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Circular production and maintenance of automotive parts: An Internet of Things (IoT) data framework and practice review

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ABSTRACT

The adoption of the Circular Economy paradigm by industry leads to increased responsibility of manufacturing to ensure a holistic awareness of the environmental impact of its operations. In mitigating negative effects in the environment, current maintenance practice must be considered for its potential contribution to a more sustainable lifecycle for the manufacturing operation, its products and related services. Focusing on the matching of digital technologies to maintenance practice in the automotive sector, this paper outlines a framework for organisations pursuing the integration of environmentally aware solutions in their production systems. This research sets out an agenda and framework for digital maintenance practice within the Circular Economy and the utilisation of Industry 4.0 technologies for this purpose.

1. Introduction

Circular Manufacturing is considered among the six disruptive manufacturing trends according to the World Manufacturing Forum (WMF, 2018). Although the relationship between maintenance engineering and management with production, supply chain, and logistics management has received significant attention and its role as a value adding activity is highlighted in international standardisation activities (e.g. ISO 55000 family of standards on asset management, EN 14485:2021 on Maintenance within Asset Management: Framework for improving the value of the physical assets through their whole lifecycle), it is still considered in many fields as a cost source. While the concept of "sustainable production" lacks an agreed definition, the University of Massachusetts's Lowell Centre for Sustainable Production (LSCP) methodology (which emphasises environmental, social and economic aspects of firms' activities) is one which underpins many sustainable production works in literature (Veleva and Ellenbecker, 2001). Industry 4.0 technologies, as well as integrated modelling of different production, maintenance, and supply chain processes within Digital Twin concepts can play a key role in establishing the sustainability and business impact benefits. The role of maintenance within production management and especially its contribution towards sustainable manufacturing was highlighted in the past with initiatives such as the Intelligent Manufacturing Systems (IMS) initiative Manufacturing Technology Platform "Maintenance within Sustainable Manufacturing" (M4SM MTP) while the rising role of Internet of Things (IoT) as a key enabler to this end was highlighted (Cannata et al., 2010; Liyanage and Badurdeen, 2010; Garetti and Taisch, 2012). From resource-aware predictive maintenance approaches to performance indicators within asset management, the need for including sustainability considerations has therefore become a key requirement. The interconnectedness of modern industrial and manufacturing enterprises is increasingly realised by their use and deployment of cloud based data collection and analysis systems through IoT (Tao et al., 2014). The automotive sector is strongly moving towards looking at the whole lifecycle aspects of the components used in vehicles and manufacturers increasingly design products for reusability and remanufacture (Shao et al., 2019). Therefore, this paper examines current practice of integrating digital maintenance within production and takes steps towards formulating a digital maintenance framework for automotive manufacturing. The structure of the paper is as follows. Section 2 discusses sustainability in current maintenance practice. Section 3 focuses on aspects of circular component design and utilisation. An outline of a circular approach within

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which a digital maintenance framework for automotive manufacturing needs to be applied is offered in Section 4. Section 5 is the conclusion and discusses further research.

2. Background

Product maintenance requirements and associated services are heavily determined at the design stage. While design for maintainability has long been established as practice, the consideration of a manufactured products' maintenance at design time is also needed for meeting circularity targets (Sanyé-Mengual et al., 2014). Holistic methodologies for sustainable maintenance practice also exist in the form of value stream mapping, where sustainability measures may be combined with other practices, such as lean, to scope improvement actions in current maintenance activities (Kasava et al., 2015). Similar methodologies are applicable also to automotive industry (Sari et al., 2015) and it is therefore of interest to examine how maintenance practice can be aligned with circular manufacturing goals. For example, opportunistic scheduling for preventive maintenance may not only target failure prevention and costs reduction but also reduced energy usage (Xia et al., 2018), which can be applicable to a whole production line, highlighting the need to apply such approaches in real-time maintenance implementations.

The remanufacturing of automotive parts is a growing area of research interest (Govindan et al., 2016). Remanufacturing of parts may lead to lower overall CO_2 outputs along with reduced energy requirements (of up to 80%) in manufacturing (Siddiqi et al., 2019). Yang et al. (2015) provide a methodology to assess the environmental impact of extending the lifecycle of products through remanufacture, proposing a framework to establish the environmental gain from this action at the design stage, along with automotive industry case study examples featuring alternators and engine blocks. The most common options for End of Life (EoL) treatment of parts are 'reuse, remanufacturing, recycling and disposal' (Yang et al., 2015), with remanufacture offing the opportunity for full circularity in a given parts use. Zlamparet et al. (2017) examine remanufacturing in terms of Waste Electrical and Electronic Equipment (WEEE) and note some limitations and concerns in automotive and aerospace industries relating to the remanufacture of safety critical WEEE components. A key enabler of remanufacturing is reverse logistics, where used parts are returned back through the supply chain for refurbishment and recycling. Zhang et al. (2017) highlight that the automotive reverse logistics supply chain is often complex with dealers, service centres, and the remanufacturers often assigned the roles of disassembly and refurbishment than the OEM (Original Equipment Manufacturer). Kurilova et al. (2018) look at the use of lean production methodology with remanufacturing in order to address issues including information deficit concerning the 'core' of the parts to be refurbished and lack of standardised processes for disassembly and remanufacturing. A further discussion of the driver and barriers for remanufacturing may be found in Chakraborty et al. (2019).

Design for Disassembly (DfD) is a subject much in alignment with remanufacture (Sherwood et al., 2000; Yang et al., 2017). Soh et al. (2014) explore this area, finding that products that are deigned from the outset to be disassembled can then be remanufactured for a lower overall cost. In their study Soh et al. (2014) note the increasing pressure on the automotive industry raise the proportion of their products which may be recycled and/or recovered; these authors propose a three-component methodology comprising technological, human factors and methodological solutions to aid design for disassembly efforts. Mayyas et al. (2012) provide a wider perspective of design for sustainability, taking into account the overall lifecycle of the automotive product and its environmental impact.

Circularity considerations need to be contextualised to the targeted business environment and to this end business sustainability criteria with regard to maintenance practice and the selection of optimised maintenance strategies by an organisation need to be set (Nezami and Yildirim, 2013). The Triple Bottom Line (TBL) concept is accordingly examined and placed within different decision making frameworks, such as Analytical Hierarchy Process (AHP) (Sénéchal, 2017) or Multi-Criteria Decision Making (MCDM) (Pires et al., 2016). While the latter seeks to establish a ranking among sustainability criteria, in practice there can be multiple confounding factors and complex relationships linking them with sustainability and production performance outcomes. Nonetheless the key to include elements such as sustainable value, sustainable signature, and sustainable state of the equipment is applicable to any multi-criteria decision making approach and can be combined with maintenance performance criteria, such as Sustainable Condition-Based Maintenance (SCBM) based on Remaining Sustainable Life (RSL) via key appropriately defined performance indicators (Sénéchal, 2017). The outcome is a SCBM strategy which aims to apply maintenance actions in order to control sustainability performance (Sénéchal and Trentesaux, 2019). Cost considerations are part of any viable TBL approach and to this end the whole lifecycle costing of manufacturing assets, which may include sustainability cost factors, need to be taken into account and not simply operations and maintenance costs (Jasiulewicz-Kaczmarek and Drozyner, 2011; Diez et al., 2016). Nonetheless, such decision making relies on the extent to which the validity of any underlying assumptions holds on the veracity of the involved data.

The use of digital technologies in maintenance has given rise to the term eMaintenance (Iung et al., 2009), which is further advanced by the utilisation of Industry 4.0 technologies for this practice (Johansson et al., 2019; Turner et al., 2019; Jasiulewicz-Kaczmarek and Gola, 2019). Predictive maintenance in particular is enabled by digital technologies, and has much to offer towards the effective utilisation of maintenance for sustainability. The main benefit is associated with the enhanced capability for creating, communicating, and processing of product and production data workflows. As a result, the key performance benefits associated with downtime reduction (Xia et al., 2018) and longer lifecycles for production machinery and parts (Garetti and Taisch, 2012), are now driven by digitally enhanced data and process workflows. A natural extension to Condition Based Maintenance (CBM) is to employ predictive models to anticipate events and trigger maintenance activities before a particular level of asset degradation gives rise to adverse environmental impact exceeding acceptable thresholds (Garetti and Taisch, 2012). The determination of appropriate trigger points for such actions can be the result of modelling and optimisation activities. For example, maintenance modelling and optimisation can employ penalty functions within a Monte Carlo algorithm to punish excess energy consumption and CO_2 emissions (Jiang et al., 2018). Production machinery operation always has environmental impact but idle production lines still have an environmental footprint and it is therefore desirable to ensure machinery utilisation in production lines via preventive, predictive, or proactive maintenance approaches (Sénéchal, 2016). Industry 4.0 technologies enable further improvements for optimised maintenance planning and scheduling, enabling far greater deployment of real time maintenance driven by sensorised machines relaying data streams to intelligent systems capable of diagnosing or anticipating faults to drive maintenance actions (Johansson et al., 2019). Such maintenance actions often involve parts replacement and in maintenance inventories management parts stocking is a typical source of cost and waste. Cheng et al. (2020) describe a method for maintenance planning based on data acquisition via. IoT sensor network installed in newly developed buildings. Cheng et al. (2020) envisages the use of Ontology to standardise the maintenance data model as a future research action. Turner et al. (2021b) also put forward a digital framework for use in newly fabricated building sections with application to both maintenance and capture and use of circularity indicators. Maintenance data quality is always limited by the systems and activities in place in an operation to collect and codify such actions (Mahlamäki et al., 2016). The authors Mahlamäki et al. (2016) point to the need for the establishment of efficient data collection processes and assurances of quality, in their study of extended equipment warranties in product service scenarios. Sala et al. (2021) note that the role data in decision making for maintenance is now essential to maintain competitiveness of organisations and realise viable supporting product service systems. In the work Sala et al. (2021) the maintenance framework put forward enables two distinct flows, one relating to maintenance services and the other describing machine derived data streams; the two flows are used to dynamically generate service plans relating to machine data and maintenance needs. In study of Kumar et al. (2018) suggest that despite the use of automated data collection systems derived from Industry 4.0 digitisation initiatives it is still the case that a knowledgeable workforce of maintenance and scheduling personnel are still required to ensure data quality along with an integrated operations planning approach for the optimisation implementation and use of automated systems. Brundage et al. (2019) go further stating many automation systems lack proper adaptation to human use and do not replicate the knowledge and experience of workers. In addressing this shortfall of human and digital maintenance system integration Brundage et al. (2019) suggest that artificial intelligence may provide a level of adaptation to bridge the gap between human and assistive maintenance tools. The use of ontology in combination with context awareness Al-Shdifat et al. (2020) state that maintenance data in itself should be valued Turner et al. (2021a) and Emmanouilidis et al. (2019) set out the case for human in the loop systems, where artificial intelligence is used to aid man-machine interactivity and cooperation in the completion of industrial tasks; a direction also envisaged in the form of human centric industrial systems described in the emerging Industry 5.0 agenda (Breque et al., 2021).

Throughout the journey of technology-driven innovation in maintenance, via. e-maintenance (Iung et al., 2009), intelligent (Liyanage et al., 2009) or smart maintenance (Bokrantz et al., 2019), connectivity has always been a key contributor. However, to align digitalised maintenance within circular manufacturing targets (Parida and Galar, 2012) there are challenges beyond connectivity. While data value chain management, context awareness, usability, interaction, and visualisation, as well as human learning and continuous integration are proposed as prime targets (El Kadiri et al., 2016). The need to integrate extended enterprise functions to ensure that digitally-enhanced maintenance is aligned and contributing to circular production, is a further challenge.

The Internet of Things (IoT) or Industrial Internet of Things (IIoT) provides a new level of connectivity across the automotive sector operations, including connected supply chain, production, and services, as well as operational monitoring of both the vehicle status and its status within the overall road infrastructure (Rahim et al., 2020), going down to the level of individual sensor equipped parts.

It is clear from existing research scope exists for a maintenance framework that implements circular economy practice utilising context sensitive IoT data. The use of ontology to establish data context and structure is not new, though its utilisation in circular maintenance along with the capture and intelligent analysis of tacit worker knowledge could provide a novel contribution in this field. The potential of IoT connectivity to enable the expansion of circular economy practice with regard to Hydrogen powered car automotive components is therefore of high interest and is considered further in the next section.

3. Circular component design and use

Design for Disassembly (DfD) is one direction an organisation can take to acknowledge circular values; other directions include design for recycling (DfR), Design for Remanufacturing and reuse (DfR) and Design for Environment (DfE) (Urbinati et al., 2017). Harivardhini et al. (2017) advocate the consideration of End of Life (EoL) disassembly processes when designing new products, proposing a framework for DfD and noting that this process also assists maintenance practice while the product under consideration is still in use. The support of disassembly processes through the use of sequence graphs is investigated the work of Smith et al. (2012) who propose an algorithm for the formation of graphs for particular disassembly activities related to manufactured products.

The use of RFID (Radio-Frequency IDentification) to provide an inventory of constituent materials within a product, attached as a tag, has been proposed by Nowakowski (2018). Such as system could also contain information to aid with disassembly. Yi and Park (2015) have also explored the possibility of using RFID tags and Zigbee wireless communications to transmit part dismantling and recycling data regarding vehicles at the end of their useful life. In this technique a recommended dismantling process is communicated back once the end of life vehicle is identified by a central server. It is interesting to note that in a review by Islam and Huda (2018) it was found that the three Circular Economy factors recycling, remanufacturing and reuse and repair have not been considered as a combined approach. Studies involving the recycling of waste electrical equipment have shown a potential role for IoT in waste collection and processing sites for the detection of different material types (Gu et al., 2017). In relation to the maintenance of heavy vehicles Saidani et al. (2018) point to the value of IoT sensor to feedback vehicle and component performance in real time. Such data capture as proposed by Saidani et al. (2018) is valuable for the purpose of maintenance planning and predictive maintenance practice, ensuring that vehicles run in an efficient manner on the road. It is also the case that providers of product service contracts for maintenance would be key utilisers of such a methodology (Tukker, 2015). Design for Maintenance (DfM) has been evident in life cycle literature in the last decade. This has recently been acknowledged as a key aspect of circular manufacturing by researchers and industry practitioners. For instance, DfM has been argued by Takata (2013) and Franciosi et al. (2018) to be a core component of circular manufacturing which links into product use and product reuse & production. When centred on value, the aim of maintenance is to maximise value generated by operations rather than minimising the maintenance cost Takata (2013). These include corrective, preventive, risk-based, and condition-based maintenance (Wakiru et al., 2018) and does not have to wait for when the component is damaged, as with repair. This is consistent with the accepted understanding of CE (Circular Economy) principles which are framed on value-retention for both biological and technical cycles (EMF, 2013).

Thus, circular value thinking includes the impact of maintenance on the lifecycle of the product.

When considering the safety of maintenance activities Lopez-Arquillos et al. (2015) provide an analysis of the highest risk actions that may be performed on hybrid, electric and hydrogen fuel cell powered cars. In Lopez-Arquillos et al. (2015), unsurprisingly, some of the most frequently performed activities involve the maintenance worker receiving some form of electric shock from the power unit and ancillary parts. For fuel cell vehicles the removal or installation of the Hydrogen tank and tank repairs attract the highest risk tariffs. For electric vehicles the risk of battery fires is a concern (Held and Brönnimann, 2016).

The tracing and identification of automotive parts supported through metadata described entities is an ongoing research thread. Fraga-Lamas et al. (2019) point to the potential role of Blockchain for the assurance of component traceability within a circular economy, raising the possibility for long term validation and retrieval of embedded data within automotive parts. Beyond traceability, blockchain technology provides accountability, integrity, robustness, privacy as well as higher operational efficiency to the whole automotive industry (Yli-Huumo et al., 2016). Furthermore, as the automotive industry adopts Industry 4.0 technologies such as Cyber-Physical Systems (CPS), blockchain has shown promise with its cybersecurity features. Studies have shown that blockchain and Content-Centric Networking (CCN) can be used to ensure the security requirements for trusted 5G vehicular networks (Fraga-Lamas and Fernández-Caramés, 2019; Ortega et al., 2018) Finally, the broad adoption of blockchain in automotive applications can unlock a wide area of short and medium term impacts that can create new circular and digitally-enabled business models and disrupt the car-sharing economy, providing new opportunities for users. With Blockchain it is possible to ensure traceability of parts throughout the supply chain as each transaction relating to a tracked entity is recorded and timestamped in an immutable way (Fraga-Lamas and Fernández-Caramés, 2019). Similarly parts that have reached the end of their life can be recorded as 'scrap only' or 'for remanufacture', ensuring that they do not re-enter the supply chain as potentially dangerous substandard or fake products (Fraga-Lamas and Fernández-Caramés, 2019). The nature of the distributed leger system also means that data control and verification across multiple organisations is easier to administrate as changes at one node are reflected across the network (Fraga-Lamas and Fernández-Caramés, 2019). By ensuring full traceability of parts the circularity potential can be more readily enforced, extending the lifespan of products, signalling when maintenance interventions are necessary for damaged and highly polluting parts and indicating when and how parts can be taken out of service and their composite materials reclaimed (Fraga-Lamas and Fernández-Caramés, 2019).

While the use of RFID for data sharing in the promotion of green supply chains is not new (Nativi and Lee, 2010), it has further advanced combined with smart chips and the connectivity provided by IoT. Gu and Liu (2013) scope the use of IoT in providing a back-flow of information from products into reverse logistics systems. These authors also raise the point that the capture and collection of data about products in a circular economy needs to be considered over longer periods of time to take into account the whole life use (Gu and Liu, 2013). Component origin and raw material verification can be provided by smart chips or RFID technology with implications for the practice of reverse logistics (Makarova et al., 2018). Makarova et al. (2018) point to the need to address problems such as the need for though life tracking of vehicles and their constituent components and the need for the centralised collection and curation of complex

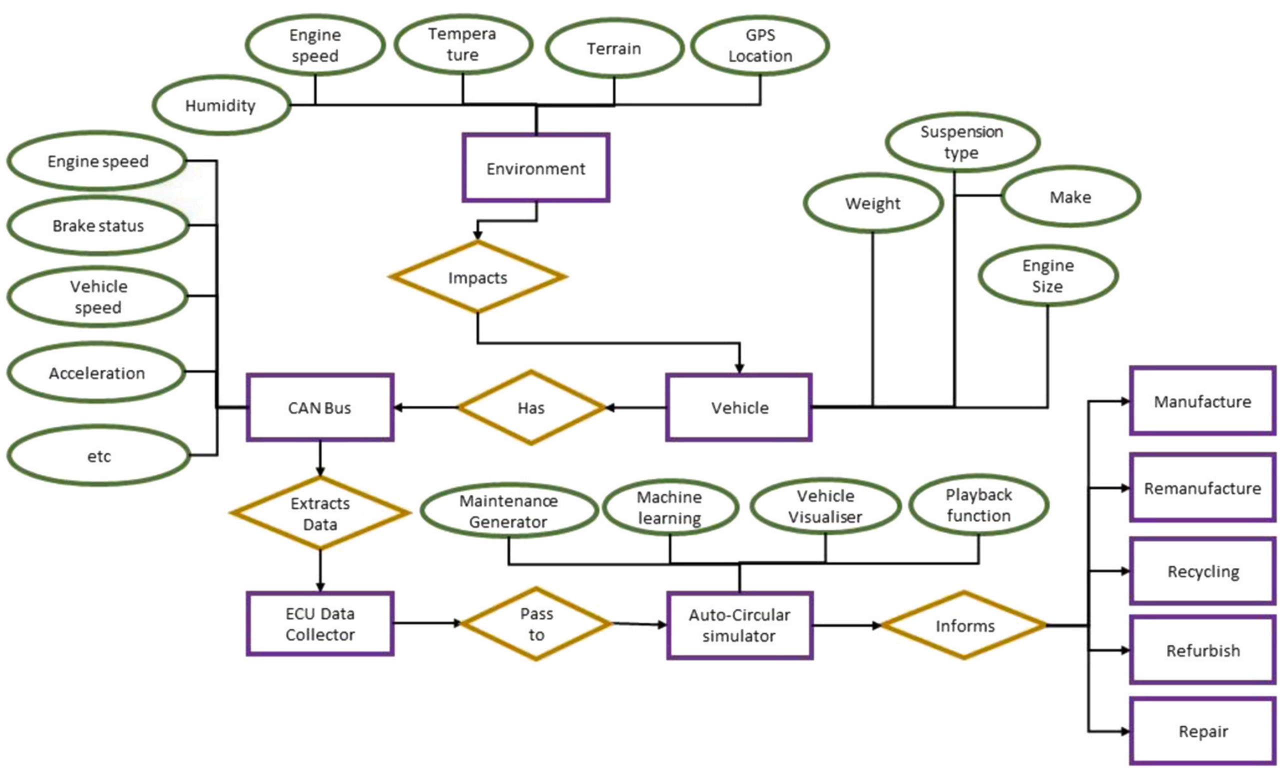

Fig. 1. Framework for IoT enabled circular maintenance practice and treatment of automotive parts.

data generated from each vehicle to be considered. Such developments point to the need for bringing the circular production of automotive parts under a systematic framework, as introduced in the next section.

4. Framework for circular production of automotive parts

In order to establish an appropriate baseline to compose a framework for the circular production of automotive parts, the present work has analysed relevant literature at the intersection of the following fields: maintenance; industrial sustainability; circular manufacturing; circular parts design. From this analysis it was possible to identify a gap in the research in the area of a holistic framework to map both streaming and static data sources for automotive vehicles for the purposes of circular production. Based on the combined outcomes of this analysis and through industry expert consultation, it was possible to derive a set of parameters to encompass the description of a manufactured asset for the purposes of through life circularity considerations. This has been presented in earlier publications by the authors (Charnley et al., 2019; Okorie et al., 2018).

The asset class in question was that of automotive vehicles; this asset class is characterised by considerable complexity and potential to benefit from a consideration of lifecycle environmental impact mitigation through circular production techniques. The framework depicted in Fig. 1 was developed from this aforementioned identified parameter set with the intention to describe the major data conduits and parameter categories available from modern automotive products via their major constituent components.

In Fig. 1 it can be seen that different components of the graphic have identifying colours:

- Green ovals represent parameter categories generated by vehicle sensors and functions that process captured parameters
- Yellow diamonds show notional actions on the data streams.
- Blue rectangles represent component parts and assemblies of parts (and use cases for the processed data streams at the right of Fig. 1, such as remanufacture)

In Fig. 1 the Auto-circular simulator provides visualisation and analytics toolbox capabilities, enabling the presentation of data in both tabular and graph formats, schematic form – relating data outputs to diagrammatic representations of vehicle architectures and Discrete Event Simulations of maintenance facilities and circular supply chains relating to vehicle parts involved in repair activities.

In operation the framework will make possible a holistic visualisation of the complex data streams emanating from individual parts and part assemblies. Data collection from general vehicle sensors (such as those describing sensed environment factors such temperature and terrain) may be made available through the Controller Area Network (CAN Bus). This decentralised network is a robust bus standard that enables a number of data items to be communicated between the microcontrollers within an automotive vehicle (Dellantoni et al., 2020). Vehicle ECUs (Electronic Control Unit) can provide a general interface to the data streams emanating from sensors connected though the CAN Bus. This framework proposes an Auto-circular simulator tool which will be responsible for the analytics required to provide processed data streams, result sets and what-if scenarios for use in circular maintenance, re-manufacturing and recycling systems. The following result outputs will be produced by the Auto-Circular simulator:

- Schematics of individual vehicle types will be generated by the simulator with visual mappings to senor stream data provided – providing a holistic depiction of all data streams possible from a vehicle type
- Generated scenarios will describe the optimal configuration of supply chains to recognise circularity in maintenance activities and treatment of used automotive parts.
- Maintenance task descriptions will take the form of process flow charts describing the correct enaction of maintenance activities - based on the latest data available on past recorded maintenance actions and automotive part reliability and wear data
- Data streams will be available in tabular summaries and it will be possible to create custom graphical representations

The interface to the Auto-circular simulator will be in the form of a data dashboard, providing traditional graph views and data mining facilities with graphical simulation views allowing what-if experimentation to take place (utilising machine learning techniques). The simulator will also draw on developments in mixed reality visualisation techniques allowing users, though the use of a headset, to view the potential effects of what-if scenarios developed within the simulator (before submission to circular economy users of the processed data) (Turner et al., 2016).

Tsybunov et al. (2017) demonstrate that the use of vehicle ECU is limited due to its restricted scope for future expansion of functionality. In response to this limitation the authors propose the possibility to use mobile network functionality for in-field diagnosis of vehicle faults and suggest the capturing of data on faulty parts from service centres for the development of improved diagnostics and prognostics for vehicle maintenance practice Tsybunov et al. (2017). A typical family car is made up of 150 ECUs that monitor various aspects of a car such as overseeing, regulating and altering the operation of a car's electronic systems, fuel injection, anti-lock braking system and so on. The ECUs contain sensors that measure various modalities such as temperature, speed, acceleration and engine speed. This framework also includes part identification for end of life and reuse/remanufacture considerations. The framework distinguishes also between repair and maintenance; maintenance is crucial for true circular manufacturing as opposed to simply adding reverse flows to conventional manufacturing systems (Takata, 2013). To this end the framework will be able to cross reference part numbers, codes and human provided annotations/documents to establish component composition and parameterise assembly /disassembly considerations (should such documents exist) through the use of semantic text mining techniques (such inputs could provide valuable context for the enrichment of what-if scenarios within the Auto-circular simulator shown in Fig. 1) (Emmanouilidis et al., 2019; Turner et al., 2021a).

With electronics shrinking in size and requisite reductions in unit cost, a larger set of vehicle operation parameters are being stored onboard for diagnostic purposes. Furthermore, the CAN Bus enables the possibility to extract data from specific ECUs for the purposes of monitoring driver behaviour (Wang et al., 2020; Evin et al., 2020). This opens up the possibility of collecting data on vehicle usage as well as degradation over time. Through the use of simulations and digital twins, this research proposes the use of data present on ECUs to track the conditions of vehicle usage and offer insights into which of its components might be appropriate for reuse, repair or re manufacture (Magargle et al., 2017; Merkle et al., 2021; Son et al., 2021). This combination of sensors, network communication technology and

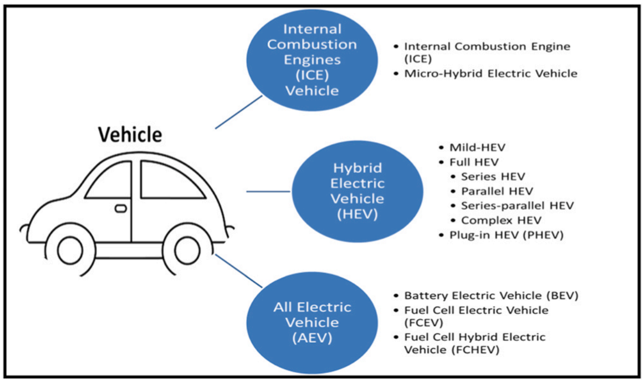

Fig. 2. The various classifications of a vehicle.
Adapted from Das et al. (2017).

analytic simulations will be informative in the implementation of circular economy behaviour within the automotive industry. This is especially true as automotive companies are under pressure to bring new models to market in order to stay ahead of the competition and remain competitive. The maintenance, reuse, repair, and refurbishment of vehicle components driven by digital technologies has the capability of reducing the burden on automotive adopters supply chain (through reducing costs) and also augmenting their social and sustainability credentials and practices. Overall, this will lead to increased profitability for automotive companies that utilise this framework and use to its fullest capability.

5. Case study: ontology for hybrid vehicle hydrogen fuel cell maintenance

In this section of the paper a case study focussed on an automotive industry example is provided to illustrate the data harvesting and processing part of the framework in action. The aim of this case study is to summarise how data can be drawn from automotive components and then utilised as part of the automated decision making process for maintenance and circular treatment of worn/damaged parts. In facilitating the required data collection process an ontology has been developed to allow for the identification of linked components related to test questions that may be asked by a range of actors in a sustainable automotive manufacturing value chain. Most vehicular systems are classified under three.

principal categories as shown in Fig. 2. These includes, internal combustion engine vehicles (ICEV), Hybrid electric vehicles (HEV) and all electric vehicles (AEV). For HEVs and AEVs, the use of batteries, ultracapacitors and fuel cells as energy sources is distinct to these vehicles. The hybridisation of the ICEVs and the AEVs give rise to the hybrid system which is employed by the Hydrogen Fuel Cell Electric Vehicle (HFCV), the case under study (Das et al., 2017; Hames et al., 2018). Hybridisation of vehicle results in an enhancement of the fuel economy often expressed as mile per gallon (MPG). Hybridisation is regarded as a promising and a green technology due to their fuel efficiency, as the energy sources can assist internal combustion engines to always run in the high efficiency area and improve the dynamic performances of vehicles (Uebel et al., 2018; Zhou et al., 2019).

The HFCV forms part of the emerging trend in the automotive industry which is the production of low and zero emission products. The Hydrogen fuel cell is an innovation that uses H2 as a fuel to produce electricity to power an electric motor, in the case of a vehicle. Hence the basic operation of the hydrogen fuel cell is the reverse operation of the process of electrolysis; hydrogen and oxygen are recombining to produce an electric current and water (Larminie et al., 2003). About 4% of hydrogen produced globally is produced by electrolysis (Koj et al., 2017). Several works have examined the cost of various electrolysis technologies. These includes solid oxide, proton exchange membrane and alkaline (Parra et al., 2019; Saba et al., 2018). This gives the HFCVs a high energy efficiency and several literature argue that this offsets for their lower power density and slower power response (Chan, 2007; Hames et al., 2018; Khaligh and Li, 2010). Furthermore, HFCVs are built with supercapacitors (SCAPs), batteries (BATs) and energy storage systems (used with the fuel cells) in order to reduce the disadvantages of related to (Burke, 2007; Saygili et al., 2015; Thounthong et al., 2009). These components are seen in the schematic in Fig. 3. Thus, the HFCVs are fully designed to take the place of the conventional internal combustion engine vehicle, while contributing to reducing global warming (Gurz et al., 2017; Hames et al., 2018).

As shown in Fig. 3, the HFCV configuration contains the control mechanism that consists of the FC, the BAT, SCAP, DC/DC converter (Garcia et al., 2013; Gurz et al., 2017). The mechanical parts of the HFCVs includes three-phase traction motor, auxiliary devices, energy storage systems and DC bus. Previous research undertaken in this area includes a study investigating the end-of-life option the fuel cell

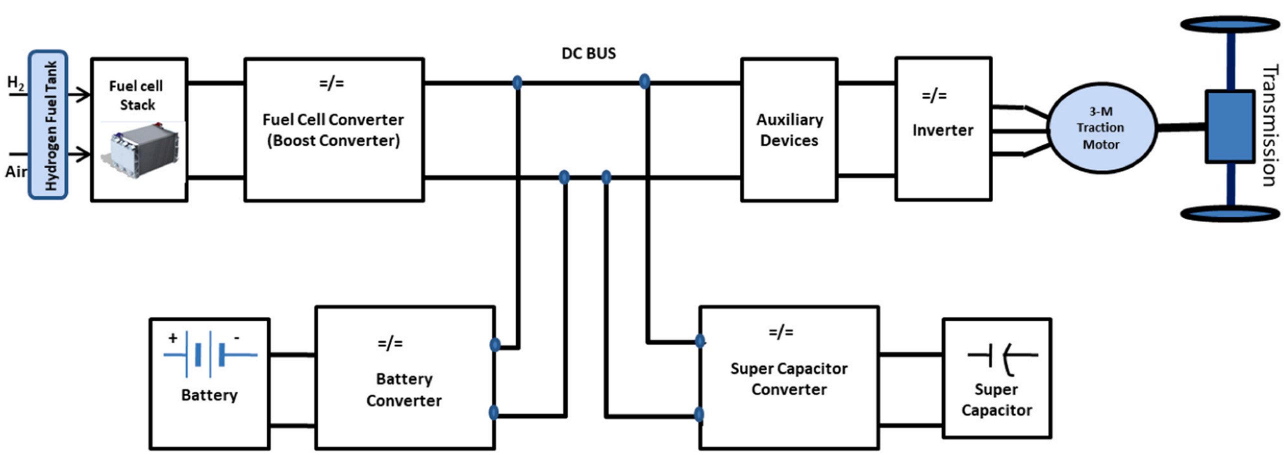

Fig. 3. The configuration of a hydrogen fuel cell electric vehicle (HFCV).
Adapted from Gurz et al. (2017).

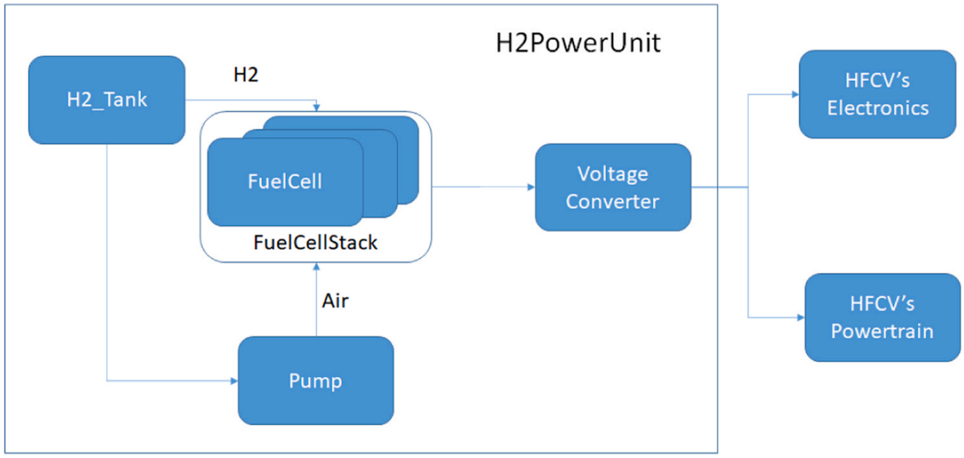

Fig. 4. Schematic of the case study HFCV power unit (H2PowerUnit).

(Okorie et al., 2018). The batteries and supercapacitors are used to overcome the performance limitations caused by the delayed response time of the fuel cells (Gurz et al., 2017; Zhang et al., 2008). The required power-energy transformation and balances required by the vehicle are provided by the healthy functioning of all these modules (Hames et al., 2018). Fuel cells remain the main energy source for HFCVs (Bauman et al., 2008; Burke, 2007). As seen in Fig. 3, the FC converters serve as an intermediate layer for connecting FC to the DC-bus (Bauman et al., 2008; Hames et al., 2018; Torreglosa et al., 2014), while maintaining the voltage regulation of the BAT (Harfman Todorovic et al., 2008; Marchesoni and Vacca, 2007; Torreglosa et al., 2014). Accordingly, the battery generates extra power for both the DC-bus and the FC during the periods when the fuel cell's power is not enough (Hames et al., 2018). Finally, the supercapacitors (SCAP) control the DC-bus voltage. It generates specific power that the FC and BAT in conjunction cannot generate to offer the HFCV's any sudden power demand (Hames et al., 2018).

The case study Hydrogen Fuel Cell Electric Vehicle (HFCV) is examined in terms of its power unit, represented as H2PowerUnit in Fig. 4. The H2PowerUnit provides the motion source for the HFCV and is composed of the following sub units: H2_Tank – holding the hydrogen fuel source; VoltageConverter – transforming the current from the FuelCellStack to the required voltage; Pump – used to pressurise the FuelCells in the FuelCellStack; FuelCell – provides the electrical current output based on chemical reactions of the hydrogen fuel source; FuelCellStack – composed of between 1 and 10 individual fuel cells.

5.1. Ontology design methodology

In the development of the ontology works such as Alvarez-Coello and Gómez (2021) were consulted, focusing on the development of semantic approaches to vehicle related data. Alvarez-Coello and Gómez (2021) utilise the Data, Information, Knowledge, Wisdom (DIKW) hierarchy of Rowley (2007). The DIKW methodology utilises the four hierarchical layers to formulate a contextual ontology around available data, integrating information provided in the form of document and application bound repositories, knowledge as a context based codification of identified relevant parameters from the first two layers expressed as an ontology and wisdom often involving the integration of relevant tacit knowledge of workers and non-digitised materials and the application of knowledge in a decision making context.

In this case study the data streams emanating from the H2PowerUnit entity provide the majority of parameters, though scope exists for information in applications and other electronic document stores to provide additional parameters. An initial UML model was drawn to describe the relationships between the H2PowerUnit sub-components and the types of functions that would call on sensor provided data streams (shown in Fig. 5).

The ontology was formed from a combination of the identified parameters most likely to provide a reliable summary of a particular automotive part's current state (and previous recorded states). In addition the design of the ontology was informed by the style and conventions provided by the Autosar sematic specification relating to vehicle health monitoring (Autosar, 2019). The methodology employed in this case study also allows for the integration of observations provided by maintenance workers who may record, via a laptop or tablet device, detailed observations about a part or the performance of a maintenance task.

Fig. 6 shows the ontology that describes the main components of the H2PowerUnit and generic data properties. As can also be seen in Fig. 6a number of generic data properties have been subclassed from the H2PowerUnit object class (indicated by the orange circle with equals sign); these properties may be realised by subclasses that enact a selection of the generic data properties (provided in the form of a superclass interface). The ontology has been produced with the software tool Protégé (version 5.5) and utilises the XML (Extensible Markup Language) based OWL 2 (Web Ontology Language) as a semantic description format.

As can be seen in Table 1 a range of data properties are exposed by each sub-unit of the H2PowerUnit. In addition to the generic data properties, provided as interfaces sub classed from the H2PowerUnit class, bespoke measurement functions can also be accommodated; an example of a bespoke data property is the hasH2QuantityUsed measure exposed by the H2Tank.

The inferred (semantically correct ordering of the object hierarchy) hierarchy can be seen in Fig. 7. The inferred hierarchy demonstrates one particular way in which parameters shared by different sub-units may be quickly identified and iterated by a calling software function. This hierarchy can form the backbone of a dynamically updated ontology for the active identification and

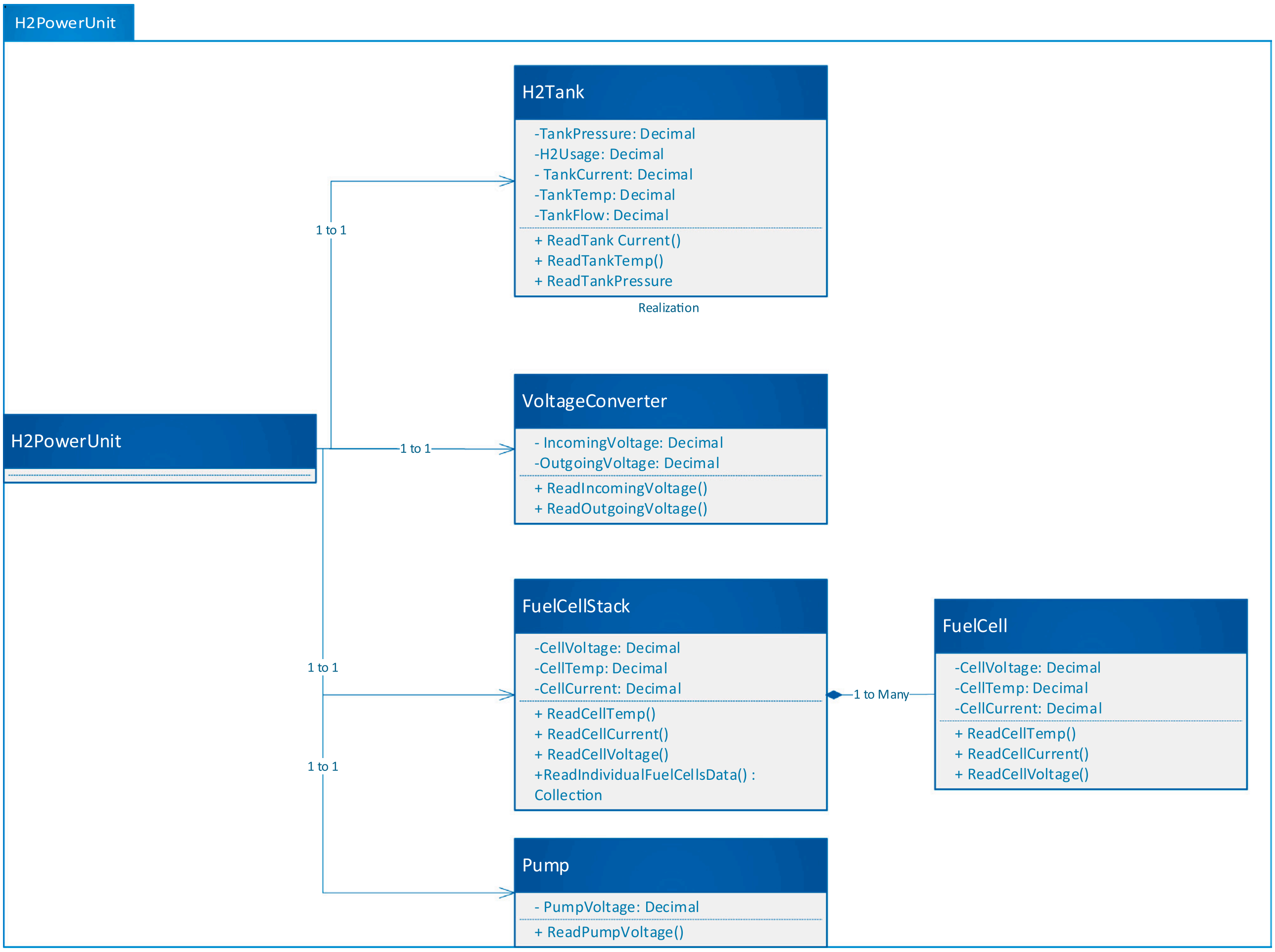

Fig. 5. UML (Unified Modelling Language) diagram for hydrogen car power unit.

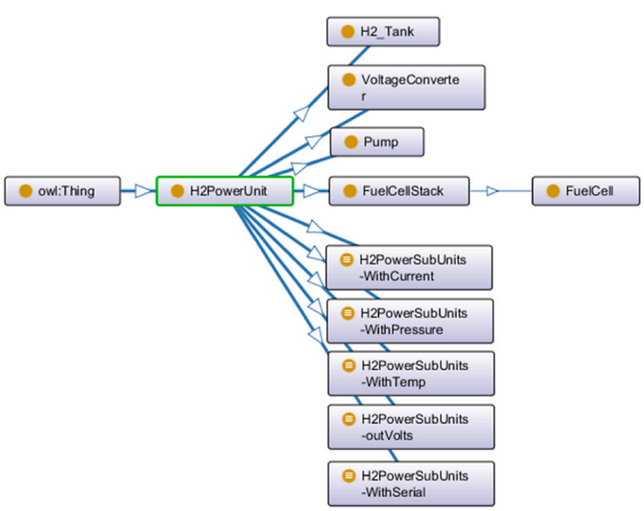

Fig. 6. Asserted ontology for hydrogen car power unit.

retrieval of parameters of interest. In the next section a future use and development of this capability will be outlined.

5.2. Ontology questions and interested value chain parties

Table 2 provides four example questions that the hydrogen car power unit Ontology (shown in Fig. 7) may be used to answer. The first question is concern with detected drops in MPG level returned by the vehicle. In this case value chain actors such as component manufacturers may wish to review the material that compose parts such as fuel cells, the re-manufacturer may wish to take back and repair and refurbish fuel cells and the manufacturer could choose to revise the manufacturing system and identify new parameters to sense, measure and retrieve from vehicle stock by adjusting the part design and the ontology. In the second question the detection of vibration in a vehicle may trigger a maintenance action to be undertaken requiring engineers to check parameters relating to pump. Similarly component suppliers would be keen to improve reliability of the part though re-design and re-manufacturers the possibility to recondition existing faulty pumps. For questions 3 and 4 changes in environmental parameters concerning the vehicle when in use will be of interest to

Table 1
Hydrogen car power unit entities described by class, object properties and exposed data properties.

Class	Object Properties	Data Properties
H2PowerUnit	HasFuelCellStack (exactly 1) HasH2Tank (exactly 1 xsd:decimal) HasPump (exactly 1 xsd:decimal) HasVoltageConverter (exactly 1 xsd:decimal)	outVolts (hasOutgoingVoltage exactly 1 xsd:decimal) WithCurrent (hasVoltage exactly 1 xsd:decimal) WithPressure (hasPressure exactly 1 xsd:decimal) WithSerial (hasSerialNumber exactly 1 xsd:decimal) WithTemp (hasTemperature exactly 1 xsd:decimal)
FuelCellStack	HasFuelCell (min 1; max 10)	WithCurrent WithSerial WithTemperature
FuelCell		WithCurrent WithSerial WithTemperature
H2_Tank		WithCurrent WithSerial WithTemperature WithPressure hasFlow exactly 1 xsd:decimal hasH2QuantityUsed exactly 1 xsd:decimal
Pump		WithCurrent WithSerial WithTemperature
VoltageConverter		outVolts WithCurrent

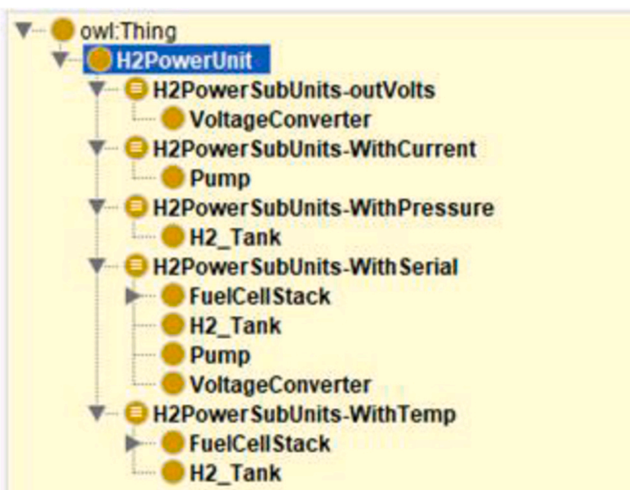

Fig. 7. Inferred ontology for hydrogen car power unit.

maintenance engineers, component suppliers and OEM (Original Equipment Manufacturer) vehicle producers. Re-manufacturers would also be interested to know when is best in a components lifespan to refurbish or remanufacture components to maximise this parameter.

It is also the case that interest parties could also include government and regulatory bodies, with interests in: safety of vehicle operation; sustainable production and use of manufactured goods and components (increased lifespan of products), and reduced pollution in production and in use. Customers would also be interested in speed of vehicle fault diagnosis, which the use of such an ontology may expedite through service centre consultations and consumer facing online diagnosis systems.

6. Discussion and future research actions

When considering the design of maintenance processes it is clear that intuition and prior knowledge play a vital role in the completion of tasks in relation to complex automotive products. Such knowledge is gained through task completion over many years and quite often maintenance practice evolves slowly, and often new processes do not emerge until new product models are encountered. The dynamic redesign of processes based on sensed evidence and captured observations of maintenance technicians would provide a valuable tool for established workers and those learning maintenance practice alike. Further extensions to the existing parameter set considered by the auto circular simulator are possible. Table 3 details a number of additional context parameters that, if provided by the part manufacturers, would enable additional insights to be made concerning maintenance activities, circular end of life treatments and lifespan relating to those given parts.

One particular extension to the ontology could be a parameter to indicate the current health status of a particular part (shown in Fig. 8). This indicator would possess a timestamp to indicate a moment in time when the estimate was assigned and a timestamp to show the next 'service interval' when the part is estimated to have degraded further.

The health indicator could be a number between 1 and 5 indicating the current degradation level this will indicate when removal and remanufacture or scrapping is required or is predicted to be required (1 being a new part and 5 part needs to be considered for removal). Intermediate grades may relate to when a part may be removed and then remanufactured rather than recycled into its base raw materials. Knowledge of when a part may be treated for a particular end of life process can help to match component availability to recycling/remanufacturing part markets – a need for remanufactured parts can trigger maintenance activities to make available more parts to the market or indicate that a part may be recycled earlier than indicated by wear level (perhaps triggered by raw material prices vs price of new redesigned replacement parts). Similarly when new more environmentally sustainable processes for remanufacture become available suitable parts can be identified and marked in preparation for that end of life treatment (taking into account the amount of wear allowed).

This also makes it possible to incorporate the use of newly developed life extending coatings and treatments not available when the part was manufactured. Government legislation and environmental standards and targets may also be incorporated by the auto circular simulator in its operation and actioned through the way

Table 2
Questions the Ontology Could be Used to Answer.

Value Chain Questions	Suppliers	Maintenance Engineers	Customers	OEM Manufacturer	Government Regulators	Re-manufacturer
1. Why has the Miles Per Gallon (MPG) measure dropped?	Quality of raw materials used to develop FuelCellStack e.g platinum	VoltageConverter;, Maintenance timings; H2_Tank; FuelCellStack.	MPG dashboard	Entire ontology and systems approach	Ethical sourcing issues Infrastructure issues Geo-political climate issues Driving up efficiency	Repair/Refurbish part under investigation
2. Why is there an increase of sound or vibration coming from the vehicle?	Reliability of parts Design and compactibility issues	Pump	Acoustic emissions	Pump	Reliability of parts	Pump reconditioning
3. Why is there an increase in condensation from tail pipe or in the vehicle?	Materials used for the H2_Tank and pipes	H2_Tank and pipe	Water condensations	sub-systems related to pump and H2_Tank	Safety of systems	H2-Tank reconditioning
4. Why is there an increase or drop in temperature in the vehicle?	Materials used in the FuelCellStack	FuelCellStack; VoltageConverter; Pump faults; H2_Tank.	Thermostat warning	sub-systems associated with temperature changes	Safety of systems	Repair/Refurbish

Table 3
Expansion of HFCV power unit parameter set for intelligent maintenance purposes.

Activity	Power Unit entities	Parameters required	Additional Context Parameters Needed	Circularity Implications
Safely remove hydrogen fuel cell stack	FuelCellStack FuelCell	WithCurrent (hasVoltage exactly 1 xsd:decimal) WithTemp (hasTemperature exactly 1 xsd:decimal)	Hydrogen leak sensor Electrical grounding of Hydrogen Circuit H2PowerUnit Earthing Indicator	Regular check for leaks, grease, corrosion foreign objects and replace if necessary. Cells and stack can be recycled once replaced
Safely remove Hydrogen Fuel Tank	FuelTank	WithCurrent (hasVoltage exactly 1 xsd:decimal) WithPressure (hasPressure exactly 1 xsd:decimal) WithTemp (hasTemperature exactly 1 xsd:decimal)	Air Condensation level on Valve measurement in Hydrogen Tank	Replace if leak is detected. Fuel tank can be recycled or remanufactured if faulty.
Diagnose Fuel Cell Fault Warning	FuelCellStack FuelCell	WithCurrent (hasVoltage exactly 1 xsd:decimal) WithTemp (hasTemperature exactly 1 xsd:decimal)	Fault Indicator Part history Model of Average Driving conditions	Fault warning system should be regularly tested and replaced if bad. Replace and recycle

```
H2FuelCell WithHealthStatus (hasHealthStatus exactly 1 xsd:decimal) (hasdateStamp extactly 1 xsd.date) (has
PredictedDate extactly 1 xsd.date)

Ontology Ont = Import Ontology(<http://www.example.com/CircularMaintenance.owl>)

Function AllPartsForRemanufacture( VehicleNo Decimal; HealthStatus Integer; Ont Ontology){

        Object Collection  = (returnParts(VehicleNo, Ont; HealthStatus)){

        ………..further code implementation

hasHealthStatus

        }

}
```

Fig. 8. Health status indicator for use with circular end of life treatments for parts with calling pseudocode function.

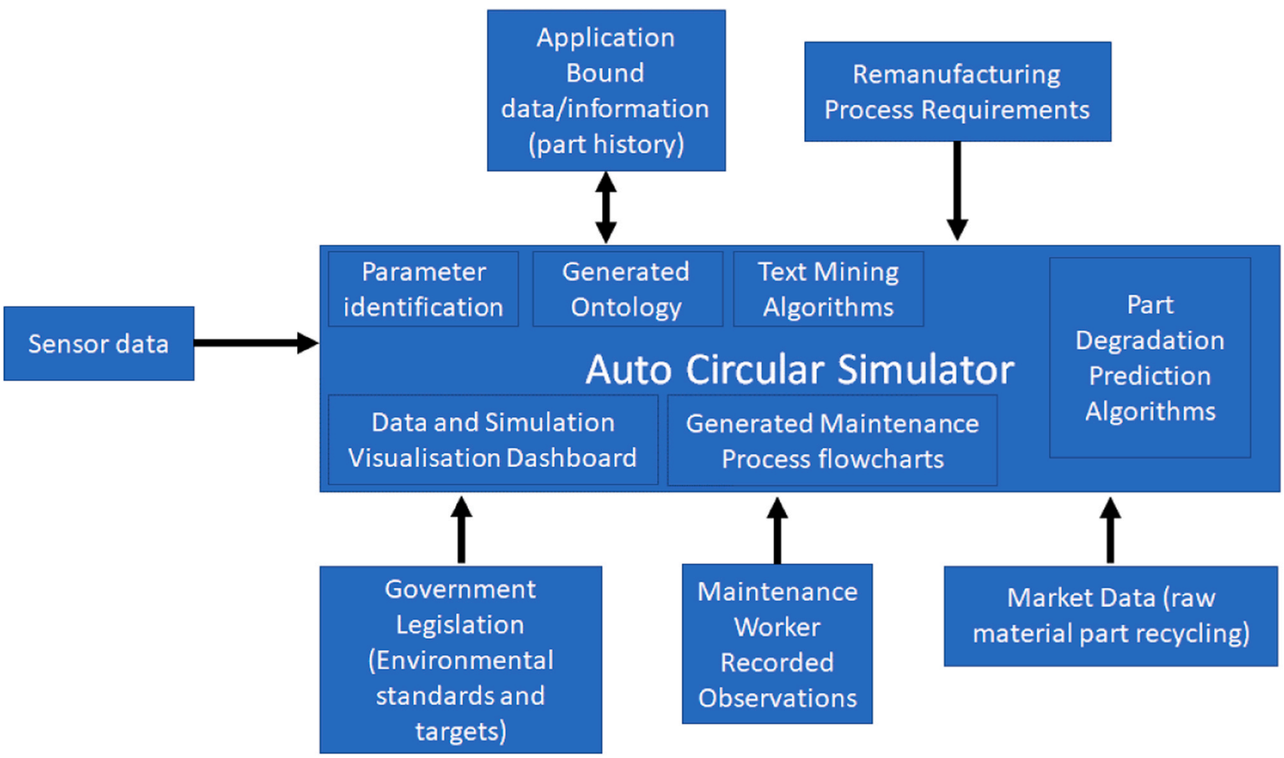

Fig. 9. Schematic of the Auto Circular Simulator and data/information flows.

health ratings are calculated, availability of remanufacturing and/or recycling processes and maintenance processes generated. These further refinements to the Auto Circular Simulator are depicted in Fig. 9. The dynamic process inherent in the auto circular simulator operation would utilise an amalgam of all senor data and predictive models; with such models also reflecting the gathered data from all serviced vehicles and parts for a vehicle model type. Such a process would be able to add and delete stages based on real time data collected from a range of maintenance sources, and suggest new maintenance actions based on evolving route causes analysis outcomes. Pirasteh et al. (2019) in their study of commercial vehicle Diagnostic trouble codes and predictive maintenance recommend the further grouping of recorded failure modes, seen in serviced vehicles, into common repair descriptions with the addition of domain knowledge (perhaps provided in textual form by the servicing technician via a tablet device). Such repair descriptions may be mined and form further contributions to a dynamically updated repair process. Giobergia et al. (2018) also note that in the mining of sensor data for predictive maintenance purposes context information regarding driving conditions are desirable so generalised 'use' models may be developed. As envisaged in Fig. 1 such real world 'in use' data can be invaluable in enhancing the accuracy of predictive models. In Madenas et al. (2016) warranty claim data, among other factors, is analysed and fed back into a product lifecycle management framework for a large automotive company. Madenas et al. (2016) go onto describe how the analysed warranty information can positively influence the next generation of new products for a manufacturer and aid the development of mature root causes analysis identification practice within an organisation.

In Quintana-Amate et al. (2017) the value of context based knowledge and data for the full lifecycle of a product can provide a coherent annotation of fault occurrence which may prove invaluable in improving maintenance practice, the prediction of failures and provide root cause analysis evidence for the identification and elimination of faults and input into the design of new parts.

In line with this research additional parameters identified from warranty claims could be included in context ontology for revised repair routines. A live view and history of all instances of a given part type maintained in the past could be maintained in order to establish a reliability record. Partnered with ‘in the field’ product use data both prediction routines and overall diagnosis and elimination of faults may be achieved through one comprehensive tool. The savings in failed parts and sub optimal operation within the vehicle are much reduced in such a scenario as presented here. In addition it may be possible to attain a more accurate picture of parts that are removed from a vehicle in terms of their suitability for re-manufacture or recycling. In mining past use data and establishing root cause of failure the scrappage route may be avoided for certain types of parts and this decision support need would be facilitated through the auto circular simulator tool depicted in Fig. 1. The auto circular simulator will allow for complex scenarios to be developed based on actual parts usage data, root cause analysis of their failure and estimation of full lifecycle. Once optimised scenarios have been developed the information can be fed back into maintenance processes and even passed onto component manufacturers to inform new part design, remanufacture and redesign tasks. Tier one suppliers may also be joint parties to this tool, and its data and outputs.

The work of Sala et al. (2021) provides in its proposed framework for data based maintenance decision making. In common with the approach proposed in this paper with that of Sala et al. (2021) is the focus on data derived from assets, the ability to generate maintenance plans and the use of machine learning to enable this. Though it is the case that the focus on ontology in the approach proposed here along with the focus on circularity measures for sustainable maintenance practice provide a unique contribution in this field. The Auto circular simulator allows for the generation of maintenance plans that are tailored towards meeting environmental goals whilst delivering dynamically generated and evolving maintenance processes based on sensed parameters and the tacit knowledge of workers.

6.1. FMEA considerations

The use of Failure Mode Effects Analysis (FMEA) as a quantitative analysis method for the discovery of cause and effect relationships is a future direction for this research.

For a full FMEA consideration additional parameters relating to severity and likelihood of occurrence would need to be provided along with potential causes of failure. Such a detailed schedule of context based descriptions could allow future ontologies, with the aid of reasoning techniques, to resolve the context of any queries and ‘pick out’ action recommendations. An additional parameter column would also need to be added for candidate action recommendations.

Use of machine learning could be made, together with the tagging of data with ontology concepts, to describe identified failure nodes. This tagging (or knowledge enrichment) would be the basis for expanding the range of data and states that the machine learning model can work with. This data enrichment process could extend the scope of the failure prediction process utilised in the auto circular simulator to the areas covered by the FMEA analysis.

7. Conclusion

This paper has outlined research in Digital Maintenance Practice for sustainable production. In summarising current research it is clear that there is a trend for modern maintenance practice to consider the whole life impact and use of component parts. In doing so advances in both sensing and computing technologies are increasingly being harnessed to enable sustainable practice. In setting out an agenda for digital maintenance practice and sustainable product management within the Circular Economy a framework has been presented in this paper with application to automotive parts. The automotive industry presents a valuable template for the further exploration of the application of circular economy thinking for sustainable maintenance practice due to the sheer range and complexity of constituent components in a modern vehicle. This industry in particular is experiencing pressures for reuse, repair and refurbishment of components.

In further research the ontology developed in this paper, based on the hybrid vehicle fuel cell case study, will form a central component of an automated maintenance process generator and will be form a central deliverable of the framework in use. In future research a dynamic root cause data communication and capture tool for maintenance issues with vehicle (provided as a part of the auto circular simulator tool), metadata tagging to identify causal paths between components. Such a tool would suggest a dynamically generated process for the maintenance technician to follow based on the sensor outputs, fault codes and predictive models available and applicable to a given vehicle to be repaired. Capacity will exist for end users to provide their own text responses and diagram annotations relating to the performance of automotive maintenance actions, providing an additional data source for analysis by the auto-circular simulator.

The ability to simulate and analyse offline and real time data emanating from maintenance activities and vehicle parts in use will be realised by the auto circular simulator tool component of the framework for the IoT enabled circular maintenance practice. This tool will be responsible for the analytics required to provide processed data streams, result sets and what-if scenarios for use in circular maintenance, re-manufacturing and recycling systems.

Actual feedback from parts whilst being used ‘in the field’ will also form a valuable data stream for this tool. The ability to track the real world degrading and reliability of parts will also form a valuable data set and live view, informing the correct end of life treatments most aligned with circular maintenance practice (as enabled by the auto circular simulator tool). A number of valuable result sets and outputs will be provided by this tool: Schematics of individual vehicle types will be generated by the simulator; Generated scenarios will describe the optimal configuration of supply chains to realise the treatment of used automotive parts; Maintenance task descriptions will take the form of process flow charts describing the correct enaction of maintenance activities; Data streams will be available in tabular summaries and graphical representations.

It is intended that the framework will be extended for use in other case study sectors such as aerospace and energy production (Oyekan et al., 2020). This work is also applicable to the field of circular design whereby data gathered from the use of existing assets ‘in the field’ is incorporated within the design processes utilised in the development of a new generation of products. The framework as described could well be utilised as a stand-alone application, though future activities will be focused on its integration with Digital Twin implementations in the automotive manufacturing sector and distributed maintenance systems; providing potential to link with research shaping the future direction of management dashboard design, data mining practice and the presentation of analytics.

CRediT authorship contribution statement

C. Turner: Conceptualization, Methodology, Writing – original draft. **O. Okorie:** Writing – original draft. **C. Emmanouilidis:**

Conceptualization, Methodology, Writing – original draft. **J. Oyekan:** Writing – original draft.

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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