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A Digital Maintenance Practice Framework for Circular Production of Automotive Parts

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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, not just for the reduction of its own direct impact but also 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 acts as a primer for digital maintenance practice within the Circular Economy and the utilisation of Industry 4.0 technologies for this purpose.

Keywords: Sustainability; Intelligent maintenance systems; Maintenance models and services.

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, CEN TC319 on Maintenance and WG10 on Maintenance within Asset Management), 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 the one which underpins many sustainable production works in the literature (Veleva & Ellenbecker, 2001). Industry 4.0 technologies, as well as integrated modelling of different production, maintenance, and supply chain processes within extended Digital Twin concepts can play a key role in establishing the sustainability and business impact benefits of such an approach. The role of maintenance within production management and especially its contribution towards sustainable manufacturing was highlighted in the past with initiatives such as the Manufacturing Technology Platform "Maintenance within Sustainable Manufacturing" (M4SM MTP), supported by the IMS Forum, the IFAC A-MEST WG and the IFIP WG 5.7 and it was within this initiative that 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 which a digital maintenance approach for automotive manufacturing needs to be applied is offered in Section 4. Section 5 is the conclusion and discusses further research.

2. SUSTAINABILITY IN MAINTENANCE PRACTICE

Product maintenance requirements and associated services are heavily determined at the design stage. While design for

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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 different maintenance strategies 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.

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 Yildrim, 2013). The Triple Bottom Line (TPL) 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)(Ziez et al. 2016). Nonetheless, such decision making relies on the extent to which the validity of any underlying assumptions holds and 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 is one particular area, enabled by digital technologies, that 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 CO2 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.

Throughout the journey of technology-driven innovation in maintenance, through 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, 2016), the need to integrate extended enterprise functions to ensure that digitally-enhanced maintenance is aligned and contributing to circular production, is faces with further challenges.

3. CIRCULAR COMPONENT DESIGN AND USE

It is the case that there are several design directions an organisation can take to acknowledge circular values such as design for recycling (DfR), design for remanufacturing and reuse (DfR), design for disassembly (DfD) and design for environment (DfE) (Urbinati et al., 2017). Harivardhini et al. (2017) also advocate the consideration of End of Life (EoL) disassembly processes when designing new products. A framework for DfD is proposed by Harivardhini et al. (2017) 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

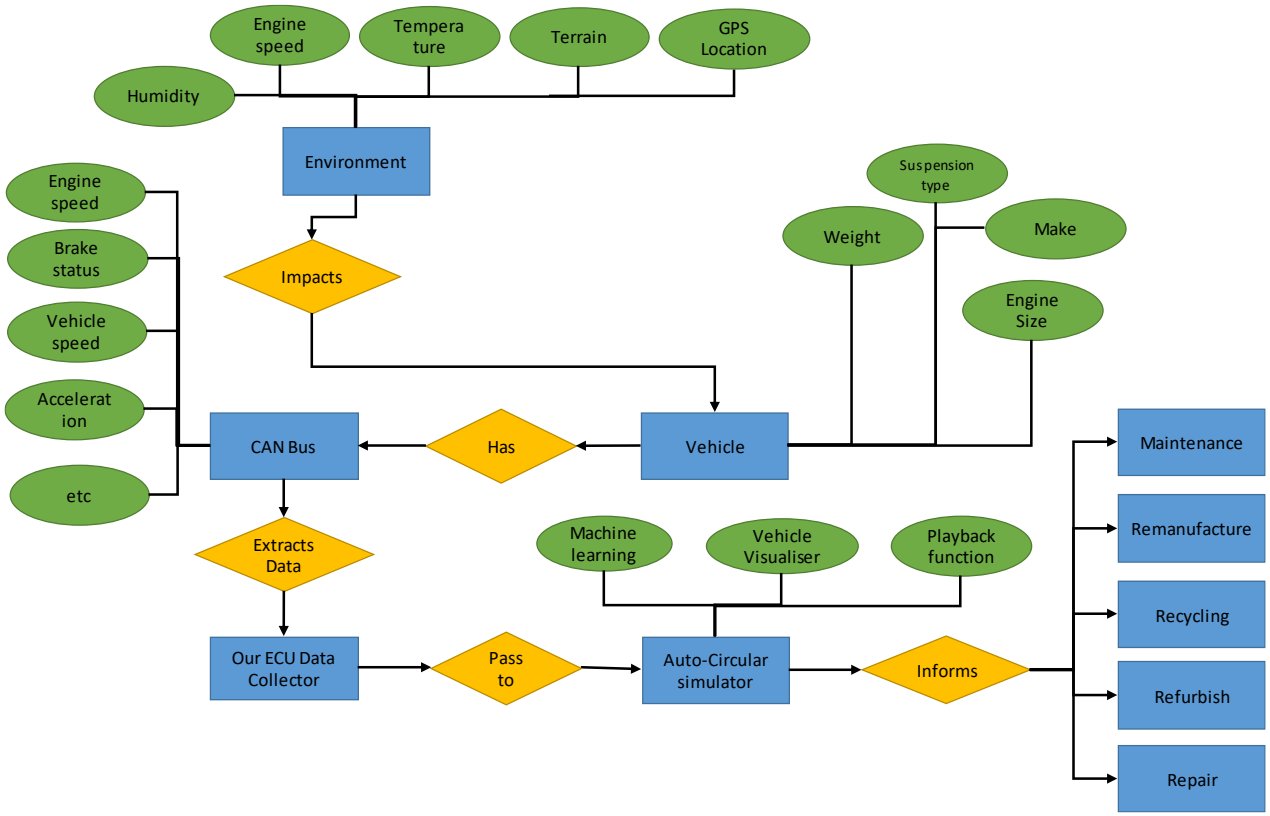


Fig. 1. Framework for application of digital technology to enable circular economy treatment of automotive parts.

products. The use of RFID to provide an inventory of constituent materials within a product, attached as a tag, has been proposed by Nowakowski (2018). Such as system as proposed by Nowakowski (2018) 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. (2017) 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. (2017) 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 et al. 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 (2017) 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 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.

While the use of RFID for data sharing in the promotion of green supply chains is not new (Nativi and Lee, 2010) the combination with smart chips and the connectivity provided by IoT is a more recent adoption. 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 data generated from each vehicle to be considered.

4. FRAMEWORK FOR CIRCULAR PRODUCTION OF AUTOMOTIVE PARTS

The framework has been designed after consultation of the available literature at the intersection of the following fields: maintenance; industrial sustainability; circular manufacturing; circular parts design. From this review 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. From that review it was possible to derive, via a combination of analysis and industry expert consultation, a set of parameters to encompass the description of a manufactured asset for the purposes of through life circularity considerations. The asset class in question was that of automotive vehicles; this asset class was selected due to its complex nature and potential to benefit from a consideration of through life 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 graph have identifying colours; in this case the green ovals represent parameter categories (and from the Auto-circular demonstrator visualisation and analytics toolbox capabilities), the blue rectangles represent component parts and assemblies of parts at the centre of Fig. 1 and use cases for the processed data steams at the right of Fig. 1 (such as remanufacture), with yellow diamonds showing notional actions on the data streams. 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 module 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 interface to the Auto-circular simulator will be in the form of a data dashboard, providing traditional graph views and data mining facilities and 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. (2018) 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 telematics 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. 2018). 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 recognises the need for part identification for end of life and reuse/remanufacture considerations. The framework recognises the distinction 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 and codes 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).

With electronics shrinking in size and requisite reductions in unit cost, a larger set of vehicle parameters are being stored on-board 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. This combination of sensors, network communication technology and 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. DISCUSSION AND 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. Acting as a primer 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 it is intended that the framework will be extended for use other case study sectors such as aerospace and energy production. 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.

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