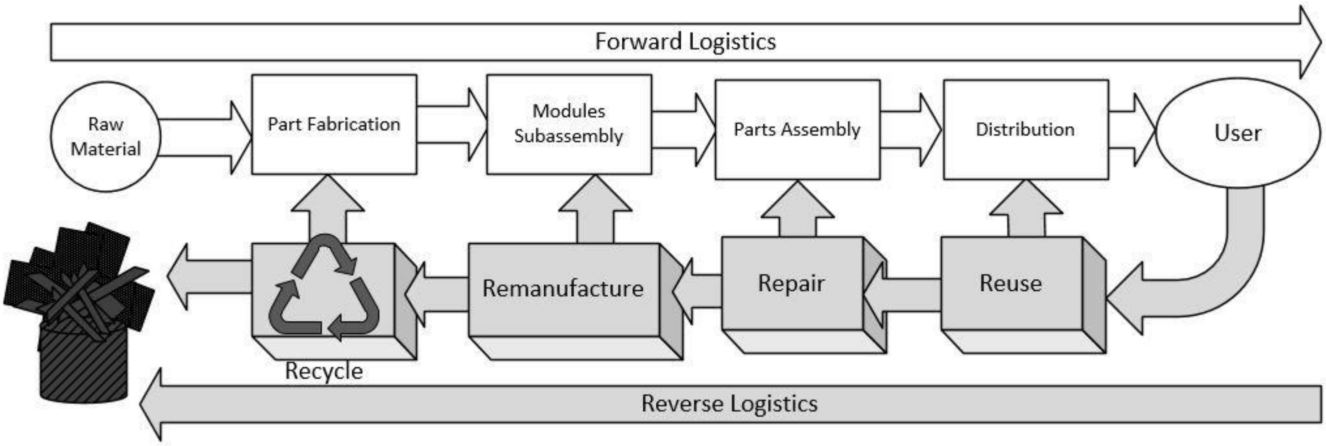

FIGURE 1 Differences between forward and reverse logistics. Adopted from Hanafi[45]

finite. Hence, resources need to be used with caution at different stages ranging from manufacturer to the consumers. CE model is proposed as a resource efficient alternative where products could be used for longer thus capturing value for businesses.

CE is an industrial system that is restorative and regenerative by design and intention[7]. The End of Life (EOL) concept is replaced by shifts toward restoration, supported by using renewable energy and avoiding use of toxic chemicals that negatively affect reuse and return of materials to biosphere. It aims to eliminate waste completely by rethinking the economy via superior design of materials, products, systems and business models. It should be noted that, although CE is normally associated with recycling, they are not the same. CE deals with several materials cycles with their powers which reduces waste greatly[7], contrary to recycling economy today which still generates large amounts of waste[5].

The term material circularity in CE stems from a "butterfly diagram" in a report by EMF[7] where materials are categorized into biological and technical cycle. The strategy of the biological cycles is to restore nutrients to the biosphere while rebuilding capital. In the technical cycle, usually for products produced from non-biodegradable materials, same strategy is used however, through repair, reuse, remanufacture/refurbish, recycle or cascade path[6]. Thus, products made from technical materials are maintained and reused, thereby preserving value and increasing the usage period, while minimizing the waste to the landfill. Material circularity helps to create more value by product life extension, component life extension and material recovery[15, 26]. "Product/components life extension is the postponement or reversal of the obsolescence of a product/component, starting a new usecycle, either through reuse, repair or refurbishment"[44].

[5] Recycling and the circular economy not same. https://www.ellenmacarthurfoundation.org/news/recycling-and-the-circular-economy

[6] Butterfly diagram animation https://www.youtube.com/watch?v=EqBivOsNtFg

There are however, key challenges in adopting CE in practice by organisations. First, uncertainty of products residual value leading to lack of understanding in the value that will be created from CE is a substantial obstacle in businesses adoption[10, 20]. Second, as pointed out by Mishra et al[21], the cost of collection, treatment, segregation of products, components and materials is another barrier to adopting and creating value from circular business model. Organizations are therefore facing difficulties in deciding which business model to choose that can support decisions related to these challenges while focusing on capturing value.

There are two types of popular logistics models in practice: *Forward logistic*, defined "as the part of the SC process that plans, implements, and controls the efficient, effective flow and storage of goods, services, and related information from point-of-origin to the point-of-consumption in order to meet customers' requirements"[43]. *Reverse Logistics* which focuses on the movement of goods in the opposite direction, is defined "as the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal"[45]. Reverse logistics consist of collection, testing/inspection, separation, reprocessing and redistribution activities. These two logistics concepts are illustrated in Figure 1. For the circular supply chain (CSC), the loop needs to be closed[21], i.e. there should be both element of forward and reverse logistics.

EMF predicted that by 2020, about 82 billion tonnes of raw materials would have entered the global economy which is a rise from 65 billion tonnes in 2010. There is no guarantee that part or all of these resources will be reused[7]. These challenges necessitate conceptualisation of an alternative business model. CSC, focus of this work, is the linking of the end of linear SC to its beginning to target a "zero landfill" economy[9] in order to achieve the goals of a CE. We present such a Circular Economy Supply Chain model combined with a Decision Support System (DSS) that leverages the new disruptive technologies such as IoT, 5G and Industry 4.0 to address these challenges. Our model encourages reuse, repair, remanufacture, recycle and cascade cycle to capture value from products and materials after their initial life, making energy recovery the last option as against the status quo.

From ResCoM[44], we adopt the following definitions: "*Reuse* is a term covering all operations where a product is, or its components are, put back into service for a new usecycle"[44]. In our context, Reuse refers to directly putting the product or its components into service without upgrade. *Repair* is intended to "correct specific faults in a product to bring it back to satisfactory working condition". *Remanufacture* "denotes the process of disassembly of products into components, testing and recombining those components into a product of at least original performance"[44]. *Recycling* is the "process of recovering material from products at the end of their lifecycle"[44]. The recovered materials may feed back into the process as feedstock for the original or other purposes. *Cascade* here refers to recovered materials which can no longer be used by the same company or cannot be used for the original purpose but can still serve another purpose whether in the same company or a different company. For instance, textile material can serve different purposes, from clothing to furniture and carpeting[21]. A "*lifecycle* of a product begins when it is released for use after it has been manufactured or remanufactured. It ends when it is disposed of (landfill/material recycling) or dismantled to harvest/reuse its components"[44]. Most components' lifecycle can continue in new product after ending its initial lifecycle. "A *usecycle* of a product begins when it is released for use to a certain purpose. It ends when the user of the product changes; for instance, via resale, redistribution or assignment to a different user as part of a service model. It also ends when the lifecycle of the product ends. A new usecycle of a component of a product starts if the component is reused as part of a new product"[44]. The next section will discuss the integration of Industry 4.0, 5G and IoT with CE.

2.2 | Industry 4.0, 5G and Internet of Things (IoT) Integration for Circular Economy

Industry 4.0 is described by Blunck[19] as "the digital transformation of the manufacturing industry, accelerated by exponentially growing technologies, such as intelligent robots, autonomous drones, sensors and 3D-printing". This new concept was launched in Germany in 2011 that brings together digital manufacturing and Information Technologies (IT)[34]. The core concept of Industry 4.0 is the interconnection of employees, machines, orders, suppliers, customers and electronic devices with IoT.

Vermesan and others[27] defined IoT as "a concept or paradigm that considers pervasive presence in the environment of variety of things/objects that through wireless or wired connections and unique addressing schemes, are able to interact with each other and cooperate with other things/objects to create new applications/service and reach common goals". The basic idea of IoT is "pervasive presence around us of a variety of things or objects – such as Radio-Frequency Identification (RFID) tags, sensors, actuators, mobile phones, etc. – which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbours to reach common goals"[28]. This enables systems built on IoT an ability to track things/objects anywhere and in real-time, a feature exploited in our model for decision support system[51]. Every product manufactured can be embedded with IoT module or radio chip and product passport[52] which is shared between businesses, SC providers and products' end users. According to the European Resource Efficiency Platform [7], a product passport is to contain crucial information such as identity of a product placed on the market similar to the way a passport contains crucial information about its holder[8]. The product passport contains and provides all the necessary data about the product, while IoT module senses and communicates with the real-time analytic centre each time its host product is used. This will help companies/businesses track and monitor real time status of products by collecting and sending important data for critical business decisions. Our focus is to gather products' real-time usecycles and lifecycles data for business analysis. IoT however still has considerable challenges centered on reliable connectivity[9] that make its deployment difficult not only for individual organisations but the entire SC[10, 29].

The 5G and its ubiquitous connection capability helps to overcome the connectivity challenges associated with systems relying on IoT devices. 5G has several other characteristics that aids IoT-driven systems which we want to exploit in our work. These systems need high data rate, flexible bandwidth, low energy consumption, low latency especially for real-time sensing[30] and ubiquitous and pervasive networking offered by 5G[31,32]. As 5G is highly anticipated[33] for latency critical IoT applications as a key target[30], researchers are proposing different solutions for future networks and this will play a key role in future CSC.

According to Roblek[35], smart products are formed when "products are inserted with sensors and microchips that allow communication via IoT with each other and with human beings. Cars, T-shirts, watches, washing powder, and so on, are set to become "smart" as their makers attach sensors to their packaging that can detect when the product is being used and can communicate with smartphones when scanned." This will provide companies with the advantage and ability to track and monitor these smart products real-time and make optimized business decisions from the resulting smart data. Our model and the decision support system builds on this promise of Industry 4.0 on powerfully combining IoT and 5G to enable CE by manufacturing smart products where data can be collected on real-time basis.

There is limited research which investigated Industry 4.0 technologies for Circular Supply Chain to build a decision support system. Work presented by Genovese, Acquaye, Figueroa and Koh[11] involves the use of hybrid life cycle assessment (LCA) on two case studies to compare linear and circular production based on linear SC and CSC, however, they do not utilise automated real-time data driven DSS model for tracking, monitoring and analysis of products and components. Other methodologies which could either be the traditional bottom-up LCA model or top-down LCA model are termed incomplete as both rely on manual data collection[36]. Such data is not reliable and the models can hardly work for a complex product to capture all the components. In the next section, we will discuss how semantic-driven DSS model can be implored for decision support systems for CEBM.

2.3 | Semantic driven Decision Support Systems for Circular Economy Business Model

Decisions Support (DS) is a social science concept that supports managers in making decisions. It could start with any basic tool or application such as a spreadsheet. Decision Support Systems (DSS) are DS tools which when combined with IT, results in expert system[13]. DSS is therefore defined as any system built to support and improve effectiveness of decision-making[22,23]. There is limited research in extant literature which investigates DSS to support decisions for Circular Economy business models. Kifor, Oprean and Banciu[39] considered DSS for assisting making decisions in Advanced Product and Process Planning

[7] European Resource Efficiency Platform https://ec.europa.eu/environment/resource_efficiency/re_platform/index_en.htm
[8] Make resource count http://makeresourcescount.eu/whats-a-product-passport-and-can-it-work-for-businesses/
[9] ConnectivitychallengesthreatentoderaillogisticssectorIoTambitionshttps://www.inmarsat.com/news/connectivity-challenges-threaten-to-derail-logistics-sector-iot-ambitions/

and Design (APQP)[10]. The purpose of their work may to reduce or eliminate deficiencies such as “geographical distribution of meeting participants, the subjectivism, and the dominant characters of some members, the social pressure, and the constraints”. Gaur, Amini and Rao[41] consider “Closed-loop supply chain configuration for new and reconditioned products” using a decision support system with the focus on a firm’s profitability and performance, in contrast to our focus on product, material circularity and resource efficiency.

According to Blomqvist[13], one of the most basic needs of DSS model is easier and more flexible information integration methods. Semantic technologies are proven to support such information integration needs for building DSS[37,38]. Semantic technologies including RDF/OWL[42, 47] and Linked Data[53] provide a mechanism for formal data representation in DSS systems[54]. These data representations standards also make it easier to personalise and contextualise data, in order to create tailored filters, views and analysis mechanisms which are key to any DSS. There are a number of studies dedicated to using Semantic Web technologies for building a DSS[37, 41].

Our data-driven model and corresponding DSS, built using Semantic Web technologies and underpinned by IoT and 5G, is the first of such model for CEBM.

3 | PROPOSED MODEL: A SMART CIRCULAR ECONOMY MODEL TO SUPPORT CIRCULARITY DECISIONS

3.1 | Model development

In Figure 2, we describe our novel, IoT enabled DSS for CEBM to have resource efficient economy. One of the main features of our model is the combination of forward and reserve logistics models (see Figure 1), with inclusion of IoT, to create a circular model. The model, through circularity, improves the traditional forward logistics model to avoid waste generation in linearity, and exploits reverse logistics model through various loops; reuse, repair, remanufacture, recycle and cascade, thereby phasing out the linear system with its waste. It also closes the linear model loop through several re-commerce routes as defined in our model in Figure 2.

This model works alongside the principle of material circularity indicators as presented by EMF[26] where manufacturers are provided guidelines to choose materials with greater circularity over those with less circularity and implementing additive manufacturing as an industry 4.0 concept where possible. The IoT integration process starts from the manufacturing process where all the products are made IoT-enabled by embedding them with sensors and smart chips (IoT module) for real-time information tracking via 5G-enabled industrial networks. For our model, two parameters are tracked, *usecycle*, and *lifecycle* for each of the components and the assembly unit of the product. The sensor integration for this monitoring happen right at the modules sub-assembly stage (shaded in Figure 2) before parts are coupled to make the product and then packaged for market distribution. The smart component can be powered by same source of power that powers the product every time it is used or for passive products, reliable small-size power sources can be used. The IoT chip embedded in the product senses and collects data each time the product is in use and transmit it back to decision support system (explained in section 2.3) where it’s been monitored in real-time as shown in Figure 2. The products are then monitored in real-time and sensor data collected and analysed for useful business decisions and inferences as in Figure 3 to make either of the following decisions, supported by the Intelligent Material Circularity Detector (IMCD), Shown as a diamond in Figure 2) of the model. Working of the IMCD are explained in section 3.3

Reuse cycle: This route represents products that are still functional after initial use and can be directly reused without requiring upgrade of any kind after it is examined by the IMCD.

[10] APQP stands for Advanced Product Quality Planning, "a structured process aimed at ensuring customer satisfaction with new products or processes". Retrieved from https://quality-one.com/apqp/

Repair Cycle: This cycle represents products which are still in good condition and all components still operational, but might have a minor technical hitch that need fixing. The product is ready again for market distribution after performing the needed minor repair.

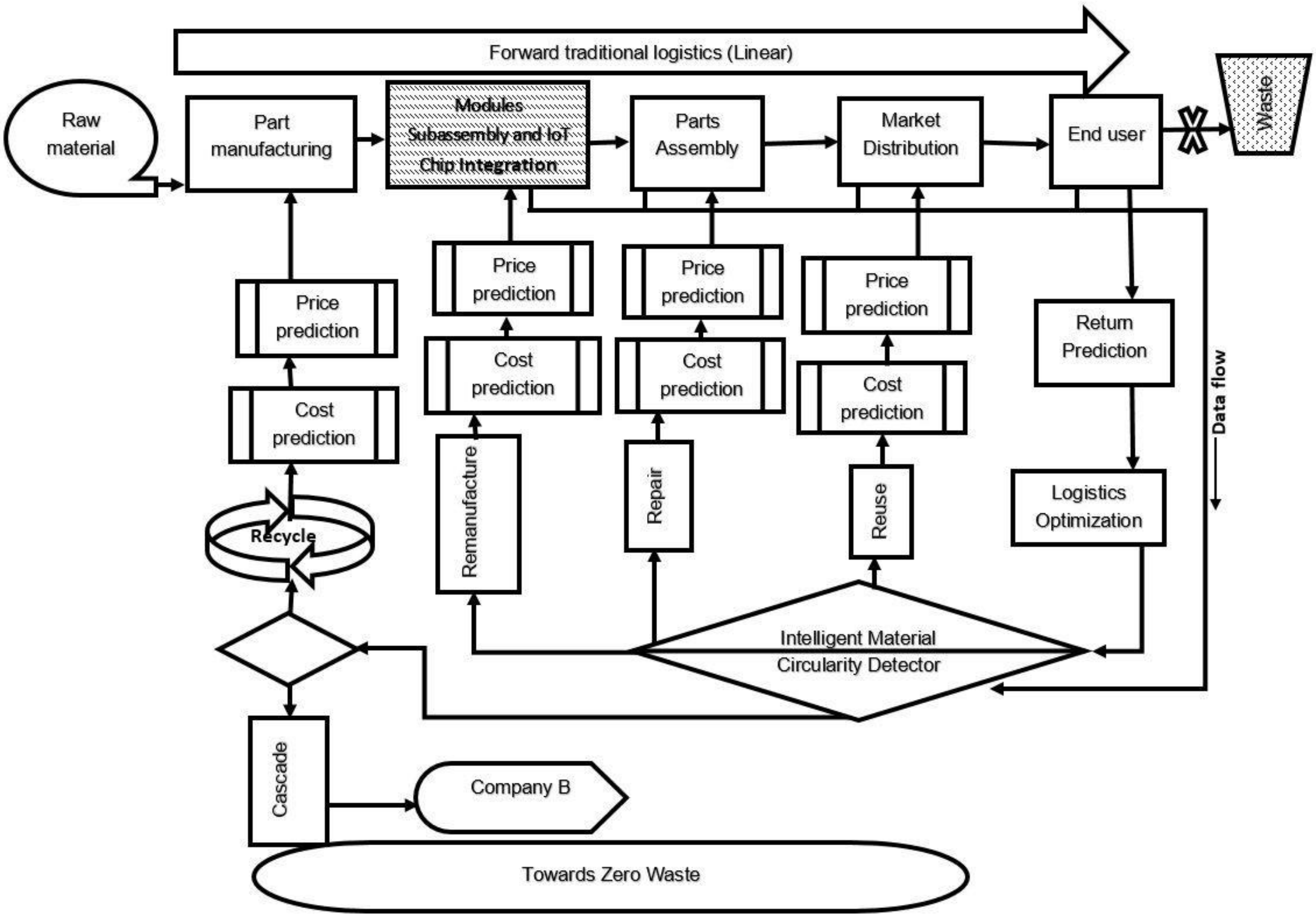

FIGURE 2 Smart Circular business model for Circular Economy Enabled with IoT

The Remanufacture cycle: This path represents products which might have malfunctioned due to a number of faulty components. This does not require manufacturing a whole new product but just the faulty part(s) and the whole product is refurbished, ready for new user and sent back to the market.

Recycle Cycle: This loop ensures that the parts of a product not suitable for the aforementioned cycles are properly recycled to avoid leakage of material as waste. This could be components replaced from the remanufacturing loop or it might be a whole product that is no longer suitable for reuse, repair or remanufacture. If all the components of a product have reached or close to the end of its lifecycle or usecycle, the best option for such product will be to recycle efficiently, which our IMCD will suggest that.

Cascade cycle: This cycle entails passing a product that cannot be used again within the same industry/company but its materials can still be recovered and used in another industry/company for a different purpose altogether. This will ensure that energy recovery from product is the last resort after higher-value products or services are exhausted. This way, nothing goes to landfill meaning zero waste for the first company and the cycles continues with a second company without waste as well though our work is only limited to the first company for the purpose of this research.

Return prediction: The products are expected to be returned after certain conditions are noticed by users which might be based on functionality, usecycles, lifecycle, and user's preferences. With the real-time data collected and continual feedback from users, it is then possible to predict and even work out the product return logistics[40]. This will not only provide businesses with an optimised reverse logistics but also determine the kind of routes to collect the product, the right incentives and future market value of the returned products which is one of the challenges businesses are facing in switching to CE.

It is well known that material circularity has a way of influencing production efficiency directly[24] and we have selected a cost function as shown in Equation 1[50] to reflect this. As per this function, Total cost (TC) depends on wage rate (w), quantity of labour (L), price per unit of capital services (r) and quantity of capital (K). Hence, any of the cost factors in this formula that can be minimised will have an impact on the total cost.

$$TC = wL + rK \tag{1}$$

From Equation 1, it can be seen that by enabling the possibility of reuse cycle, our model provides a way to reduce all other factors since there is no need for new manufacturing. This also shows the benefit of a model like ours that can support circularity decisions based on IoT data.

The following section illustrates how the IMCD using real-time monitoring of sensor data from products, can support aforementioned decisions.

3.2 | Intelligent Material Circularity Detector (IMCD)

Data obtained from products with the aid of IoT and 5G technologies will be analysed to make decision on the future flow of the returned products. Five outcomes are possible as seen in Figure 3. Every product will be monitored against functionality first, if it is functional, re-commerce is possible without further analysis but if not functional, component by component test is necessary to detect which component has failed and that may either lead to repair, remanufacture, recycle or cascade loop (see Figure 4) depending on the result of the working memory Table 1.

The IMCD is dependent on the principle of rule-based system that makes decision despite the uncertainties and ambiguities that surrounds returned products and those still with end users regardless of their locations since the data from the product is tracked and collected real-time. The factors considered includes but not limited to material lifecycle, product usecycle, and current status of the product. Each product is constantly and automatically monitored for reusability and failure by selecting each constituting components and testing it for functionality at the IMCD (Figure 4), which ensures that the material stays longer in use via different cycles thereby maximising the yields from it.

In the next subsection, we outline how these rules are developed using Semantic Web technologies.

3.3 | IMCD Model and Inference Engine Implementation using Semantic Web Technologies

3.3.1 | Ontology conceptualisation

Semantically augmented ontologies can be used for building rule-based systems[48].The model proposed in this paper is implemented as an ontology in Protégé using Web Ontology language version 2 (OWL 2)[42,47]. Each of the possible outputs of each product is created as a subclass of either functional or non-functional superclass of the product as depicted in Figure 5. This

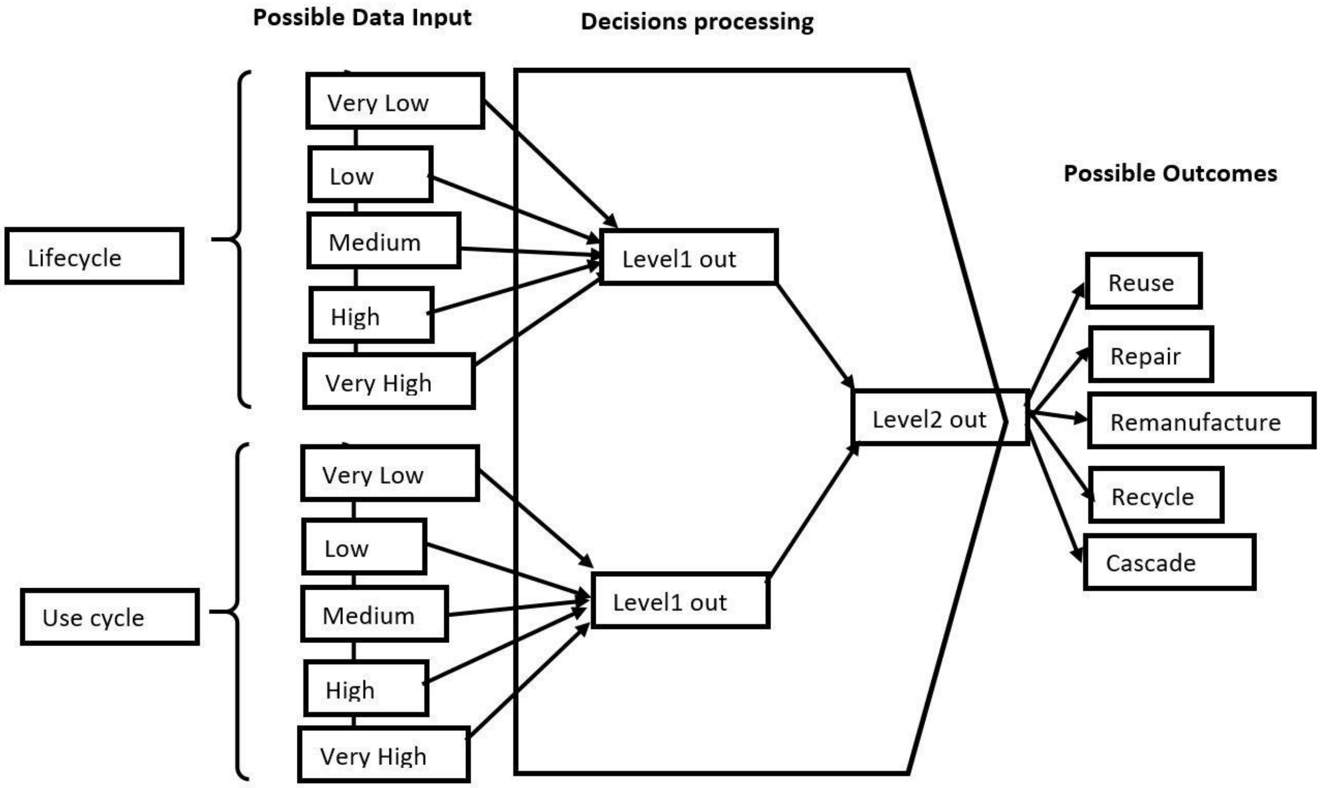

FIGURE 3 IMCD Inference Engine.

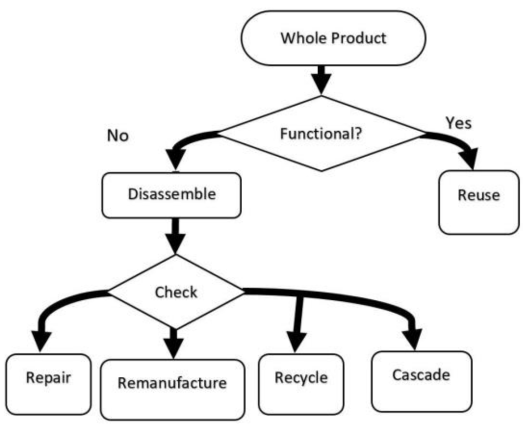

FIGURE 4 Initial and First Level decision of the model.

ontology is a depiction of concepts described in Figure 4. We created each class to be equivalent of conditions which meet the requirement for the class based on the usecycle and lifecycle. In Protégé it is possible to create data restrictions for different classes based on the logical rules desired for such class. We therefore use data property restrictions to differentiate the classes from other sibling classes.

It is not possible for a product that is for reuse to still be for recycle or any other class, so each subclass is disjointed from sibling class(es) for both the high and the low level. Two data properties; “UseCycle” and “LifeCycle” were define as the sub properties of super property "usage time". The conditions from very low UseCycles to very high UseCycles are declared as integers and defined for reusability and failure analysis as discussed earlier. The entire ontology is shown in Figure 6.

TABLE 1 IMCD Working Memory Decision matrix.

LifeCycle / UseCycle		VeryHigh	High	Medium	Low	VeryLow
VeryLow		Reuse				
Low		Reuse				
Medium				Cascade		
High			Remanufacture			
VeryHigh					Recycle	

TABLE 2 Circularity Decisions Model Ontology features.

Feature	Value
Classes	17
Number of properties	2
Number of individuals	10
Number of axioms	67
Logical axiom count	20

Figure 6 also show the ten different instances or individuals from our data set data (c.f. Table 5) from a coffee machine use case.

The features of the ontology are described in Table 2.

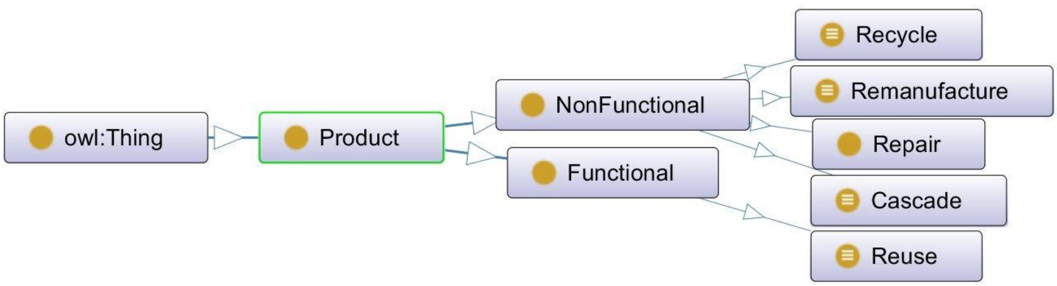

FIGURE 5 Classes and subclasses up to third level of the ontology.

These classes are then used to define rules as defined in Table 1, and each contains and are guided by IMCD rules that determine the real-time status of each product.

3.3.2 | Ontology/Rules layer

The rules shown in table 1, as conceptualised in our decision support system, are implemented using Semantic Web Rule Language,and it builds on the ontological concepts in previous section. Simplified examples of the semantic rules are shown in Table 3. The use of semantic technologies allows the ease of changing and customising rules. The following provides explanation of each of the rules described in Table 3 regarding products and components.

R1. For functional product/component, if the usecycle is low and Lifecycle is very high, recommendation will be direct *reuse*.
R2. For functional product/component, if the usecycle is very low and Lifecycle is very high, recommendation will be *reuse*.
R3. For non-functional product/component, if the usecycle is very high and Lifecycle is low, recommendation will be *recycling*.

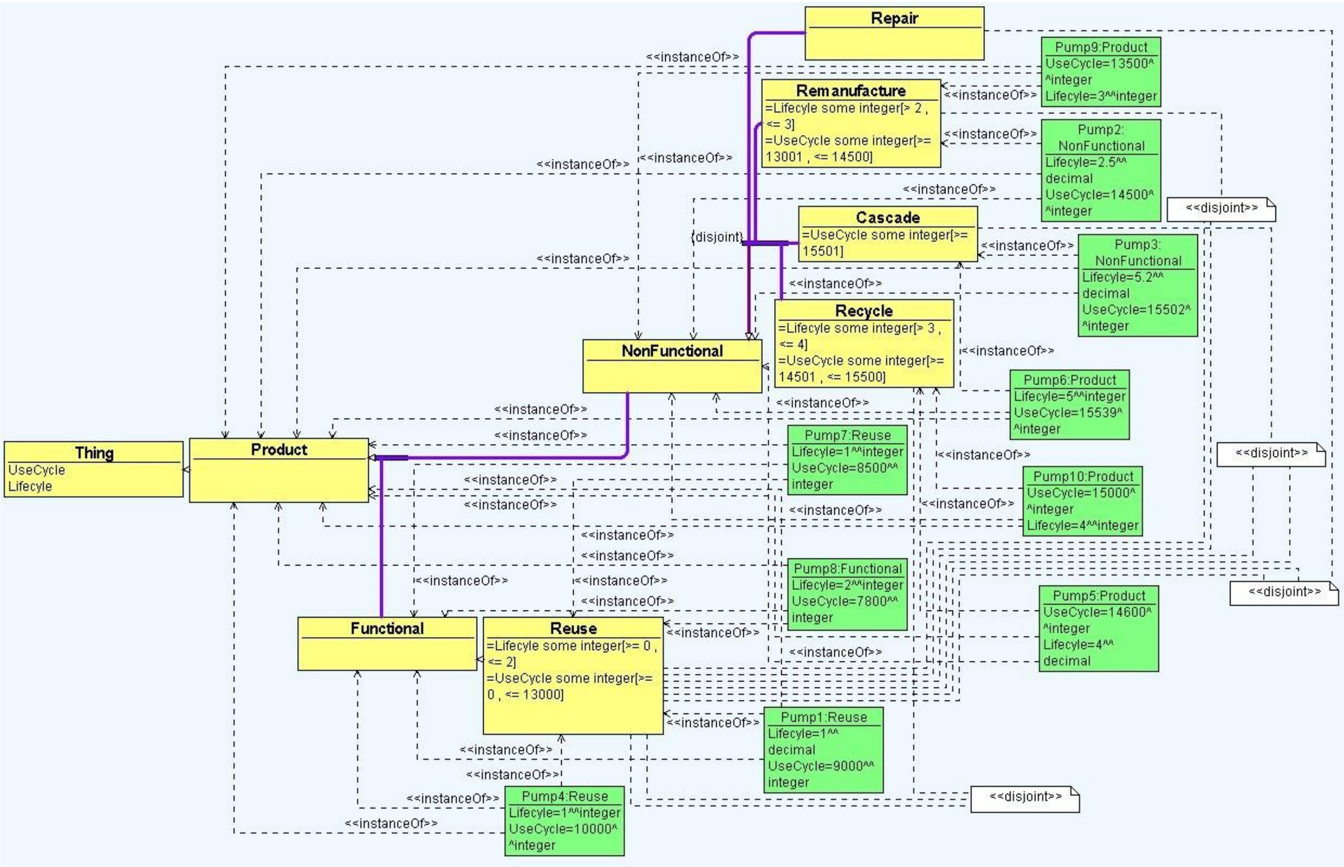

FIGURE 6 : Entire Ontology with Inferred classes and instances as viewed in OWLGrEd.

TABLE 3 Rules with ROWL Plugins in Protegee.

Rules ID	Rules Samples
R1	Reuse(?x)^Functional(?x)^UseCyleLow(?x,?y)^LifeCycleVeryHigh(?x,?z)->Product(?x)
R2	Reuse(?x)^Functional(?x)^UseCycleVeryLow(?x,?y)^LifeCycleVeryHigh(?x,?z)->Product(?x)
R3	Recycle(?x)^NonFunctional(?x)^LifeCycleLow(?x,?y)^UseCycleVeryHigh(?x,?z)->Product(?x)
R4	Remanufacture(?x)^NonFunctional(?x)^UseCycleHigh(?x,?y)^LifeCycleHigh(?x,?z)->Product(?x)
R5	Cascade(?x)^NonFunctional(?x)^UseCycleVeryHigh(?x,?y)^LifeCycleLow(?x,?z)->Product(?x)

R4. For non-functional product/component, if the usecycle is high and Lifecycle is high, recommendation will be *remanufacturing*
R5. For non-functional product/component, if the usecycle is very high and Lifecycle is low, recommendation will be *cascade* and then goes on like that.

The rules, classes and properties for the ontology were built using ROWLTab Protégé plugin for simplicity. This plugin was developed as a SWRL Rule to OWL Axiom converter[47].

An illustration of how the reasoning can be applied using the concepts and rules described so far is shown in Figure 7. Depending upon the lifecycle and usecycle of pumps (in Coffee machine use case as described in section 4.2), the rules engine automatically classifies them into one of the circularity classes.

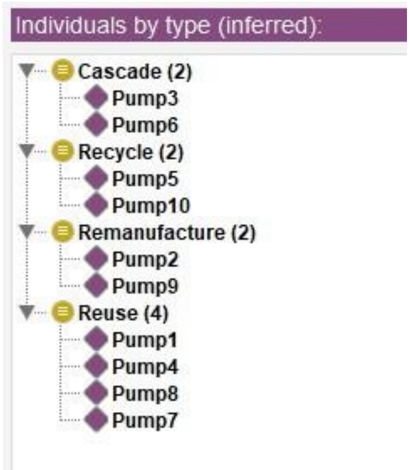

FIGURE 7 Inferred Individuals by type based on lifecycle and usecycle of pumps (as part of coffee machines use case).

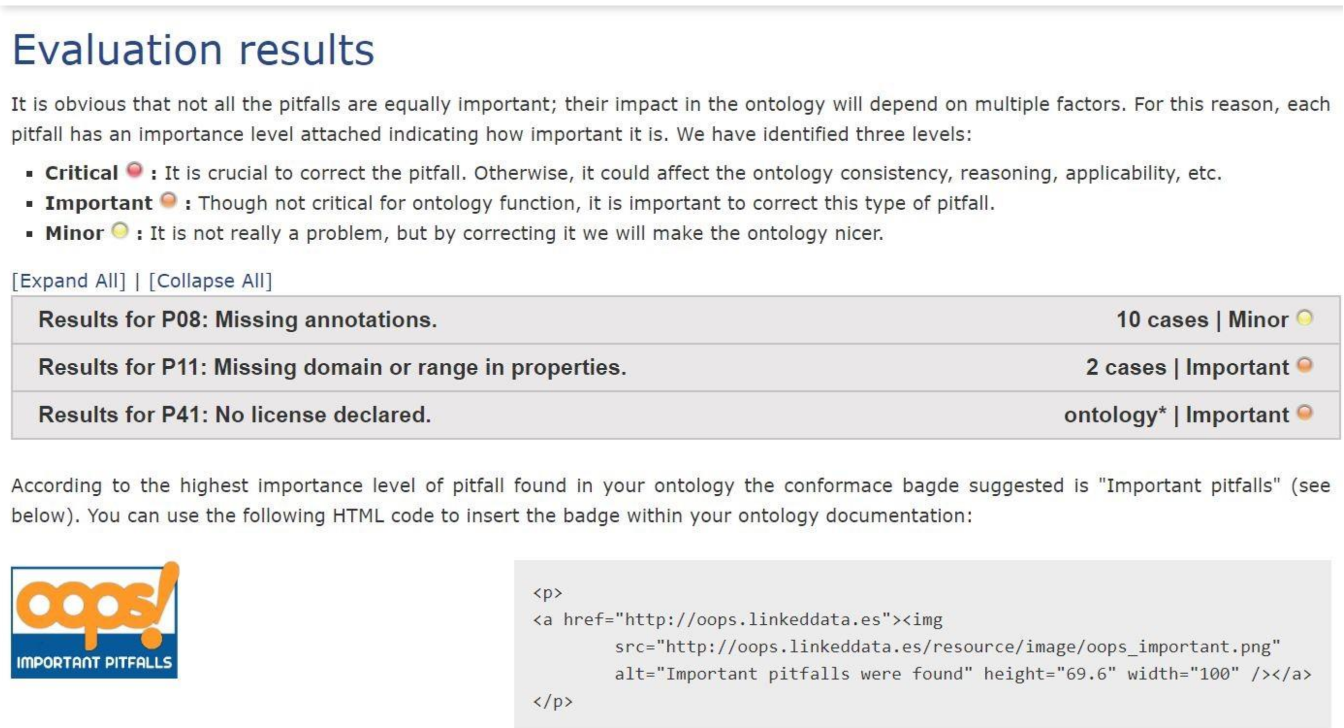

FIGURE 8 Ontology Evaluation Result from Oops!, an online ontology pitfall scanner[49]

3.4 | Ontology Evaluation

To be able to assess the quality, reliability, reusability, scalability of any ontology, it is common practice to evaluate ontologies. The ontology for supporting circularity decisions is one of the contributions of our work. Such ontologies need to be evaluated on how consistent, concise and complete they are, before other users will consider reusing the ontology. Our ontology was evaluated using an ontology pitfalls scanner called OOPS![49]. OOPS! classifies three levels of pitfalls: critical, important and minor, depending on the intensity of the pitfall (see Figure 8). The evaluated result shows that there are no critical pitfalls that could hinder the use of the ontology from reasoning, reusability and scalability but there few missing annotations for users' simplicity and easy understanding. These annotations were added in the ontology post evaluation.

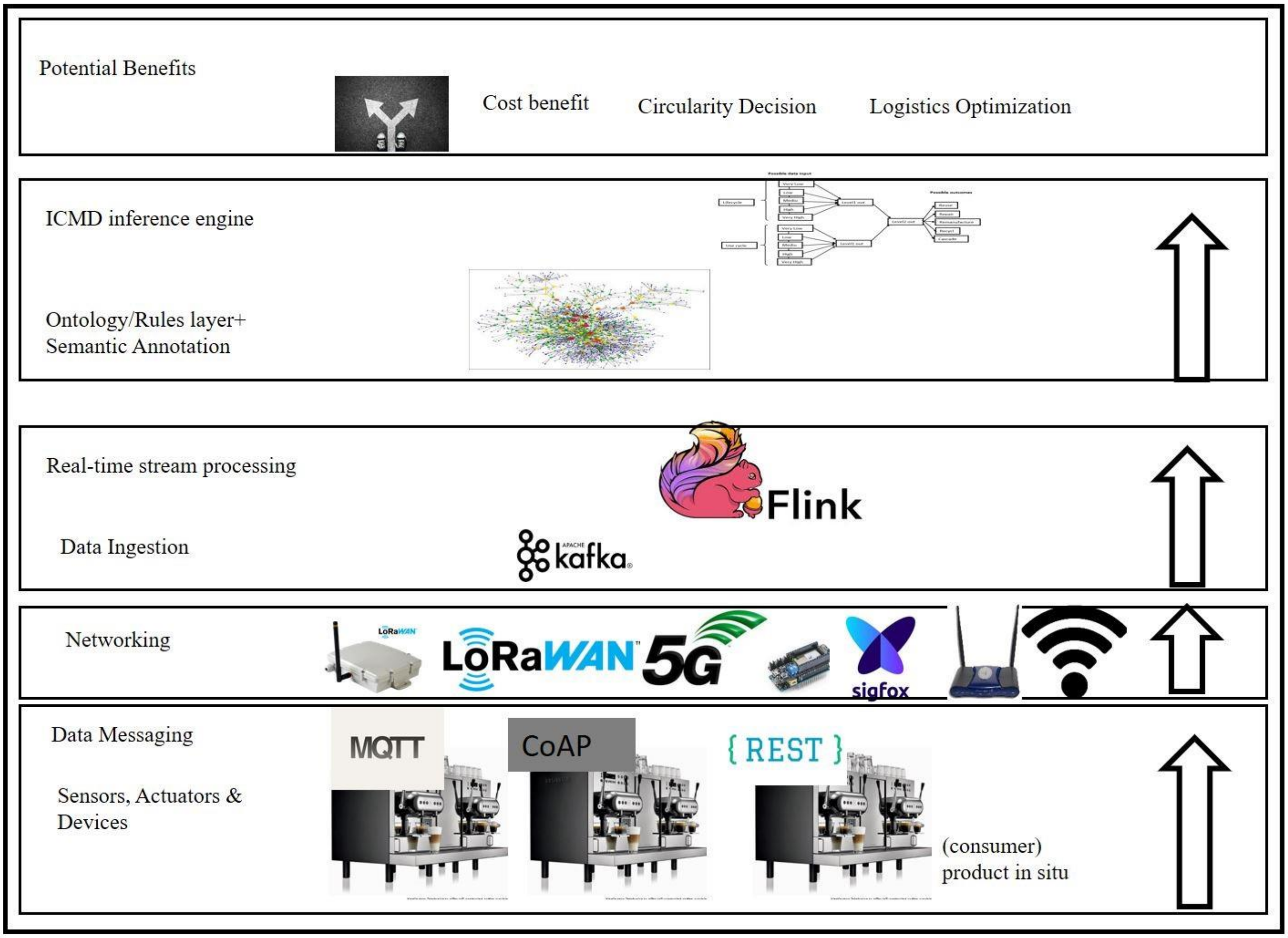

FIGURE 9 Envisaged Architecture for the Model.

4 EXPERIMENTAL STUDY

4.1 Use Case and Envisaged Architecture

Our circularity model is designed to motivate businesses to embrace and adopt IoT and 5G – Industry 4.0 technologies as enabler for CE in Industry 4.0. We demonstrate applicability of our model using a case study of coffee machine manufacturing and distribution. This use case is a representative of many electronic consumer products often classified as e-waste[25]. Since these products Coffee machines, are continually produced and sold but limited value is being captured from the continual waste generation. There are already companies that have started embedding IoT into coffee machines for predictive maintenance purposes[46] and this same smart coffee machines can be used for CSC purpose when we apply our novel model. Although the focus of our implementation is on the model and corresponding inference engine (ICMD), in the following we illustrate how a coffee manufacturer can develop a real-time monitoring implementation.

As shown in Figure 9, The system can collect usecycles and lifecycles data with sensors on the coffee machines and gets transmitted back to the IMCD using the data messaging protocols such as MQTT, CoAp and REST and with the help of 5G, Wifi, LoRAWAN, sigfox, communication networks. In terms of data ingestion and real-time stream processing, KaFka and Apache Flink are possible to utilise.

The coffee machine in our use case typically consists of seven components made from six different sub materials with costs given in Table 4 from a company manufacturing such machines. The actual costs are masked altering the values using a formula thattheyrepresenttherealvalues.Thecomponentsarepump,heatingunit,powersupplyunit(includingcables),casingincluding water tank, internal structure, controller chip and assembly (that is screws, glues, small cables etc.). The materials used are steel, **TABLE 4** Cost of various items for the coffee machines (USD).

Item	Linear	Re-commerce	Refurbishment	Recycling
Manufacturing Cost ($)	58.71		25.60 (Pump)	1.38
Secondary market Sourcing cost ($)		27.45	20.44	7.05
Distribution cost ($)	41.95	17.62	20.44	
Total cost ($)	100.66	45.07	66.48	8.43
Customer Revenue ($)	168.79	111.39	142.08	9.28
Profit ($)	68.13	66.32	75.60	0.85

Source: From a company that manufactures and market Coffee machines (prices are masked in proportion to hide the actual prices).

copper, aluminium, precious metals, Polypropylene (PP), and High-density polyethylene (HDPE) polymers. The data obtained includes bill of materials from the engineering department; Processing Input (volume) (from assembly department); Processing Input (prices) (from operations controlling); Failure/reusability analysis (from customer care and engineering department; and Material costs and recycling data (from engineering, procurement department).

Our system first starts with reusability and failure analysis by considering the usecycles of a component and lifecycle of materials used in manufacturing the product. For instance, a pump that is made from steel, copper and PP will be tested based on the lifecycle of the three materials used and still perform reuse analysis by comparing the number of times it has been used against its usecycle. The next stage will then be to decide right incentive using the re-commerce market value, secondary market sourcing and distribution costs. This way, the business can safely deal with the uncertainty issue of market residual value and maintain optimal ROS.

4.2 | Dataset and Experimental Scenarios

We have shown an envisaged architecture for supporting real-time monitoring of coffee machines and their components. For the purpose of the experimental analysis, we have generated such data based on experts' recommendations to show lifecycle and usecycle of different components of a number of machines already in use (see Table 5).

The current business model of this company is linear in the sense that they manufacture and distribute coffee machines but do not know what happen to the machine after it is sold, its functionality, customer's feedback or even attempt to get back the product for re-commerce. Our circular model intends to close this gap by helping companies to pro-actively anticipate, and plan for circularity decisions based on real-time analysis as illustrated in the following scenarios. We needed a comparative cost function to evaluate these scenarios.

Scenario 1: This is the status quo of economic model of this company that is linear economic model. Recall the forward logistics in Figure 1 and the forward logistics in our model Figure 2, without the reverse logistics part included, there will be large amount of waste generation. The implication is that waste will be generated despite the linear model being profitable. The Return on Sales(ROS) for the company is calculated as 40% using Equation 2 and the data in Table 4.

$$ROS = (\text{Operating Profit})/(\text{NetSale})X100 \quad (2)$$

$$ROS = (168.79-100.66)/(168.79)X100 = 40\% \quad (3)$$

Scenario 2: This scenario represents the reuse cycle in our model as explained in section 3.1 and shown in figure 2, 4, 5 and 6. It is mean for products that can be directly reused by a different user after first user returned them but are still functional. The reuse loop will need repackaging and sourcing a secondary market for the distribution of the product a second time which is missing in traditional linear model. From Table 4, this entails a ROS of 60% (USD 66.32) which would have lost if the linear model was the only option pursued by this company. This is the case of pump 1, 4 and 7 in Table 5. It can be observed that if the company implement a Circular business model like our own, there is a possibility of making more profits (ROS = 60%) as compared to the linear model (ROS = 40%) in scenario 1 above.

TABLE 5 Sample dataset of 10 Pumps with lifecycle and usecycle collected through sensors and passed through the ICMD Rule Engine. Standard Usecycle = 15000

Item	UseCycle	LifeCycle(years)	Decision
Pump 1	9000	1	Reuse
Pump 2	14500	2.5	Remanufature
Pump 3	15502	5.2	Casacde
Pump 4	10000	1	Reuse
Pump 5	14600	4	Recycle
Pump 6	15539	5	Cascade
Pump 7	8500	1	Reuse
Pump 8	7800	2	Reuse
Pump 9	13500	3	Remanufature
Pump 10	15000	4	Recycle

Source: Data generated based on expert recommendations.

$$ROS = (111.39-45.07)/(111.39)X100 = 60\% \quad (4)$$

Scenario 3: This scenario represents the remanufacture cycle in our model as explained in section 3.1 and shown in Figure 2, 4, 5 and 6..If the component is not functional, for example, the pump 2 in Table 5, with 14500/15000 as usecycle and 2.5/5 years as lifecycle, then the parts of the pump will recycle and new pump manufactured to refurbish the machine provided all other components are functional and still good enough for reuse. The cost of manufacturing a pump and getting it working is USD 25.60. If market sourcing and distribution cost is added, it will amount to total cost of USD 47.16 (see Table 4). With the revenue of USD 111.39 from remanufacture or refurbishment as shown in the Table 4, the ROS from will stand at 53% (USD 75.60) which would still higher than the 40% returns in liner model in Equation 2.

$$ROS = (142.08-66.48)/(142.08)X100 = 53\% \quad (5)$$

These scenarios show that with the use of our IoT-enabled circular supply chain model, businesses can get more return on sales compared to a liner model. scenario 2 (reuse cycle) gave 60% ROS higher than scenario 1 40% ROS (linear model) and scenario 3 (remanufacture cycle) gave 53% ROS also higher than scenario 1 linear model 40% ROS.

5 | CONCLUSIONS

The aim of our research is to design an IoT-enabled Decision Support System for Circular Economy Business Model. In this paper, we have demonstrated how products can be tracked and monitored real-time for business analytics. In particular, we have addressed the requirement of real-time monitoring of products lifecycle using Industry 4.0 technologies, namely, IoT and 5G.

Our model allows addressing the uncertainty of products residual value using Industry 4.0 technologies. In addition, we utilise semantic web technologies to convert this model into an ontological model and rule-base systems. This model is evaluated for its' technical soundness and improved based on the evaluation. We have utilised this ontology to build a DSS. The DSS uses the ontology and rules to suggest decisions based on the lifecycle and usecycle traced from the sensors.

We have carried out an experimental study with a real world use case that is representative of many electronic consumer products, and a dataset to demonstrate how businesses can create more value by adopting our model and using the DSS compared to a linear SC.

For future research, we aim to focus on logistics optimisation and price and cost prediction. In particular, we will work on a use case where datasets are available, in order for us to expand our ontology and corresponding DSS to support return prediction of products, and price and cost prediction to improve the utility of our system further.

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