A review of data driven approaches for circular economy in manufacturing

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This paper seeks to examine the area of circular economy, providing an overview of the development of data driven circular approaches in manufacturing, particularly Industry 4.0, from the point of view of Reuse, Remanufacturing, Redistribution and Recycle. This paper also aims to develop a working framework for future circular economy research.

The Design, methodological approach of this paper focuses on a comprehensive review of literature covering over 51 research papers. These papers are analysed using pie charts and bar charts to understand current trends in circular economy and circular economy related research and future research directions in the field.

Findings show that research on circular economy has been steady and gradual with 2014 and 2015 having the most papers on the subject with 43% of the papers from engineering related research. Research which links circular strategies and their application within Industry 4.0 to digital technologies is still a very new area of research and, as such, is an area for further studies.

Although papers on Circular Economy and Circular Economy Approaches exists, however, there are no papers that offer an overview of the development of circular approaches within manufacturing. The contribution of this paper is to provide a summary of current trends in circular economy research in manufacturing, within focus on Industry 4.0. A review of this development has been provided in the form of illustrative charts and graphs that identifies these trends. From this a framework for future circular economy research as it relates to manufacturing was developed.

Keywords: *circular economy, industry 4.0, reuse, remanufacturing, recycle, data.*

1. INTRODUCTION

The origin of the circular economy –the retention of resources in a circular loop –can be traced to developments from the Linear Economy. The Linear Economy, which dates back to the Industrial Revolution of 1760- 1820, ensures the product or material goes through the 'take-make-use-dispose' model of consumption. However, (Vaidehi Shah, 2014) argues that the linear economy has a passive culture, which involves the 'throwing away of resources'. (Qiao and Qiao, 2013) go on to argue that a more 'renewable' form of economy was needed. They argue that they traditional linear economy pursues a growth model which solely focused

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on GDP growth and not the environment nor other aspects of sustainability. (Qiao and Qiao, 2013) further argue that the Linear Economy model has obvious ethical flaws hence the "from cradle to grave" approach which has been used to define the Linear Economy model, (Bellmann, K and Khare, 2000)

"Cradle to Reincarnation", according to (Bellmann, K and Khare, 2000) emphasises that products can be reincarnated into new products –either higher or lower valued- through recycling. Thus the question from Linear Economy which produced "Circular Economy" was, 'Is there a design from Cradle to Grave?' 'Can a product be reused after it has fulfilled its useful life?' Thus the Circular Economy attempts to answer this question by providing a Circular Approach which implies the holistic value principle and sustainable value principle, which according to (Qiao and Qiao, 2013) can repair the ethical flaws which the inherent in the traditional linear economy model. (Jacobsen, 2006) defines a Circular Economy as an economy paradigm where the resources are kept in use as long as possible. Hence the maximum value is extracted from the resources. Circular economy paradigm has its basic roots in industrial ecology. It emphasises the benefits of recycling waste materials and by-products.

Thus the principles of circular economy utilises a paradigm that is opposed to the Linear Economy 'take-make-dispose' resource model that generates a significant amount of waste, (Ellen MacArthur Foundation, 2015). Natural resources are finite and many current reserves are limited. Asides these challenge of abundance, there are other threats to supply of materials. These include, political instability, land grabbing and ring fencing of reserves and bribery and corruption, (Ludden, 2012). Population growth and increasing GDP also impacts on resource availability, (Goossens YA, Makipaa P, 2007) with the anticipated population growth of 9.6 billion by 2050 (UN, 2012) estimated to have an unprecedented impact on demand for resources and metals, minerals and fossil fuels. Thus, there is growing resource-need for ensuring that resources are kept in use and as long as possible. Circular Economy approach is very similar to natural life cycles where dead organic material decomposes to become a 'useful' nutrients –for plants and food for animals.

The question this review shall attempt to answer is this: how does data produced from the manufacturing process enable circularity? While research in Circular Economy has been a common feature in research and as observed by (Lacy and Rutqvist, 2016), understanding how manufacturing data enables circularity has not been investigated in research (Lieder and Rashid, 2016) provides a comprehensive review of circular economy researches in the context of the manufacturing industry. We shall proceed to discuss the existing literature pertinent to this research.

2. PERTINENT LITERATURE

This section analyses the literature which is closely related to the subject (that is, any previous reviews related to manufacturing data and circular economy approaches) and identifies the distinct features that differentiate these previously published reviews and the contribution of this research.

A search on SCOPUS was carried out and there were no search results that review manufacturing data in the circular economy. There were however review publications that focused on the circular economy or aspect of the circular economy that discusses the interactions with manufacturing data and digital technologies. The papers are briefly

highlighted below and shall be utilised in developing a framework from the gaps. Reviews with interplay from the circular economy largely focuses on aspects from the circular economy which are centred on issues outside the manufacturing data of a production process. (Ghisellini, Cialani and Ulgiati, 2016) for instance reviews literature concerned with the ecology of circular economy and its implementation at different levels –micro, meso and macro. (Elia, Gnoni and Tornese, 2017) on the other hand reviews circular economy strategies through index models, proposing a reference framework for the monitoring phase of a Circular Economy in a taxonomy of index-based methodologies.

Another group of review papers focuses on the ecology and policy aspects of circular economy, manufacturing industry and country specific. (Pan *et al.*, 2014) reviewed the literature that focused on implementation of waste-to-energy (WTE) supply chain for circular economy arguing that, for effectiveness, a policy mechanism should have a multi-approach tackling the barriers from regulation, institution, finance and technology at once. (Geissdoerfer *et al.*, 2017) reviewed 67 articles and reviews from the Web of Science that discusses the relationship between circular economy and sustainability. Circular Economy, here, was viewed as a condition for sustainability, having a *"beneficial relationship"*.(Su *et al.*, 2013) reviewed papers discussing the circular economy in China, reviewing current Circular Economy practices at micro-level, meso-level and macro-level. Subsequently, CE was assessed and the challenges and barriers towards the successful implementation was reviewed. This work was important as it gave a useful analysis of CE in China, the second largest economy in the world. (Lieder and Rashid, 2016) in a comprehensive review, investigated on research efforts encompassing aspects of resources scarcity, waste generation and economic advantages in manufacturing. An implementation strategy using a top-down and bottom-up approach in a concurrent manner was proposed. This research focused on a total of 158 papers from SCOPUS and Web of Science Database.

The only study that overlaps Circular Economy approaches and digital technologies is the study by (Pagoropoulos, Pigosso and McAloone, 2017). They carried out a review of the emergent role of digital technologies in the Circular Economy –the closest review to this current research. The main question in their study was understanding how digital technologies supports a transition to a circular economy. The researchers, (Pagoropoulos, Pigosso and McAloone, 2017) undertook a systematic literature review based on a review protocol. 135 articles were first reviewed and, after evaluation and analysis 12 articles were included in the final review. In their final analysis, seven main technologies were identified and grouped under three architecture perspectives (data collection, data analysis and data integration). Their results show that the intersection between the Circular Economy and digital technologies is a growing area albeit, at the moment, small. They describe it as a research in its pre-paradigmatic stage. Gaps discovered in their review was the "limited technological perspective". They suggest that future research "evaluates the application of digital technologies in actual circular economy case studies", by circular economy case studies, reuse, recycling, remanufacturing of the "three R's", (Lacy and Rutqvist, 2016) take centre stage. This review paper aims to develop a framework that addresses that research gap. Three studies considered most important for this work are, (Pagoropoulos, Pigosso and McAloone, 2017), as we shall attempt to build on the future work proffered here and (Lieder and Rashid, 2016) and (May *et al.*, 2016) whose methodology shall be adopted for this research.

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3. RESEARCH METHODOLOGY

According to (May *et al.*, 2016), academic works are framed within a piece of literature review, either as a standalone part or as a composition of the sections within the research, which includes the discussion of results. (Hart, 1998) argues that a literature review is important in any research in order to define and justify the choice of research design, objectives and methodology. (Fink, 2005) discusses literature review as the most crucial approach for the practical identification and evaluation of the main parts relating to a specific research subject. Therefore, (Tranfield, Denyer and Smart, 2003) concludes by opining that a literature review exists in order investigate, analyse and evaluation with references, an existing knowledge in a particular field and to identify possible gaps in the research. For this research, building a framework from the gaps in the research shall be a purpose of the literature review.

The objective of this systematic review is to outline and evaluate the current state of research in data-driven approaches for circular economy in manufacturing for digital technologies and identifying potential future research opportunities in this area. From the gaps found in the literature a framework that intersects with the objective shall be developed. To the best of the knowledge of the researcher, there is no research that summarises key findings in this area nor develops a framework from the key findings.

Shappiro and Markoff (1997), Mayring (2000) and Krippendorff, (1980) offer a definitive process of analysing the content of the literature. These are;

- Stage 1: Material Collection - definition of unit of analysis and confining potential material.
- Stage 2: Descriptive analysis – definition of formal characteristics and assessment of material.
- Stage 3: Category selection – definition of analytical categories and application to material.
- Stage 4: Material evaluation – analysis of materials according to the categories as defined in Stage 3.

SCOPUS was chosen as the prime online database due to the ease of search and the ability to allow for bespoke searches. The year for search was put at 1990 – 2017, that is the last 27 years and the search followed the methodology as illustrated in Fig 1.

The key terms for the search were extracted from the title of the review paper. “Industry 4.0” OR “digital technolog*” OR “manufactur* data” were combined. “Technolog*” in the search could return “technology” and “technologies”; “manufactur*” could return “manufacturing” and “manufacture” and “manufactured”, wherever they appeared in a research. Also included the key search words were “reuse”, “recycl*” which could return “recycling” or “recycle” and “remanufacture*” which could return “remanufacturing” and “remanufacture” and “remanufactured” in the articles. These terms were used on SCOPUS and returned various search results. For Reuse, 107 set of papers were returned. For Recycling, 45 set of papers were returned; for remanufacturing, 15 set of papers were returned. Sustainability produced the largest set, which is 148. The next step was filtering the papers; the language was selected as “English”, publications were limited to a start year of 1990 and the paper type was limited to journal articles and conference papers, documents which can be analysed by the content of its abstract.

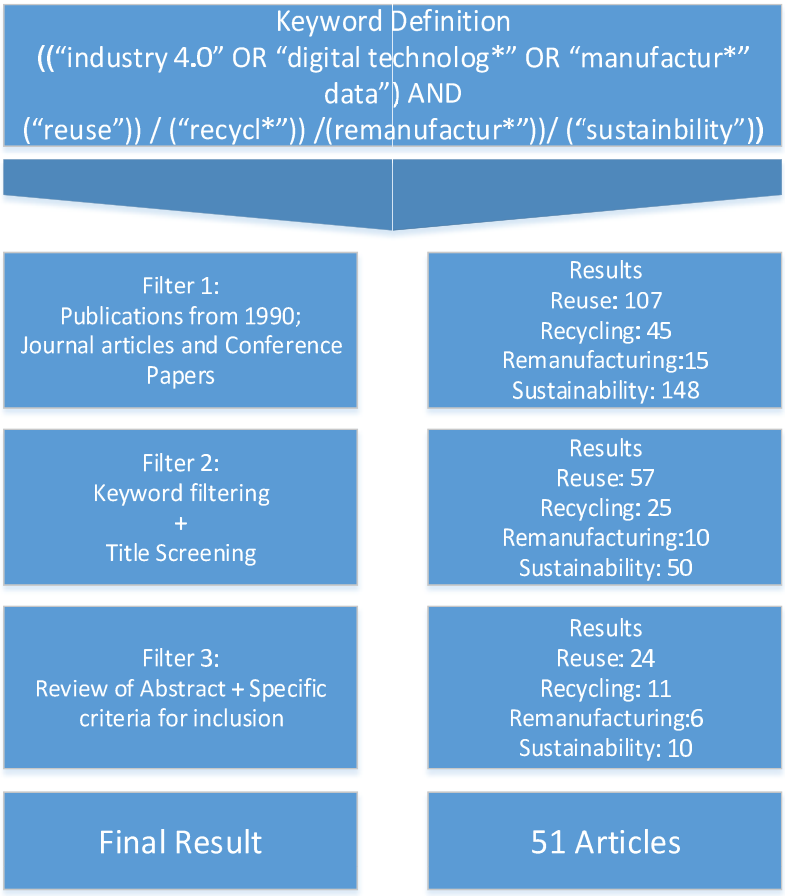

Figure 1: *Search Process*

The total documents returned after this filtering was 142, with papers on circular economy, manufacturing data and reuse being the highest at 57. The papers were then filtered based on key words and the title relevant to the research. The papers were then reviewed by abstract as the researcher searched for papers that offered titles and keywords close to the papers sought. The final filtered papers were 51 in total. Reuse, 24; Recycling, 11; Remanufacturing 6 and Sustainability, 10 papers.

For these papers, the following criteria were utilised as criteria for selection:

- Studies where circular economy review is the main topic
- Studies that are offer a contribution to circular strategies at for products at end of life in terms of decision-making.
- Papers that show the development of digital technologies in enabling the circular economy.

Subsequently each abstract, introduction, objectives, methodology and future work were read and analysed to create a detailed classification which will help us understand the research trends in the research area as well as identify gaps for use to build a viable framework. While “sustainability” is not a circular approach, it was included with the aim of enriching the research. The classification was then done based on i) subject type ii) number of

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papers iii) year published and iv) most popular journals/ conference papers. After the classification, the evaluation of the results was carried out.

4. RESULTS

This section presents the outcomes of the research after a careful analysis of the trends of the papers selected for review. A framework is proposed based on the identification of the principal research streams on the topic of data-driven approaches for circular economy in manufacturing for digital technologies. This research streams are then analysed to obtain a broad picture of current trends. The below is a descriptive analysis that evaluates the 51 articles by subject, the numbers of papers vs End-Of-Life Strategy and the most popular journals/ conference papers. Figure 2-5 gives the papers featuring Industry 4.0/ Digital Technology/ Manufacturing Data with Reuse, Recycling, Manufacturing and Sustainability. Figure 6 gives a chart of the most popular journals by numbers.

4.1.1 Papers Featuring Industry 4.0/Digital Technology/ Manufacturing Data with Reuse

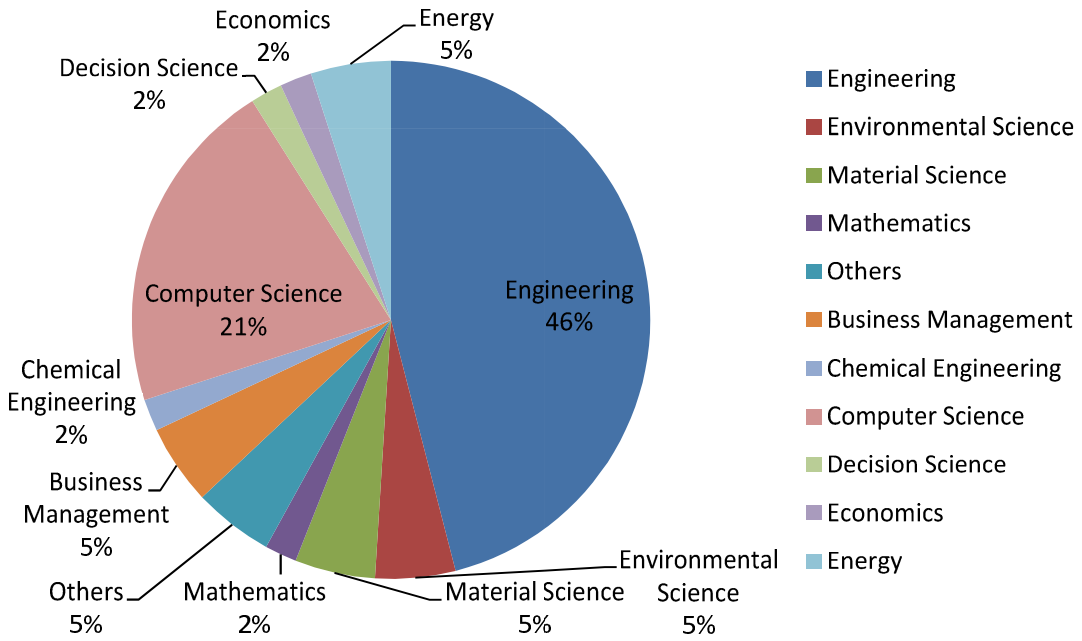

Figure 2: *Reuse: Analysis by Subject Type*

4.1.2 Papers Featuring Industry 4.0/ Digital Technology/ Manufacturing Data with Recycling

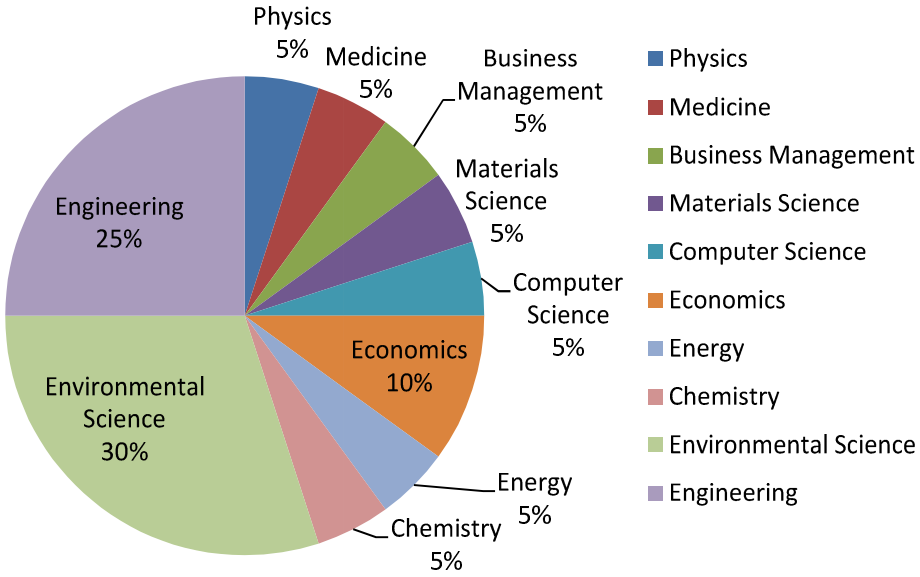

Figure 3: *Recycling: Analysis by Subject Type*

4.1.3 Papers Featuring Industry 4.0/ Digital Technology/ Manufacturing Data with Remanufacturing

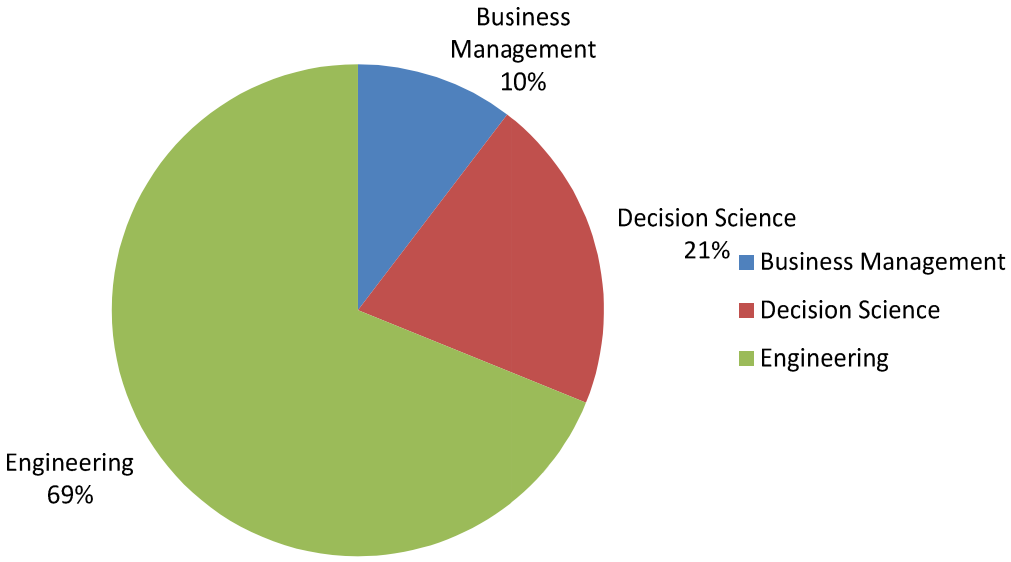

Figure 4: *Remanufacture: Analysis by Subject Type*

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4.1.4 Papers Featuring Industry 4.0/ Digital Technology/ Manufacturing Data with Sustainability

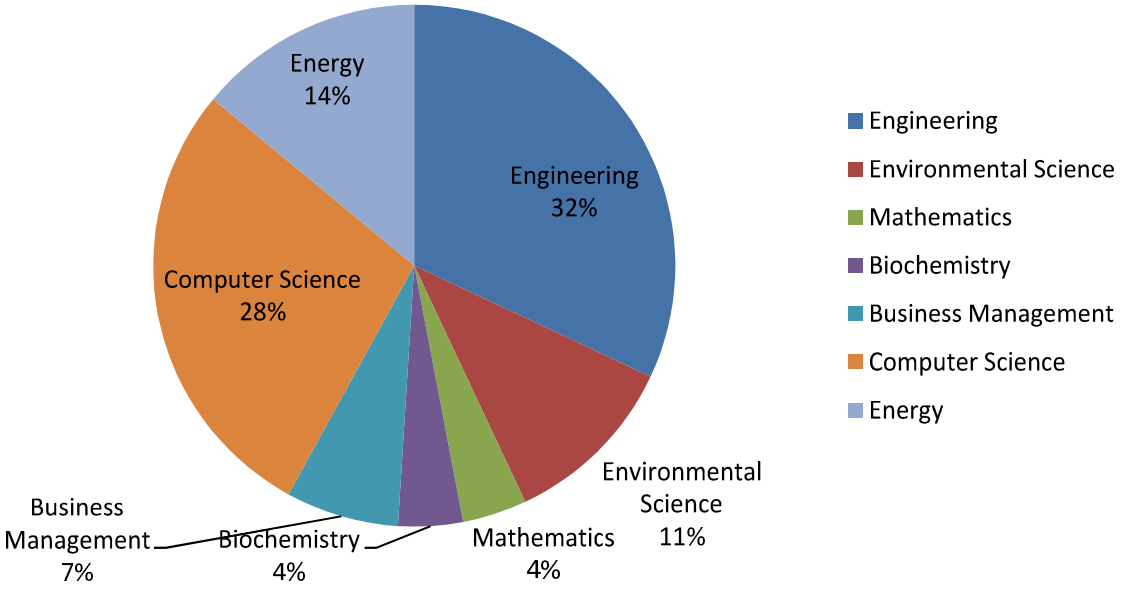

Figure 5: *Sustainability: Analysis by Subject*

4.1.5 Number of Papers vs Circular Approaches

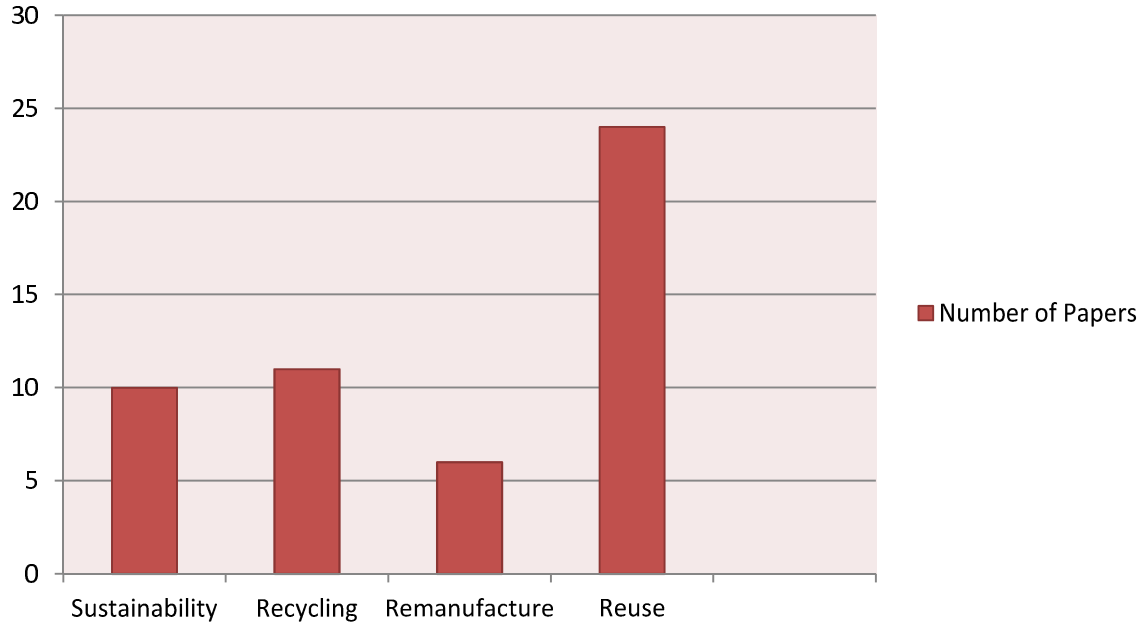

Figure 6: *Most Popular Journals/Conference Papers*

4.2 Analysis of Results

The relevant literature in this search is 16% of the initial search results returned for all the search output on SCOPUS before filtering was done. Thus this suggests that the research that intersects circular approaches, digital technologies and manufacturing data is still a new and developing area. There is a three-fold renewed focus on CE by the government, (Dustin Benton, 2015), the industry (Ellen MacArthur Foundation, 2015) and the academia, (Lacy and Rutqvist, 2016). This interest is set to grow in the face of policymakers push towards IoT enabled devices and the digitalisation of the workspace. (May *et al.*, 2016) suggests a variety of algorithms and computer aided control methods which are directed at industrial sectors and particular equipment. The push for sensors-enabled devices and products such as electric vehicles indicate that digital technologies is an increasingly important member of Industry 4.0. This publication confirm this and also suggests the question: what happens to these products at end-of-life? The low papers on this, especially as regards the "three R's", suggests that this particular area is still at its elementary stage of study.

Engineering-related research papers recorded the highest number of papers under the subject under review. Once analysed, information and communication technologies (ICT) can be seen to be quite common in the study. Within this context, ICT includes, (May *et al.*, 2016) a changing number of resources and technologies which are in a constant flux of evolution, giving rise to innovations for enabling the CE. Identified within the surveyed papers are sub categories in the ICT research field. These include, (i) integration of processes and information flows [(Ness *et al.*, 2015), (van der Harst, Potting and Kroeze, 2014)] (ii) process automation [(Vol, 2013), (Ness *et al.*, 2015), (Huang *et al.*, 2009)] (iii) IoT and Big Data (Stark *et al.*, 2010), (Shrouf, Ordieres and Miragliotta, 2014), (Zhang *et al.*, 2017), (Luckow *et al.*, 2015)(Wang and Alexander, 2015)] (iv) integration of processes and information flows [(Ness *et al.*, 2015), (Pauwels *et al.*, 2013), (Kohtala, 2015)]. One of the findings from this analysis is that researchers' interest in this field is aim towards finding operational solutions to the challenges of digital technologies in the CE. Few papers focused on the ecology, technology selection, development and deployment, standardization and policy and other strategic decisions that digital technology in the CE will employ.

The Journal of Cleaner Production, the transdisciplinary and international journal forum for research concepts primarily around technologies and sustainability was the most used journal by authors in this area. As this research tries to understand circularity from a manufacturing data point of view, conference articles and papers from the IEEE- the Institute of Electrical and Electronic Engineers- ranks highest (with the Journal of Cleaner Production) for research site. Journals and conference papers, however, were pulled from across the world**.**

Based on the main themes identified in the research and the systematic literature review, we proceed towards developing a framework based on the keywords which have been identified in the abstract of this paper as well as the gaps in the pertinent literature. The framework, which is given in Figure 7, attempts to link the manufacturing data emanating from a manufacturing process into the product and then the end of life approach for that product.

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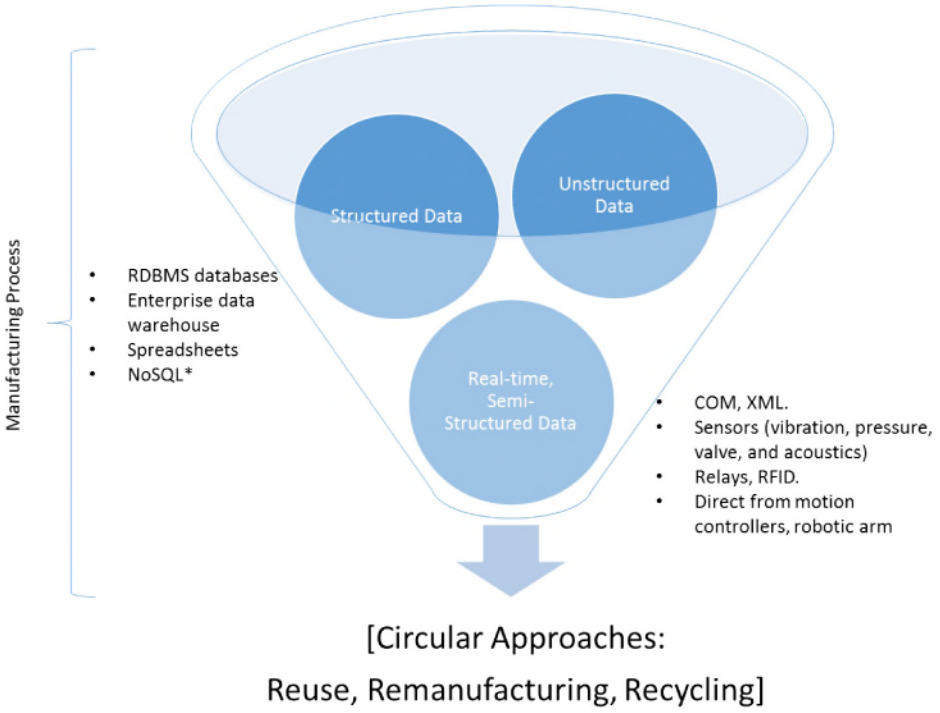

Figure 7: *Manufacturing data with Circular Approaches*

5. CONCLUSION

The study attempted to answer the following research question:

RQ: How does data produced from the manufacturing process enable circularity?

Through a systematic literature review based on methodology which involved selecting papers via SCOPUS and a filtering system that includes three levels of filtering. At the end 51 papers consisting of papers with reuse, recycling, remanufacturing and sustainability as main perspectives were analysed. The results show that the intersection between digital technologies, manufacturing data and the circular economy is still a growing area, with current focus on the technology and innovation growing faster than research on areas as the ecology and policy making. As there is a link between manufacturing data, circular approaches and digital technologies, future research will focus on finding solutions to challenges within the different links, with the aim of retaining products as long as possible within the circular loop.

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