Internet of Materials: A FANTASY OR THE FUTURE?

An explorative study on the Internet of Material, including the impact of datafication & digital technologies on material recovery in the supply chain industry, and its contribution towards a Circular Economy.

Master thesis Business Administration

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I - Abstract

Purpose – The integration of disruptive technologies (i.e. IoT, Machine Learning) and Datafication as one, a concept that is known as the Internet of Materials (IoM), is underexposed in academic literature. This thesis contributes to literature by describing the content (roles, goals and process) of the IoM concept; proposing a conceptual framework that explains the involved (Industry 4.0) technologies and its benefits; and identifying how IoM can be used to benefit the Circular Economy by using circular (business) strategies.

Methodology – In this research thesis, a systematic 'literature review methodology' of the Circular Economy and the Industry 4.0 was conducted. Furthermore, empirical data was obtained from semi-structured interviews to support academic literature findings and identify practical applications.

Findings – The goals of IoM (provide insight in material degradation, product redesign, material tracking and the quantified-self) have positive effects on Circular Supply Chain Management and contributes to a Circular Economy by enhancing closed-loop material/product life-cycles and by proposing (material-) efficiency in manufacturing operations and logistic operations.

Practical implications – Refinement of circular business models & strategies; Improve inter-supply-chain collaborations. Change mindset of management to prioritize sustainable investments.

Future research – "To what extent does the adaptation of more complex digital technologies benefit the IoM configuration?"; "What is the cost vs benefit ratio of integrating an IoM into organizations?"; "Does high-energy consumption of Deep Learning techniques limit the applicability of deep learning oriented IoM configurations?".

Keywords – *Internet of Materials (IoM), Industry 4.0, Datafication, Internet of Things (IoT), Digital Technology, Circular Supply Chain Management (CSCM), Smart Manufacturing, Cloud Computing.*

II - Preface

I have to admit that this thesis has been a struggle. Combining a thesis with a part time consultant job at the Radboud University Hospital during the Corona pandemic has been hard. Progress was lacking and content was hard to acquire. However, after valuable feedback I have finally completed the thesis.

I would like to thank my supervisor Prof. dr. Jonker for his support and guidance. I am truly thankful for all your patience and willingness to take me on as a thesis candidate.

- Steven Gerards

III - Table of content

IV - Definition list:

10-Retention strategies of CE (10Rs): "*Several circularity strategies exist to reduce the consumption of natural resources and materials, and minimise the production of waste. They can be ordered for priority according to their levels of circularity, forming the 10Rs" (Potting et al., 2017, p4).*

1st industrial revolution: "*the first industrial revolution begins began at the end of the 18th century and is was represented by mechanical production plants based on water and steam power" (Lu, 2017, p1)*

2nd industrial revolution: *"the second industrial revolution starts started at the beginning of the 20th century with the symbol of mass labor production based on electrical energy" (Lu, 2017, p1)*

3D-printing: "*the manufacturing of solid objects by the deposition of layers of material (such as plastic) in accordance with specifications that are stored and displayed in electronic form as a digital model" (Merriam-Webster dictionary, n.d.)*

3rd industrial revolution: "*the third industrial revolution begins began in the 1970s with the characteristic of automatic production based on electronics and internet technology" (Lu, 2017, p1)*

4th industrial revolution: *"the fourth industrial revolution, namely Industry 4.0, is ongoing, with the characteristics of cyber physical systems production, based on heterogeneous data and knowledge integration" (Lu, 2017, p1).*

Additive manufacturing technology: *[See: '3D-printing']*

Artificial intelligence (AI): *"Artificial intelligence is an umbrella term that entails the theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages" (Lexico dictionary, n.d.)*

Autonomous robot technology: *"Technology in which a robot that is designed and engineered to deal with its environment on its own, and work for extended periods of time without human intervention. Autonomous robots often have sophisticated features that can help them to understand their physical environment and automate parts of their maintenance and direction that used to be done by human hands" (Techopedia dictionary, n.d.)*

Big Data: "*Big data refers to the large, diverse sets of information that grow at ever-increasing rates. It encompasses the volume of information, the velocity or speed at which it is created and collected, and the variety or scope of the data points being covered" (Investopedia dictionary, 2021)*

Big Data analytics (BDA): *"Big data analytics refers to the strategy of analyzing large volumes of data, or Big Data. This Big Data is gathered from a wide variety of sources, including social networks, videos, digital images, sensors, and sales transaction records. The aim in analyzing all this data is to uncover patterns and connections that might otherwise be invisible, and that might provide valuable insights about the users who created it." (Techopedia dictionary, n.d.)*

Circular economy (CE): *"an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations" (Kirchherr et al., 2017, p224-225)*

Circular strategies: *[See: '10-Retention strategies of CE']*

Circular Supply Chain Management (CSCM): *"the coordinated forward and Reverse Supply Chain Managements via purposeful business ecosystem integration for value creation from products/ services, by-products and useful waste flows through prolonged life cycles that improve the economic, social and environmental sustainability of organizations" (Batista et al., 2018, p446)*

Cloud computing technology: "*Cloud computing is the delivery of different services through the Internet. These resources include tools and applications like data storage, servers, databases, networking, and software. Rather than keeping files on a proprietary hard drive or local storage device, cloud-based storage makes it possible to save them to a remote database. As long as an electronic* *device has access to the web, it has access to the data and the software programs to run it." (Investopedia dictionary, 2020)*

Computational Materials Science: "*In computational material science, data is used in modeling, simulations, for theories, and informatics with the purpose to better understand materials"* (LeSar, 2013)

Computer Science: *"Computer science is the study of both computer hardware and software design. It encompasses both the study of theoretical algorithms and the practical problems involved in implementing them through computer hardware & software. The study of computer science has many branches, including artificial intelligence, software engineering, programming and computer graphics. The need for computer science as a discipline has grown as computers become more integrated into our day-to-day lives and technology continues to advance"* (Techopedia dictionary, n.d.)

Cyber-physical systems / environment: "*CPS is the merger of ''cyber" as electric and electronic systems with ''physical" things. The ''cyber component" allows the ''physical component" (such as mechanical systems) to interact with the physical world by creating a virtual copy of it. This virtual copy will include the ''physical component" of the CPS (i.e., a cyber representation) through the digitalization of data and information. By this, CPS can be assumed as a range of transformative technologies to manage interconnected computational and physical capabilities"* (Trappey et al., 2016)

Cyber security technology: "*Cybersecurity technology refers to preventative methods used to protect information from being stolen, compromised or attacked. It requires an understanding of potential information threats, such as viruses and other malicious code"* (Techopedia dictionary, n.d.)

Datafication: *"Datafication refers to the process by which subjects, objects, and practices are transformed into digital data. Associated with the rise of digital technologies, digitization, and Big Data, many scholars argue datafication is intensifying as more dimensions of social life play out in digital spaces."* (Southerton, 2020)

Digitalisation: *"Digitization is the process of converting analog signals or information of any form into a digital format that can be understood by computer systems or electronic devices. The term is used when converting information, like text, images or voices and sounds, into binary code. Digitized information is easier to store, access and transmit, and digitization is used by a number of consumer electronic devices."* (Techopedia dictionary, n.d.)

Digital modeling and fabrication: "*Digital modeling and fabrication is a design and production process that combines 3-D modeling or computing-aided design with additive and subtractive manufacturing. Additive manufacturing is also known as 3-D printing. The purpose of digital modeling and fabrication is to allow designers to create physical models that can be used to test the success of a design. Digital modeling and fabrication's potential uses span a variety of industries, from manufacturing to architecture to fashion."* (Cole, 2014)

Digital technology: "*The branch of scientific or engineering knowledge that deals with the creation and practical use of digital or computerized devices, methods, systems, etc"* (Dictionary.com, n.d.)

Digital twin: "*A digital twin is a fully mapped digital version of something existing in the physical world. People talk about digital twins in describing digital systems that are set up to simulate or correlate to real-world systems" (Techopedia, n.d.)*

Disruptive technologies: *"Disruptive technology is an innovation that significantly alters the way that consumers, industries, or businesses operate. A disruptive technology sweeps away the systems or habits it replaces because it has attributes that are recognizably superior"* (Investopedia dictionary, n.d.)

Electrical Engineering: *"the branch of engineering that deals with the practical application of the theory of electricity to the construction of machinery, power supplies, etc."* (Dictionary.com, n.d.)

Horizontal and Vertical systems: *[See: 'cyber-physical environment']*

Industry 4.0: *[See: '4th industrial revolution']*

Information technology (IT): *[Similar to computer science] "The technology involving the development, maintenance, and use of computer systems, software, and networks for the processing and distribution of data"* (Merriam-Webster dictionary, 2020)

Internet of Things (IoT): *"The Internet of Things (IoT) is a computing concept that describes the idea of everyday physical objects being connected to the internet and being able to identify themselves to* *other devices and send and receive data. The term is closely identified with radio frequency identification (RFID) as the method of communication, although it also may include other sensor technologies, wireless technologies or QR codes"* (Techopedia dictionary, n.d.)

Linear economy: *"The linear economy is a traditional economy model based on a 'take-make-consume-throw away' approach of resources"* (Eionet.Europe, n.d.)

Machine learning (ML): "*Machine learning is an application of artificial intelligence that provides systems the ability to automatically learn and improve from experience without being explicitly programmed. Machine learning focuses on the development of computer programs that can access data and use it to learn for themselves"* (Expert.ai Dictionary)

Material physics: *"The scientific study of the properties and applications of materials of construction or manufacture (such as ceramics, metals, polymers, and composites)"* (Merriam-Webster dictionary, 2020)

Material science: *[See: 'Material Physics']*

Operational Technology (OT): *"Operational technology (OT) is hardware and software that detects or causes a change, through the direct monitoring and/or control of industrial equipment, assets, processes and events."* (Gartner, n.d.)

Reverse Supply Chain Management: *"Reverse supply chain management (RSCM) is defined as the effective implementation of the series of activities involved in collecting a product from any stage of the forward supply chain to either dispose it or recover value. In the Reverse Supply Chain Management, there are a sequence of steps required to pick up the used product and to carry out the most suitable product disposition strategy like reuse, remanufacturing and/or recycling. The Reverse Supply Chain Management initiates with accumulation of products from different stages of the supply chain which includes firms as well as customers. These members of the supply chain are generally widely dispersed geographically."* (Karamchandani et al., 2017)

Smartification: "*Smartification refers to the digital refinement of an existing product by embedding digital technologies and smart services. Primary product-determining factors still must be accounted for and a product's primary function must remain in place. When new technologies are embedded, completely new digital performances are offered"* (Schuh et al., 2019)

Smart manufacturing (SM): "*Smart manufacturing is the notion of orchestrating physical and digital processes within factories and across other supply chain functions to optimize current and future supply and demand requirements. This is accomplished by transforming and improving ways in which people, process and technology operate to deliver the critical information needed to impact decision quality, efficiency, cost and agility"* (Gartner, n.d.)

Sustainable supply chain management (SSCM): "*We define Sustainable Supply Chain Management (SSCM) as a set of managerial practices that include all of the following: Environmental impact as an imperative; Consideration of all stages across the entire value chain for each product; and a multi-disciplinary perspective, encompassing the entire product life-cycle."* (Gupta & Palsule-Desai, 2011)

1. Introduction

1.1 Problem statement

Most economic systems tend to answer three basic questions; ‘What to produce?’, ‘How to produce it?’, and ‘In what quantities to produce it?’. Competitive economic systems are coordinated by ‘prices’ and would lead to a production of goods and services which are valued most highly by the consumers (Coase, 2005). Our society is driven by a desire for material needs, products are manufactured with raw materials and thrown-away after usage (Gardetti, 2019). Due to a take-make-waste economy, known as a linear economy, the earth can no longer sustain itself and disruptive changes towards a more sustainable economy are essential (Ellen MacArthur Foundation, 2015). Our planet has its limits and the unsustainable and non-durable take-make-dispose system is the reason for exceeding the environmental boundaries (Rockström et al,. 2009). These planetary boundaries make us question the continuity of the linear economy and experts deem a global Circular Economy (CE) to be the solution, “an industrial system that is restorative or regenerative by intention and design” (MacArthur 2013).

European, Japanese and Chinese governments, are implementing incentives and regulations to pursue CE principles (Ghisellini, Cialani & Ulgiati, 2016; Mathews & Tans, 2016) by setting basic requirements for the CE transition and stimulating the creation of new policies enhancing sustainability (Padilla-Rivera et al., 2020). Simultaneously, corporations have started to implement circular strategies to be less dependent on raw materials while improving financial objectives. Global companies have the power to force the change of implementing a CE in our daily life, instead, the majority choose to prioritize revenues over circularity (MacArthur 2013; Geipele et al., 2018). The CE provides new business opportunities for organizations while solving multiple ecological issues at the same time (MacArthur 2013). Unfortunately, these governmental and corporate circular strategies have been insufficiently and not systematized (Kristoffersen et al., 2019; Kristoffersen et al., 2020), as a result, the world is only 9% circular and the trend is heading in the wrong direction (Circle Economy, 2019). Legislative adjustments and Corporate Social Responsibility stimulants mainly focus on economic-environment perspectives, while social aspects (CE support) are still missing (Padilla-Rivera et al., 2020). Cultural barriers, such as a lack of interest, knowledge or engagement throughout the entire value chain can make sure that the circular movement remains slow (Hart et al., 2019). The challenge to change the mindset of society concerning the concept of CE remains unsolved (Geipele et al., 2018), but literature on societal change has indicated that disruptive innovations can be used as a tool to establish or speed up this societal change (Shin & Lee, 2011). We live in an industrial age that can opportunize the evolution of technology better known as Industry 4.0. This era is known for new (business) opportunities of storing data in clouds and disruptive technologies (i.e., IoT). Industry 4.0 is transforming the next generation of product/ design. To accelerate this transformation, industrial sectors have planned to commit $907 billion US dollars per annum to industry 4.0 (Geissbauer, Vedso & Schrouf, 2016). Prior research on CE indicates that the application of these digital technologies (i.e, Internet of Things (IoT) technology) and the trend of digitalization can aid the acceleration towards a worldwide CE (Hart et al., 2019; Kristoffersen et al., 2020). Due to the ability to track products and materials, with IoT technology (i.e., sensors) and collect highly valuable data on material use through the entire product life cycle (Madakam et al., 2015). In 2018 it was expected that the number of interconnected devices would reach 50 billion devices by 2020 along with an estimated (IoT) market value of $14.4 trillion (Miao et al., 2018). Large corporations have driven the development of the IoT to benefit from the foresight and predictability that it offers.

As mentioned earlier, it is possible to overcome certain barriers to the CE by adapting emerging (digital) technologies (de Sousa Jabbour, et al., 2018) due to Industry 4.0. So far, some literature has addressed the relationship between Industry 4.0 and organisational sustainability (e.g. Stock and Seliger 2016; Trentesaux et al. 2016; Waibel et al. 2017). Some of the digital technologies of Industry 4.0 have merged to form the concept 'Smart manufacturing' (SM). This concept already exists for about a decade and has been extensively addressed by academic literature (Davis et al., 2012; Davis et al., 2015; Kusiak, 2018; Kusiak, 2019) and has also been frequently linked to the circular economy (Kristoffersen et al., 2020; Gray-Hawkins & Lăzăroiu, 2020; Ghoreishi & Happonen, 2020). So far, leading manufacturers have begun implementing SM in their factories, turning them into smart factories (Sjödin, Parida, Leksell, & Petrovic, 2018). However, most firms still lack insight into the challenges and resources for implementing smart factories (Shi et al., 2020). Therefore, it can be argued that a knowledge gap exists related to how organisations should set-up and integrate these new technologies towards sustainable operations management and the achievement of CE strategies. Although, Industry 4.0, Smart Manufacturing, Remanufacturing, Circular Supply Chain Management and Circular Economy have been researched extensively as a concept, studies that research the relationship among these 3 concepts are limited (de Sousa Jabbour et al., 2018; Bag et al., 2020). In addition, there may be a knowledge gap related to how organisations implement circular business strategies to build the path towards more sustainable operation management, while taking into consideration the current technological tendencies of Industry 4.0 (de Sousa Jabbour et al., 2018). A concept related to this emphasis has arisen in existing literature, a young concept that lacks academic research but seems to be promising. It combines the improvement of manufacturing- and logistic operations along with the applications of circular strategies. Ahmet Hosney (2015) was the first author to propose this concept as "Internet of Materials (IoM), and described it as a means to bring together 'Materials' and 'Analytics' into 'Material Analytics'. It has a high level of predictive power due to the combination of Big Data and Machine Learning. But the question remains whether the IoM can be an important means to achieve improvements to Material-design, Smart Manufacturing- and logistic operations, and thus contribute to a worldwide Circular Economy. So far, the concept has been researched to a limited extent and most of the published literature has been written from a technical perspective. This study will investigate the 'Internet of Material' by gathering existing IoM literature to describe the content (roles, goals and process) of the concept. Furthermore, literature is then used to create a conceptual framework that explains the involved (industry 4.0) technologies and its benefits. The final step of this master thesis is to identify how the Internet of Material can be used to benefit the Circular Economy by linking it to circular strategies. The latter will be presented with a framework containing the link between IoM and CE.

1.2 Research objective

The main focus of this thesis is to get a better understanding of the role, goals and process of the concept Internet of Materials (IoM), by performing an exploratory study of academic literature on the IoM concept. A concept that was introduced by A. Hosny in 2015. This thesis will validate the accuracy of existing conceptualisations of the IoM. In addition, this thesis explores the identified gap in literature by researching the relationship between IoM, the principles of Circular Economy and Industry 4.0 approaches. The author will contribute to literature by proposing a new conceptual framework for IoM from a business perspective.

With this in mind, the master thesis has two central questions.

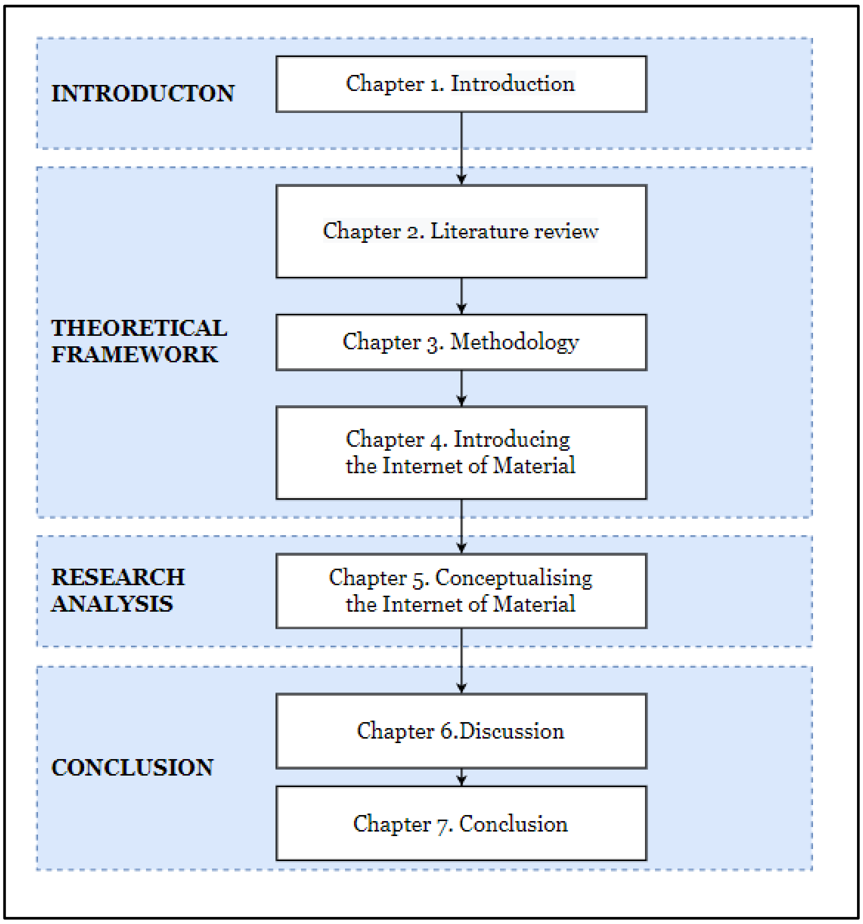
The first research question is:
" How are technologies used to conceptualise the Internet of Materials ?"

The second research question is:
" How can the Internet of Materials as a concept benefit the Circular Economy ?"

In order to answer these research questions by exploring all developments in the area of research and find gaps in knowledge that need to be addressed. Related concepts that are studied are Circular Economy, Industry 4.0 Technologies, Smart Manufacturing/ remanufacturing and Sustainable Supply Chain Management/ Reverse Supply Chain Management. In addition, the author of this thesis has performed semi structured interviews to gather (practical) information by industry and technology experts and combine these insights with findings from the extensive literature review.

1.3 Research design

The thesis starts off with a literature review chapter (2). The literature review contains background information on the Circular Economy, Industry 4.0 and IoM. The following chapter (3) contains the research methodology of this research. The fourth chapter (4) is dedicated to describe the content of the IoM based on academic findings. The fifth chapter (5) proposes a conceptual framework containing the involved IoM technologies; and a conceptual framework consisting where the relation between IoM and CE is displayed. The discussion, in chapter (6), contains research implications, limitations and future research. In the final chapter (7) a conclusion of the most important findings is given.



2. Literature review

This chapter provides a critical examination of existing research on the Circular Economy and the Industry 4.0. The purpose of this chapter is to examine what a CE entails; The role of corporations in the transition towards CE; Barriers and enablers of the CE; What the Industry 4.0 entails; Find existing literature on the Industry 4.0 linked to CE; Provide existing literature on the term IoM.

2.1. An introduction to the Circular economy

In this traditional economy system - the linear economy - products are manufactured from raw materials, purchased by consumers and eventually disposed as waste after usage (Braungart, McDonough & Bollinger, 2017). This modern economic system, based on a "take-make-dispose" philosophy, is not sustainable and will give trouble to the planetary limits (Frosch & Gallopoulos, 1989; Pagoropoulos et al., 2017). Products are increasingly becoming commodities and resource scarcity is becoming a reality for a large variety of materials (Pagoropoulos et al., 2017). Thus CE contrasts the linear economy. The CE has been identified by academics and practitioners as a means to increase sustainability through reducing, reusing and recycling products and resources (Ghisellini et al., 2016). The most renown definition of the CE as an economic system has been framed in 2013 and revised in 2015 by the Ellen MacArthur Foundation: "*A Circular Economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles*" (Ellen MacArthur Foundation, 2015). A more extensive definition is given by Kirchherr et al. (2017, p224-225), the article defined CE as: *"an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/ distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations".*

New methods to extend the life of products have long been sought since it can accelerate the shift from a linear to a CE (Garrido-Hidalgo et al., 2020). Organizations are still cautious to extend their efforts towards adoption of CE principles in order to increase circularity and further enhance the lifecycle of resources (Liu & Bai, 2014). The production and consumption in the Circular Economy is focused on restoring the value of used resources (de Sousa Jabbour et al., 2018). Multiple closed-loop cycles of remanufacturing, recycling and of reuse, can make sure that raw materials retain their physical properties and value for as long as possible (Jonker et al., 2017). The ultimate goal of a closing loop system is first of all to 'design out' waste, and if there is waste, to recycle it (Reike et al., 2018). The classic representation of CE is based on a *biological* cycle and a *technical* cycle. The biological cycle within CE has the opportunity to become completely zero waste, while the technological cycle could have the potential to generate heat from much of its waste (Ellen MacArthur Foundation, 2015). There is a need to dematerialise and (re)designed products with the aim to improve life cycles, by implementing recycling measures (closing), making efficiency improvements (narrowing), or extending the life cycle (slowing or extending) for products. Throughout the years literature has formed multiple R-imperative – starting with 3Rs and eventually forming 10Rs – refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover (Geissdoerfer et al., 2018). These 10R-imperative can be seen as circular strategies that have different gradation of circularity: from most to least circular (Reike et al., 2018; Kirchherr et al., 2017). The 10Rs are explained individually in Appx B, Fig.16.

2.1.1 Corporate contribution to Circular Economy

When defining the current state of the CE, it is clear that the concept of CE gained momentum - in the past decade - among business and policymakers on its potential to contribute to sustainable development (Geissdoerfer et al., 2017; Ghisellini et al., 2016). It is increasingly seen as a partial or complete solution to gain and maintain sustainable developments (Geissdoerfer et al., 2017). Industries have started looking for opportunities towards a CE, making it more than just a theoretical concept (Govindan, et al., 2018). Furthermore, incentives and regulations by governments to make environmentally friendly products have stimulated the organizations to focus on sustainability (Zhu, Geng & Lai, 2010).

Literature underlines that Supply Chain management (SCM) plays a crucial role in the transitioning towards a CE. It can identify new ways to add-value, get insight in product consumption and aid in value recovery (Barber et al., 2012). Prior to 2017, literature on the Circular Supply Chain was rather rare (Homrich et al., 2017) and usually referred to closed loop supply chains (Govindan et al., 2015). After 2017, additional academic literature on supply chains and CE appeared and the term Circular Supply Chain Management (CSCM) became more popular. CSCM consists of the sorting out and coordinating the supply chain to close loops, with the intention to maximize benefits of resources, products, energy consumption and synergize it to attain more sustainability across the supply chain (Marconi et al., 2018). When further considering the current state of the CE, it is necessary to develop more sustainable business models as it provides the bases for companies to better contribute to a CE (Witjes & Lozano, 2016). It paves the road for the rising number of diversified circular business models (Bocken et al., 2016) (Appx B, Fig.16). Compared to current business models, circular business models have a different value creation that drives the supply chain into retention loops (Geissdoerfer et al., 2018). Geissdoerfer et al. (2018) makes a distinction between CE loops and highlights the following approaches: *"closing loops, slowing loops, intensifying loops, narrowing loops, and dematerialising loops" (*Appx B, Fig.17 for more explanation). What makes the CE so special is that it values both the forward and the reverse flows of materials, components and products (Kumar & Putnam, 2008). By focussing on the forward and reverse flows, waste can be minimized and the objects can be used for as long as possible while keeping the operating costs at the bare minimum (Kumar & Putnam, 2008; Jonker et al., 2017). Once products reach the end-of-life stage the Reverse Supply Chain becomes responsible for management of operations to reduce the amount of non-reusable and unrecyclable resources (Garrido-Hidalgo et al., 2020). To optimize the idea of Reverse Supply Chain Management, the circular strategies or ten retention options (10Rs) can be integrated within organisations (Blomsma et al., 2019). The adoption of circular strategies in the supply chain industry is somewhat modest (Circle Economy, 2020; Haas et al., 2015; Planing, 2015; de Sousa-Zomer et al., 2018), although the interest in Reverse Supply Chain Management has grown a lot in recent years (Genovese et al., 2017). Even though the Reverse Supply Chain offers many benefits to organisations and the Circular Economy, there is a necessity to manage and monitor every single product stage, which has generated a considerable number of uncertainties for companies (Jerbia et al., 2018).

2.1.2 Barriers and enablers of the Circular Supply Chains

Hart et al. (2019) defined several barriers and enablers in a Circular Economy (CE) particularly for the supply chain industry. The assumption here is that the closer corporations get to resolving or dismantling these barriers, the better the progress towards CE (Hart et al., 2019). In the supply chain industry, these barriers can occur due to legislation and policy requirements; business leader mindsets; business models; the Economy; customer and employee understanding; manufacturing processes; product design; and the recovery of materials (Adam et al., 2019). Numerous attempts at regulatory cooperation over the years have shown that it takes a long-term commitment to implement regulatory changes (Lester & Barbee, 2013). The lack of a consistent regulatory framework, obstructing laws, regulations and incentives, are experienced as regulatory barriers (Hart et al., 2019) and need to be improved to aid the CE (Kirchherr et al., 2018). In addition, a lack of inter-organisational and B2B collaboration can be identified as cultural barriers. It reduces the knowledge, skills and engagement within the organization but also throughout the supply chain (Hart et al., 2019). According to Kassen (2019, p1): *"The development of official e-collaborative platforms provides new promising opportunities to promote mutually beneficial cooperation between government and citizens, and boost public sector innovations"*. Thus, by improving intra- and interorganizational collaboration, the regulatory and cultural barriers mentioned above can be improved. When considering the implementation of CE principles within an organisation and its supply chain, organisations are confronted with financial barriers. Generally, organisations tend to focus on market concerns rather than the fiscal environment (Hart et al., 2019). The perceived uncertainty regarding costs, return on investments and timeline concerns for implementation of CE principles often results in 'perceived difficulty to present strong business-cases for circular models' and 'initial reluctance from corporations to allocate funds for these ambitious goals' (Geng & Doberstein 2008; Su et al., 2013). So far, around 70% of companies are planning to invest in CE but only

12% have linked their digital and circular strategies (Gartner, 2020b). To overcome the barrier, additional data availability can provide the option to perform business analytics for better decision-making (Hart et al., 2019). Big Data – "*one of the most valuable assets for organisations, where large data sets may reveal patterns, trends and association"* (Oxford Online Dictionary, 2020) – can generate data-driven insights that lead to preferable decisions and business moves. It reduces risks and costs and helps an organisation operate more efficiently (Srai et al., 2016). According to Cavanillas, Curry and Wahlster (2016, p10), *"the Big Data value chain is one of the key economic assets of the future"*. Combining data with digital technologies can leverage various circular strategies, from operational processes to corporate strategies (Kristoffersen et al., 2020). Unfortunately this is not a definitive solution since companies have expressed a need for guidance on how to leverage 'data' and 'digital technologies' to optimise resource efficiency and productivity for a specific circular strategy (Kristoffersen et al., 2019; Kristoffersen et al., 2020).

2.2 Circularity through technology

2.2.1 Circular Supply Chain in the Fourth Industrial Revolution.

The western world has known multiple stages of industrial revolution driven by the invention of new ideas or technologies changing the existing society and economy (Fig.1). The first and second industrial revolution featured the use of inventions to increase the production speed with physical systems (water or steam powered machines and electric powered machines). The third industrial revolution occured in the 1960s and introduced cyber systems within the production industry featuring automated production through electronics & information technology (digitization). The 2020s is the era of the fourth industrial revolution. The industry 4.0 features the connection of physical and cyber systems and is highlighted by the use of (new) digital technologies. Appx B (Industry 4.0 ecosystems), provides a visualisation of the opportunities from Industry 4.0 for remanufacturing and its key enablers.

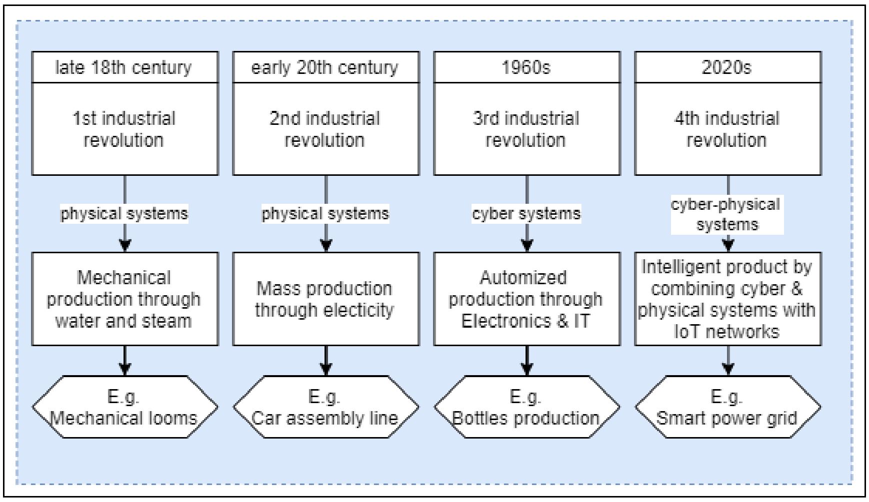


Figure 1. The industrial revolutions (Adapted from: *Lasi et al., 2014)*

As mentioned above, the new industry 4.0 is all about making business smarter and more automated. It converges Information Technology (IT) and Operational Technology (OT) in order to create a cyber-physical environment (Lasi et al., 2014). By connecting 'physical and cyber systems', supply chain logistics, production and customer service are all connected through the internet (Kagermann et al., 2016). A combination of 'Big Data and Internet of Things' enables global machine interconnectedness, smart manufacturing systems, and smart connection of devices

(Tjahjono et al., 2017). By adding additional technologies to the mix, more extensive applications can be created. Fig.2 provides an overview of the involved technologies to enable the smartification of the business processes.

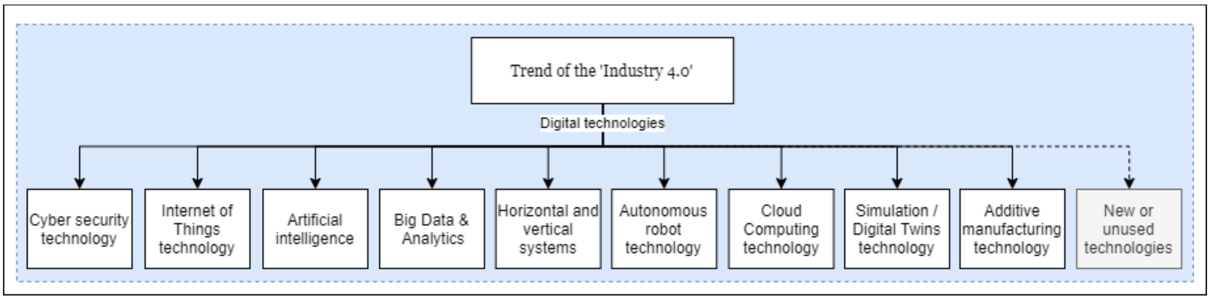


Figure 2. Some digital technologies enabling the Industry 4.0 (Reproduced from: Immerman, 2020).

The digital technologies are used to improve the production and manufacturing environment, including the supply chain practices (Tjahjono et al., 2017), by making the processes intelligent or smart. The creation of these 'intelligent' systems enables mass customization, better quality and improved productivity (Zhong et al., 2017).

The importance of Industry 4.0 to the Circular Economy cannot be underestimated. Multiple articles have stated that by bringing together the physical and digital worlds, technologies that can be used to accelerate the development of CE (de Sousa Jabbour et al., 2018; Iyer, 2018; Tjahjono, et al., 2017; Rajput & Singh, 2019). Thus the Industry 4.0 configurations may have the potential to overcome important barriers to CE (Sousa Jabbour et al., 2018; Wilts & Berg, 2017). However, no articles directly connect the 10Rs of CE (discussed in Paragraph 2.1, p14) to the Industry 4.0. Modgil et al. (2021) does state that *"These technologies"* (technologies of Fig.2), *"are capable of harnessing Big Data capabilities to help reuse, recycle and reduce the use of resources, thus supporting the objectives of the Circular Economy"* (p1). The rapid discovery of new technologies and the exponential growth of IoT applications are key to making the transition towards Circular Supply Chains possible (Lasi et al., 2014; Stock & Seliger 2016; James et al., 2015; Shrouf et al., 2014). Full collaboration, transparency and data sharing between supplier, manufacturers and customers, provided by the IoT, can help track the product from the product design, manufacturing and product dispatch until the end-of-life of the product (Tjahjono et al., 2017).

2.2.1.1 Technologies in the Industry 4.0

Big Data and the Internet of Things play a very important role in most of the Industry 4.0 configurations and are often interconnected (Tjahjono et al., 2017). IoT technology can be used to gather data from physical objects embedded sensors (GSMA, 2014) which objects are connected via the internet (Spring & Araujo 2017) and retrieve real-time information through the sensors (Rajput & Singh, 2019).

The real-time information (of IoT) is saved as Big Data and has the capability to monitor production processes and consumption patterns (Moreno & Charnley, 2016; Pagoropoulos, Pigosso & McAloone, 2017). Before Big Data can be interpreted into new insights it has to be translated with data analytics techniques (Rajput & Singh, 2019; Kortuem & Kawsar, 2010). So far, large amounts of Big Data remains uninterpreted due to the fact that organisations require better tools and methods to extract insights for IoT data (James et al., 2015). Machine learning (ML) techniques have enabled the analysis of Big Data sets (Qiu et al., 2016) and more ML techniques are developed in rapid succession (Khan et al., 2020). These existing and future ML techniques can be integrated into the IoT system in order to make it an autonome and self-analysing system (Lee et al., 2016; Adi et al., 2020). See Figure 3 for imagery.

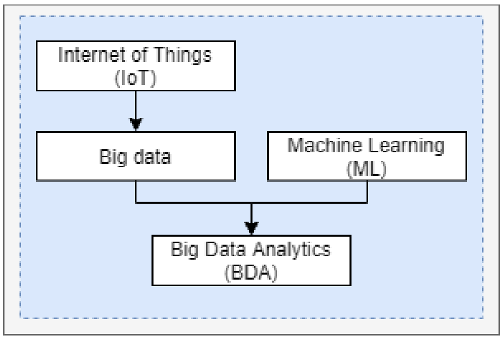


Figure 3. Cohesion of technologies Industry 4.0

To the Circular Economy, the value of IoT and Big Data is hard to deny since by adopting IoT and Big Data, the performance of systems and processes can be optimized. Data insights can be used to enhance the product and machine life-cycles and learn how to best redesign a machine or product (James et al., 2015). Fig.4 explains some of the benefits of Big Data Analytics to organisations and the Circular Economy.

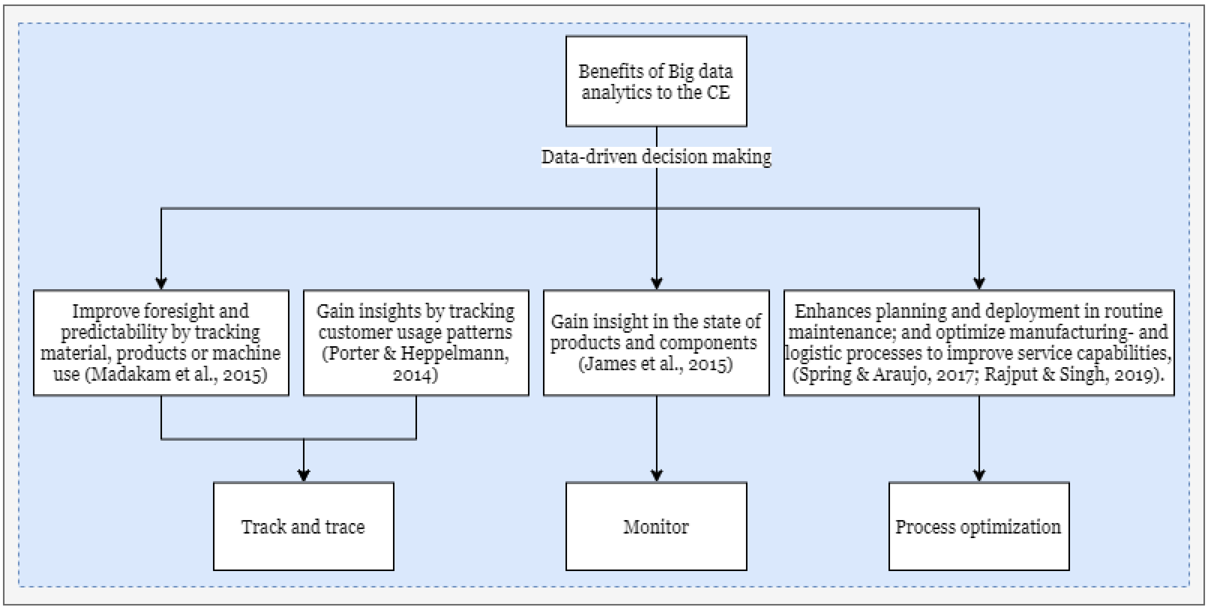


Figure 4. Benefits of Big Data according to existing literature (Produced by author S.F. Gerards, 2021)

2.2.1.1 Industry 4.0 in practice

One of the main technological configurations behind Industry 4.0 is Smart Manufacturing (Sony, 2020). Smart manufacturing (SM) has been created to be a new and more advanced solution that connects cyber and physical systems in order to improve manufacturing systems. Kusiak (2018) defines Smart manufacturing as*: "a fully integrated, collaborative manufacturing system that responds in real-time to meet changing demands and conditions in the factory, in the supply network and in customer needs".* SM allows machines to communicate with one-another without the need of human involvement (Lasi et al., 2014; Stock & Seliger 2016; Shrouf et al., 2014; Deloitte, 2014) meanwhile it can provide real time information on production, machines, and the flow of components (Zhong, Wang & Zu, 2017). By making use of Big Data Analytics, Smart Manufacturing can enhance complicated processes and help manage and improve the supply chains (Deloitte, 2014).

Additionally, the Industry 4.0 has enabled other advanced manufacturing configurations such as "Digital modeling and fabrication" and the "Internet of Materials". The first, "Digital modeling and fabrication", is regularly discussed subjects in academic literature and in practice; IoM is sporadically mentioned in literature however does not have a consistent definition. What is actually known about the Internet of Material is discussed in the next Paragraph.

2.3 Internet of Materials (IoM)

The Internet has become more complicated and technological applications such as the IoT have appeared. Carlsson et al. (2017) identify the next step to be an Internet of Material (IoM) application, but what is an IoM application? After extensive literature search, only two articles and one published book have been written with the Internet of Materials used as a key term. The literature explains the concept from a technical perspective.

Ahmet Hosny introduced the term Internet of Materials (IoM) in 2015 and described it as a combination of Sensory Technology, Machine Learning and Internet of Things (Hosny, 2015). Among many other technical statements, he states that the prediction power is what could make the Internet of Materials a useful configuration to organisations (Hosny, 2015). A few years later the term was actively used by Liaskos (2020) and in an article by Abowd (2020). Liaskos used the term 'Internet of Materials' in 2020 for the title of his book and defines it as *"the integration of artificial materials with the IoT ecosystem … to talk to materials with software commands and tune their physical properties accordingly" (p1 & p4).* He argues that IoM covers several scientific disciplines such as: Material Physics, Electrical Engineering, Manufacturing of Electronics, Communications, and Computer Science. Abowd (2020) however, argues that current technologies allow us to connect a physical object to digital representations of that object and explains that the Internet of Material is a combination of Computational Materials Science and Internet of Things technologies (Abowd, 2020). Even though the terms to describe the IoM do not match, the underlying meaning has some common ground (see Fig.5).

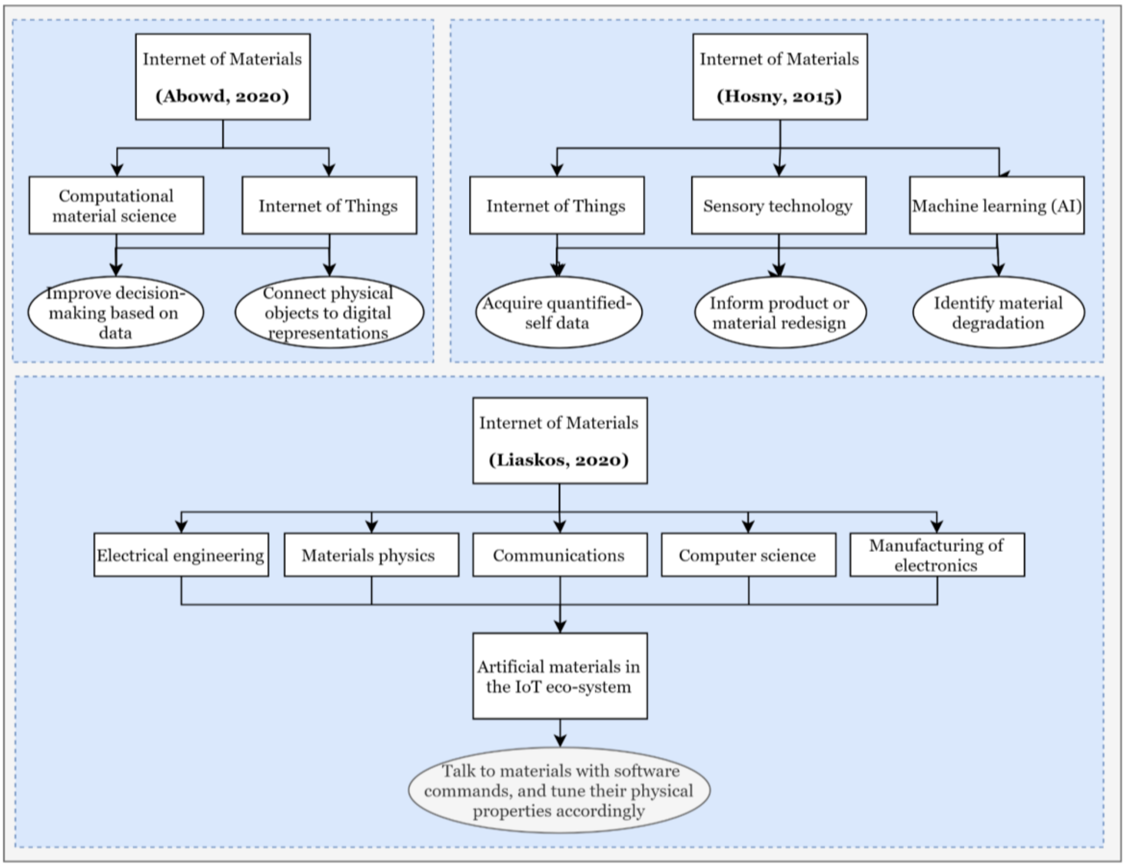


Figure 5. The term Internet of Material in existing literature

Hosny (2015), Abowd (2020) and Liaskos (2020) all discuss the application of Internet of Things to connect its hardware as well as the identification of material physicals to change the properties accordingly. By integrating datafication and IoT a user interface can be created that is not only a self sustaining mechanism for material sustainability but also helps with other Industry 4.0 applications (Mavropoulos, 2018). Meaning, IoM could be a strong benefactor to aid in the transition towards a worldwide CE. Meanwhile it helps drive growth & efficiency and supports material utility, value & sustainability (Carlsson et al., 2017). Chapter 4 will drive deeper into the content and technical layout of the Internet of Material. Chapter 5 discusses the involved technologies of the IoM and along with the link between the IoM and CE.

[To conclude: this study addresses a significant gap in literature by providing the content of an Internet of Material and proposing two conceptual IoM frameworks, one involved technologies and one linking between IoM and CE]

3. Methodology

The chapter 'methodology' describes and justifies the data collection methods, writing process and method of analysis. First, the research strategy is discussed. Subsequently, the data collection methods, the analysing techniques and research ethics is described in detail.

3.1 Research strategy

The aim of this thesis is to get a better understanding of how a combination of technologies can be used to form the Internet of Materials and how this benefits the Circular Economy.

This paper took the article of *Hosny (2015), Material Analytics: Knowledge From Mechanical Behavior Data, Harvard University Graduate School of Design*, as a starting point to come to an initial concept of the IoM. Since the article of Hosny (2015) is about material analytics, the initial IoM concept was substantiated with limited text. Additional literature on the Internet of Materials is scarce and often very technical. The first step within this thesis was to identify the current state of the Circular Economy and the role of technology within the Circular Economy. These parts are written in the first two chapters of literature review and are mostly based on academic literature and sporadically based on organisational or governmental documents. The next step in this thesis was to try and merge existing literature about the IoM and come to a conclusion to what the IoM is, what the IoM will be in the near future and how the IoM can be used to aid the CE. This part is written in the last Paragraph of the literature review and is followed by the small conclusion with the gap in current literature in relation to the current applicabilities of the Internet of Materials.

The result section mostly used academic literature. Semi-structured interviews are solely used to get familiar with the technologies and understand their interdependencies. The interviews were conducted to identify the dynamics of involved technologies of the initial IoM concept. By discussing the involved technologies, interviewees provided insights into new IoM applications due to the recent technological advancements and trends. The result section is divided into three parts. The first part of the result section provides the reader with the initial goals along with an overview of the technical steps of the IoM both are derived from existing IoM literature. The second part explains the IoM process, supported by literature and quotes from the semi-structured interviews. The third part provides the final IoM framework along with its benefits to the CE.

3.2 Data collection

<u>Literature research</u>

This thesis used the systematic literature review (SLR) methodology (Mariano et al., 2017) in the fields of CE, IoT and Data analytics. Fisch and Block (2018) describes the process of how SLRs have to be structured: (1) Planning of the strategy for literature review; (2) Conduct the literature review; (3) Report the findings of literature review. The list of papers were acquired through three internet search engines: ‘Web of Science’ by Clarivate Analytics, ‘Business Source Complete’ by EBSCO and ‘Google Scholar’ by Google LLC. These search engines are databases for academic scientific research journals, books and organisational documents. The requirements and general search techniques are provided by the Radboud University Library. Specific journal papers and organisational documents were selected for conducting the review of literature and were found through block search and snowballing techniques.

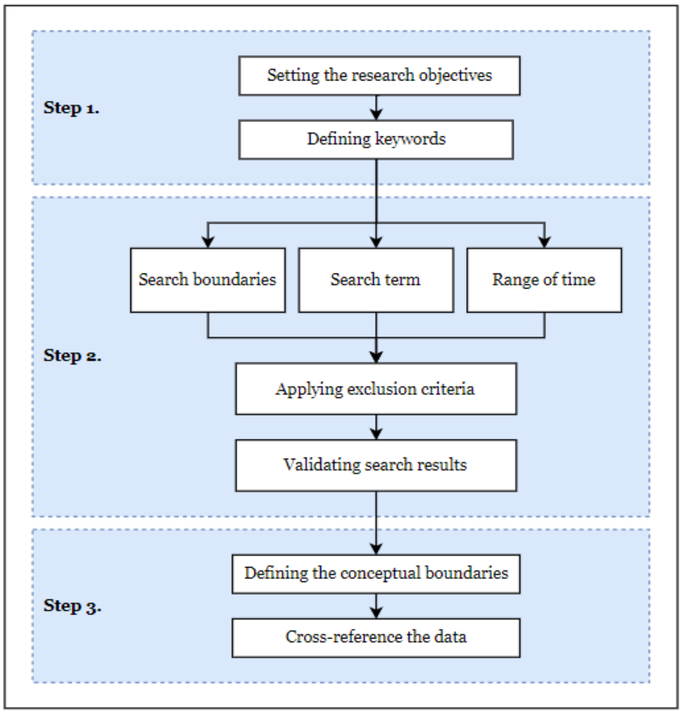


Figure 6. Steps in the data acquisition of academic literature

Empirical research

The primary data has been collected through semi-structured interviewing. This technique is well suited for exploring the perception and opinion of respondents regarding complex and sometimes sensitive issues, which provides access to more information and the clarification of answers (Barriball & While 1994). The alternative – unstructured interviews – have no pre-planned questions. This thesis needed a certain degree of topic management to conceptualise the IoM, thus, semi structured was preferred over unstructured interviewing. In general, semi-structured interviews are prefered to be conducted face-to-face with the respondent but the ongoing corona-pandemic made it impossible to conduct face to face interviews. Instead, the interviews were conducted through online video communication network 'Zoom'. An interview guide was developed for topic management guidance (Appx A – Interview guide) and contains a list of topics that were covered in the interview. Prior to the interview, consensus for recording was requested before the actual interview was conducted. The recordings were transcribed manually after which coding took place to identify which themes are relevant to be discussed in the results (Fig.7).

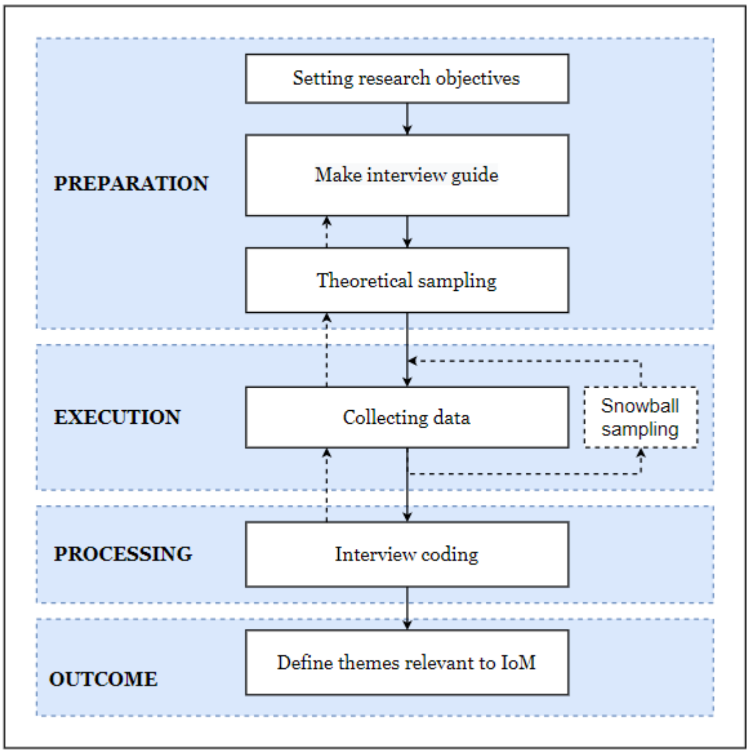


Figure 7. Data collection process.

This thesis made use of multiple sampling methods in order to get the desirable and appropriate participants. *Snowball sampling* and *theoretical sampling* methods were used for the acquisition of interviewees. Both of these methods are part of the overarching purposive sampling method in which participants are *selected strategically* (non-probability sampling). The main sampling method was 'theoretical sampling'. The less frequently used sampling method was 'snowball sampling'. In this form of sampling, earlier participants were asked to help get new participants (Bryman 2012). This thesis used academic literature and supported the findings with empirical data. Since the empirical data is only used for supporting arguments, the author decided to set the preferred amount of interviews to ten interviews. A total of 9 interviews of 1,5 hours in length have been performed with industry experts in the following fields; IoT, Sensor Technology, Programming, Engineering, Data Science, Machine Learning, AI and Algorithms. Interviewees had either a technical and business administration background. The last interview with Ahmed Hosny, the author who introduced the concept Internet of Materials, unfortunately retracted his offer to participate.

3.3 Analysis technique

This thesis aims to get important data from existing literature. To investigate the contribution of the literature and the empirical data both at once, an operationalization of the research concept has been created and can be found in Appx A. The document was continuously adjusted throughout the research. The literature that was used to write each paragraph was cross-checked with interview results to reject the findings. Even though the interviews were analysed with the atlas.ti software, the findings were not considered decisive. Therefore, when cross-checking the interviews with the academic literature, the cross-checking process and citations selection was done manually.

3.4 Research Ethics

"Research ethics are moral principles that guide researchers to conduct and report research without deception or intention to harm the participants of the study or members of the society as a whole, whether knowingly or unknowingly" (Barrow, Brannan, Khandhar, 2020, p1). This thesis takes into account certain research ethics in particular. First, the author will try to be honest and objective throughout the research. When gathering sources on online databases permission will be asked or proper login codes will be used. Furthermore, results are reported according to the APA regulations and without plagiatry. Primary data is gathered transparently and prior to the interview consent to record and process the data is requested.

Due to the Corona epidemic, the government has implied specific regulation concerning personal contact. During the interviews, there was no direct contact between the interviewer and the interviewee. In addition, the interviewees will remain anonymous.

4. Combining literature with empirical data.

The last Paragraph of the literature review discusses the available literature on the term Internet of Material (IoM). The findings support the emphasis that IoM is a combination of specific Digital technologies to acquire data-driven decision making. In this Chapter, the proposed concepts of Hosny (2015), Abowd (2020) and Liaskos (2020) are further explored and general ideas and key objectives are discussed. Within this Chapter certain statements from empirical data (interviews) are added to support the conceptualisation and applications of the Internet of Materials.

4.1 Key objectives of IoM

4.1.1 IoM - Research pathings

From the article of Hosny (2015), the research pathings of the Internet of Materials have been established (*Fig.8*). First, sensors need to be placed in the right locations within an object. It has to measure without interference and exactly what it intends to measure. Then, the sensor-data should be transmitted and stored in the cloud. At this moment, stored data is raw and uninterpretable data. And last, the data should be analysed to extract insights which can lead to data-driven (solely based on data) or data-informed (based on data and alternative inputs) decisions.

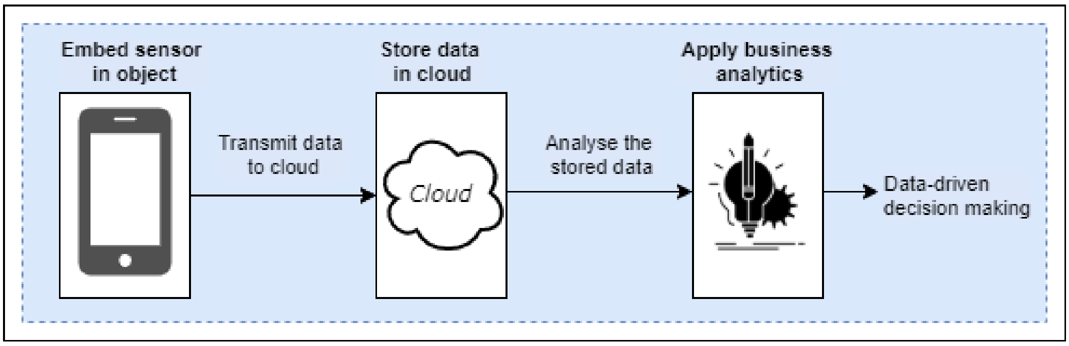


Figure 8. Basic research pathings of the IoM (adapted from Hosny, 2015).

The analytics techniques which are appropriate for the business analytics depending on the volume, variety and velocity of the stored data (Laney 2001). Large and complex data should consider to be analysed with Machine Learning techniques (Big Data Analytics will be explained more extensively in Paragraph 4.1.4.3).

4.1.2 IoM - The role and goal.

According to Hosny (2015) and supported by Abowd (2020) and Liaskos (2020), the use of IoM can lead to three important insights. First, the IoM can play an important role by helping to *understand materials* (1) which can be used to minimize degradation of a product. Second, it can inform you how to *(re)design a product* (2), -e.g. to make it more durable or easier to repair; and third, it can gather interpretable data from the *quantified-self* (3), which can be an added value for customer as well as manufacturer. Abowd (2020) and Liaskos (2020) discuss an additional role: *monitor, track & trace materials/products* (4). This role is quite similar to the first role (material degradation) but organisations can also gain insights into the life-cycle of the product or material.

Material degradation

It is difficult to detect changes in material behavior, in other words degradation, this is why often material failure can occur at any moment (Hosny 2015). It is often seen that products are manufactured with minimizing material cost. However since exceeding planetary boundaries has become a problem, there is an increased focus on the life cycle of materials (LeSar, 2013). Multiple closed-loop cycles of remanufacturing, recycling and reuse, can make sure that material value is sustained as long as possible (Jonker et al., 2017; Morlet et al., 2016; Braungart et al., 2017). To aid this endeavor, information regarding degradation can be extracted with technology such as image processing methods (Xia et al., 2020). **Interviewee 3** continues with an example of material degradation "*In case of a washing machine, there are some sensory capabilities inside the washing machine, it can notify the manufacturer in case of a malfunction. This would be both an Internet of Things case and an Internet of Materials case. It could be exactly the same algorithm to detect whether the machine is misbehaving "*

Hosny (2015) explains that data generated through an IoM can accelerate our understanding of fatigue and help build more accurate predictive models. The empirical data within this research indicates that by sharing data on materials degradation with other companies, the product can be tracked and collected for circularizing the supply chain or for recycling purposes (**Interviewee 1 & 3***)*. By informing on material degradation, the IoM can play an important part in the CE.

Product redesign

Redesign is one of the circular strategies which needs to be focussed on in order to close the loop and make a CE work (Jawahir & Bradley, 2016). According to Kagermann (2015), cutting edge technologies can help with the transition towards circularity. The IoM can benefit through data analytics since it offers insights into how products can be adjusted or redesigned (Hosny, 2015). For the Circular Economy, the identification of product (re-)design possibilities can have great additional values (Den Hollander, Bakker & Hultink, 2017).

Quantified-self

The last goal of the IoM which is described by Hosny (2015) is to gain information about the quantified-self. *"The quantified self is the practice of using wearable devices and other modern technologies to collect personalized data about one's own life and health (Fernando, 2021 p1)"*. It tracks the physical, behavioural, environmental and biological aspects of their day to day lives and offers human-object interaction models. The quantified-self does not have a direct link to improve the CE, but by applying data science to the 'personally identifiable information' it is possible to create human-object interaction models and identify current or new trendsettings and interests and thus follow the progress of the Circular Economy.

Material tracking

There is a lack of information on the life cycle of products, along with deficiencies of advanced technologies when considering cleaner production (Geng & Doberstein, 2008; Su et al., 2013). The emergence of Information technology, enabled companies to track materials and identify wasteful processes in the entire Supply Chain (Preston, 2012). By tracking raw material from the moment of extraction till the moment of disposal, valuable information can be generated for organisations that are willing to make their entire supply chain circular (Preston, 2012). **Interviewee 3** acknowledges material tracking as an important feature of the IoM: "*The Internet of Materials is part of a supply chain, where IoM plays a role in material life cycles. It means that you can track assets in the entire life cycle until it has been disposed of or disassembled".* An efficient tracking system can make it possible for organisations to recall products and find the factors that cause problems (Ping et al., 2018) and can be a way to identify working conditions in less transparent emerging economies (Ilin, Shirokova, Lepekhin, 2017).

4.1.3 The IoT technology in IoM

As mentioned in the last section of the literature review, the IoM is strongly connected to the Internet of Things. But it is hard to see the difference between IoM and IoT. The interviews of this thesis indicated that the definition of 'IoT technology' is perceived very differently. Some interviewees describe IoT as a technology that enables interconnectivity between objects, devices and systems through the use of an internet connection. These 'things' exchange data and store it (similar to the initial definition of IoT from 1999). Others would say that the IoM and the IoT are somewhat identical but would depend on the use-case of IoT (both including machine learning technology). **Interviewee 3** states a key distinction between IoT and IoM; "*How the Internet of Materials would differ compared to IoT depends on the type of sensors and on the question or relationship that you are trying to find on your algorithm, your Machine Learning algorithm".* Thus, when considering this statement, the Internet of Materials is similar to the IoT but has a specific goal and use-case. A similarity between the two fronts is that the IoT technology is used as the bodywork to bind multiple other technologies. By adding multiple building blocks (often technologies) to the IoT function – connecting objects and devices – it would lead to a more complex IoT system.

4.1.4 IoM process - 4 phases

The IoM is a continuous process that consists of four phases: (1) Data generation, acquisition and storing; (2) Data sharing; (3) Data analytics; (4) Data-driven decision making. Fig.9 shows the phases and indispensable IoM related technologies or IoM benefactors. This Paragraph dives deeper into the content of these phases and explains why they are relevant to the IoM process.

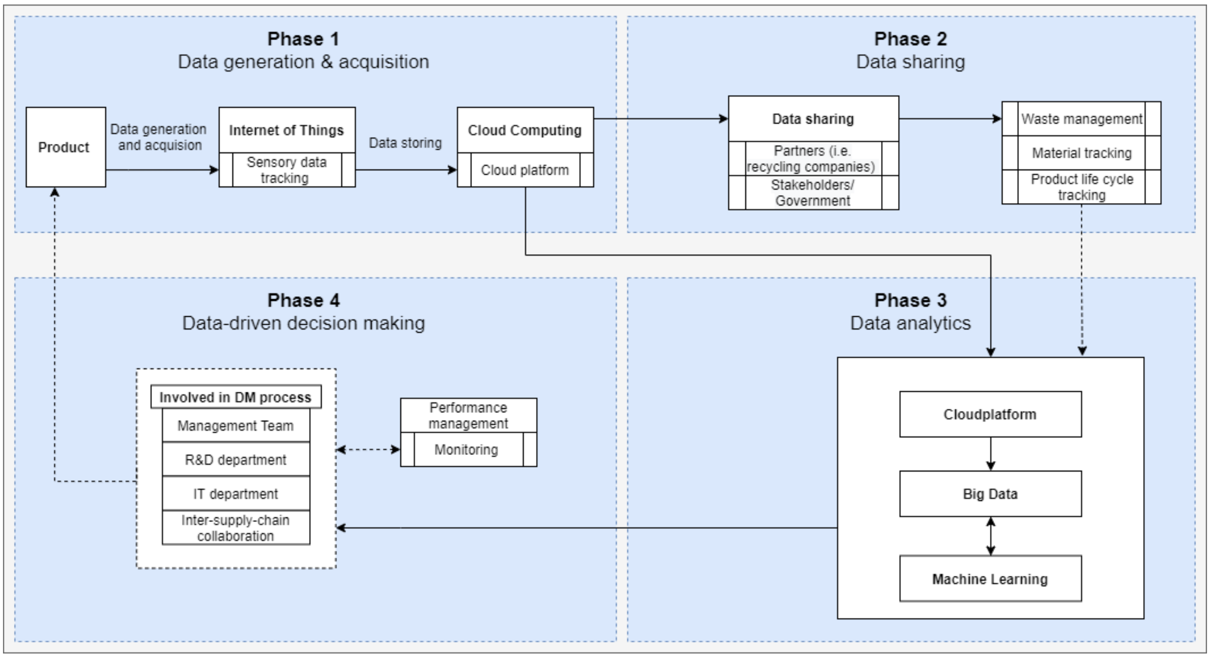


*Figure 9. The 4 phases of the IoM Process (*Produced by author: *S.F. Gerards, 2021)*

4.1.4.1 Phase 1. Data generation, acquisition and storing

Phase 1 in the IoM process is the 'data generation, acquisition and storage'. According to Rabl & Jacobsen (2012) *"It would be beneficial to have a data generator that can generate the data in different phases consistently … in order to support the various steps of Big Data processing" (p2).* The internet of materials has the ability to gather data from multiple sources within a product and throughout the supply chain at once (Abowd, 2020). The first part explains the data generation of the IoM. Here, different kinds of data and certain technologies to send and receive data are explained. The second part, data acquisition, is split into two categories, namely data acquisition during the logistic process and data acquisition during the product usage process.

Data generation

Data can be distinguished into three kinds of data, namely machine, human and business-generated data (Saggi & Jain, 2018) (Appx B, Fig.19). The IoM makes use of mainly machine generated data and occasionally – when it is inserted manually into the cloud platform – a combination of machine and business generated data. In order to send data to and from objects or devices, multiple technologies can be used. Bluetooth, ZigBee and WiFi are solutions for short range applications while LoRa, SigFox and Narrow-Band IoT for long range applications" (Pereira, Correia & Carvalho, 2018). Meanwhile each of these technologies differ in power usage: "Low power solutions are Bluetooth 5, LoRa and Sigfox, while WiFi, Narrow-Band IoT and ZigBee technologies consume significantly more" (Pereira et al., 2018). Furthermore, the release of the 5G network serves the same applications as some of the above but also enables additional possibilities such as processing massive amounts of data, using complex communication technologies and mining data by applying stronger and more advanced sensors within the IoT framework (Wang et al., 2018).

Data acquisition

This part explains how sensors are used in order to identify and track a product. The first aspect that is essential to this process is to equip products or material batches with a sensor that holds information about the object. A 'passive' radio-frequency identification (RFID) chip can execute this process without needing an energy source as it is (Ping et al., 2018). The information held by the chip are called electronic product codes (EPCs) and can contain all kinds of 'what', 'when' 'where' and 'why' information (Gnimpieba et al., 2015). The chip can be read by a RFID reader and sent to the appointed cloud platform(s) with a transmission system such as a General packet radio service (Gnimpieba et al., 2015). This process is carried out without any human interaction. In addition to the simple tracking function, it is also possible to add an action to the process such as a user-notification or an automated mechanical action. Interviewee 4. illustrates an identical process that can deliver valuable insights: *" RFID chips on products are key tracking mechanisms to follow object distribution and material use. By scanning the chip frequently during the product life cycle. Key insights are gathered on product location and/ or the state of the product. Sensors technology enables the interconnection with data storing servers. By adding sensors to objects* *the data can be gathered such as; GPS- location, temperature, vibration, humidity during transportation or use. All relevant data to collect for research purposes ".*

[data acquisition in consumer] In general, when a product or object is being used by a company, consumer or client, it does not gather raw data of the usage process. By adding sensors to the product or object, it becomes smart and data can be extracted. In order for this to work, the interaction between certain technologies are relevant.
The first technology which is relevant for data acquisition is sensory technology. In comparison to the tracking sensors (discussed in the previous alinea), the sensors which are used for smart objects are more advanced. These sensors can be physical sensors, chemical sensors and biosensors (Ping et al., 2018) and help the IoT – the second technology which is relevant for the data acquisition – 'make sense of' and 'identify changes within' the environment. As mentioned in previous chapters, IoT has the ability to let technical devices (i.e., sensors) communicate and share information with one another, and make decisions without any human involvement (Al-Fuqaha et al., 2015). These decisions can be based on human actions, for example raising the room temperature with your smartphone; opening a gate in front of your house when you arrive with your car, based on a pre-set of predetermined rules (**interviewee 9**).

Data storing

In the late-1990s, cloud computing was introduced. Cloud computing is defined as: *"the practice of storing regularly used computer data on multiple servers that can be accessed through the Internet*" (Merriam-Webster Dictionary 2020b). Multiple companies (such as Google, Amazon and IBM) started researching and offering cloud computing web services that can be either private, shared or hybrid platforms. Some organisations choose to use offsite data storage to avoid important data loss or sensitive data leakages. The IoM uses cloud computing technology to enable the process of automated data analytics through Machine Learning. Data analytics will be discussed in Paragraph 4.1.4.3.

4.1.4.2 Phase 2. Data Sharing

This phase within the IoM framework is about data sharing. Data sharing is one of the capabilities of the IoM through the IoT technology. Certain technologies, such as IoT, Cloud Computing, GPS/GPRS and RFID can be used to create a collaborative cloud-based platform that can help with positioning, identification, communication, tracking and data sharing (Gnimpieba et al., 2015). The shared platforms of the cloud computing technology– mentioned in the paragraph 4.1.4.1 – enables partners to have access to layers of supply chain related data which can be used to check and track the products or materials throughout the logistic process. In the context of the Circular Economy, supply chain relationships can have a positive effect on circularity through cross-sector collaboration and the implementation of cascading resource flows, thus access to these data streams can enable a Circular Supply Chain (De Angelis et al., 2018). Meanwhile, transparency and traceability in the supply chain enforces social security (Francisco et al., 2018), such as fair trade products or good labour conditions. Demand-driven supply networks can also enable business-to-business collaboration which improves demand chain management (Gnimpieba et al., 2015). *“Demand-driven supply networks can help suppliers react, anticipate and collaborate to the consumer’s order which decreases stock levels and reduces out of service rates" (Gnimpieba et al., 2015).* Aside from data sharing with supply chain partners, data can likewise be shared with repairing-, refurbishing- or recycling companies to stimulate the CE movement; or with governments to promote improving regulatory compliance and more efficient government communication with businesses (van de Kaa, Janssen & Rezaei, 2018).

A clear weakness of unified platforms is that an unified data system can make it harder to limit access and detect misuse due to the fact that more people have access to all data (Sinclair & Smith, 2008). Section 5.2.4. will explain the importance of inter-supply-chain collaboration for organisational performance and to the CE.

4.1.4.3 Phase 3. Data Analytics

This phase is about Big Data Analytics within the IoM process. The IoM technology acquires machine and business generated data whereafter, it is used to interpret the Big Data with data analytics. Analytics that concern large amounts of data needs advanced analytic techniques to operate and is called Big Data Analytics (Russom, 2011). Big Data can be defined as: *"Extremely large data sets that may be analysed computationally to reveal patterns, trends, and associations, especially relating to human behaviour and interactions." (Oxford Online Dictionary 2020).* The evolution and extensive growth of traditional data into Big Data, has rendered previous analysation methods useless (Dey et al., 2018). The 3Vs – volume, variety and velocity – are the three main features of Big Data (Laney, 2001) (Appx B, Fig.18 for more on the Vs of Big Data). The volume of the available data has grown way-over 10 times in the last decade and can no longer be handled by traditional analytics (Dey et al., 2018). The variety of data types and speed at which new data arrives demand new solutions to process the data and perform analytics and machine learning techniques are clearly more appropriate to capture hidden insights from Big Data (Dey et al., 2018). The development of new Machine Learning techniques and algorithms actually requires large data sets in order to learn and discover patterns in data (Dey et al., 2018). So far, multiple Machine Learning techniques have been discovered to analyse Big Data (Qiu et al., 2016) and more techniques are created in rapid succession (Khan et al., 2020). Existing and future machine learning techniques can be integrated into the IoT system in order to make the IoT an autonome and self-analysing system (Lee et al., 2016; Adi et al., 2020), which makes the IoM. Relevant and appropriate information is essential to make good choices. Sauter (2010) states that *"Improvements in artificial intelligence technologies have allowed the systems to demonstrate more sophisticated reasoning and even some learning (p17)".* When considering IoM as a Decision Support System, information that is acquired from Big Data Analytics will be useful to the business intelligence and analytics to strengthen decision making during choice processes (Sauter, 2010).

4.1.4.4 Phase 4. Data-driven decision making

An integrated IoM system can provide attractive features to multiple parties and departments, however, the implementation of the IoM brings along many changes. For organizations to facilitate organizational change, there has to be a cause. When the necessity to change is perceived to be high, those involved are more likely to support the change (Edmonds, 2011). The following Paragraphs will describe the stakeholders (MT, R&D-dep., IT-dep. & the supply chain) that are directly involved in the IoM process.

Management Team

It is clear by now that there is a need to create changes in value chains, from product (re)design, new operational systems of production and consumption, and material recovery by restoring the value of used resources (Ghaffar et al., 2019; Geissdoerfer et al., 2017). However, what will top and middle management teams get out of the use of the Internet of Materials? According to Geng and Doberstein (2008), a supply chain that is fully automated would be *"more flexible, sustainable, self-organized, secured, interoperable and highly embedded with information and communication technology"*. The IoT technology within the IoM configuration offers new options regarding 'business models' and 'maintenance, replacement and disposal' due to the technological possibilities and data orientation (Spring & Araujo, 2017). When organisations consider changes to implement circular strategies, manufacturing companies have to change their business models (Manzini & Vezzoli, 2003), while other companies need to make adjustments throughout the entire value chain (Fonseca et al., 2018). Top-Management can use the IoM to improve their decision making through data analytics; Collaborate with other parties along the supply chain; Monitor products during their lifecycle to identify product improvements and monitor the performance of a department or production line (**interviewee 1 & 3**).

R&D-department

The 'Industry 4.0' is undoubtedly related to increasing R&D projects. It brings a number of cutting-edge solutions that can be used globally (Švarcová et al., 2019). The integration of an IoM can deliver great values to the R&D department since it can be a tool to gather data from used and unused products and materials.

As Paragraph 4.1.2 describes, data can be used to analyze product or material characteristics (*understand materials*), e.g. in order to identify which parts of the product have the highest failure rates (Mboli, Thakker & Mishra, 2020). The interpreted data is then used to create new product designs or improve current designs. Redesign can have different functions: improve performance, make it more sustainable, lower the cost, or make your product more reliable. To make it more sustainable, R&D can improve the accessibility of weak parts so that these parts can be more easily replaced or repaired, thus resulting in that the product does not have to be disposed of, when it's broken.

Computational material science can benefit from the identification of problematic materials. Sinnott (2021) wrote an article about computational material science and described it as: *"The application of modern computational methods alone or in conjunction with experimental techniques to discover new materials and investigate existing inorganic materials".* This science can help to create new materials with different properties which can replace vulnerable product parts. New parts can be created to be substitutive and more durable meanwhile being better for the environment.

Manufacturing setups are featured to share a dual responsibility (Yang et al., 2018). On one hand, a substantial return on investment is expected. On the other side negative impacts on the environment are to be addressed (Elhabashy et al., 2019). As mentioned in the literature review, technologies such as the IoT, Big Data, Artificial Intelligence and Cloud Computing can help improve high-quality product manufacturing. Meanwhile, keeping the costs minimal. Unfortunately, *"From a technical approach the possibilities with data tracking devices are endless, from a practical perspective including sensoring technology in product manufacturing is still rare! The reality is that even though the technology exists, there is still a limited number of products with embedded sensor devices (**interviewee 1**)".* The IoT can help reduce the human data entry efforts meaning data is generated without the interference of human actions. *"The potential for sustainable production lies in collaboration and data management since the product components require environmental measures in order to evaluate their environmental impact (Gmelin & Seuring, 2014)"*. The data collaboration between suppliers can create data that can facilitate teamwork across the supply chain which eventually helps with the development of new production processes (Gmelin & Seuring, 2014). The implementation of CE also depends on the adoption of cleaner production (Sousa-Zomer et al., 2018).

IT-department

Business analytics needs to be viewed as a part of the organization's strategic assets (Chen & Siau, 2020). To effectively use and promote business analytics, it is necessary for organizations to have a flexible IT infrastructure (Chen & Siau, 2020). Firms should consider outsourcing the IT infrastructure, when certain support functions are done faster, cheaper, or better by an external organization (Lankford & Parsa, 1999). SMEs that are using Industry 4.0 concepts are benefiting from keeping the practices in-house but are often outsourcing R&D activities due to the lack of human, financial and technical resources (Lalic et al., 2018). MNCs are better off insourcing the IT-infrastructure since outsourcing can lead to 'Loss of control of the activity'; 'Lead to hidden and unforeseen costs'; 'Loss of IT expertise' and more (Aubert, Patry & Rivard, 1998; **Interviewee 1**). The IT knowledge through data engineers, data scientists and data analysts needs to be acquired internally to integrate the IoM within the organisational infrastructure (**Interviewee 5**). In-house knowledge is necessary to keep control of the data acquisition, data analysis and data interpretation (**interviewee 1**). Processes such as online data storage or the algorithm- and application development can better be outsourced to organisations such as Microsoft, Google and Amazon to save time and money (**interviewee 5**). A lack of human, financial and technical resources can be perceived as a barrier for SMEs to make use of the IoM technology. By partly or entirely outsourcing this process, most of these resource requirements can be minimized (Belcourt, 2006).

Inter-supply-chain collaboration

Back in 2004, Mark Barratt wrote that a *"supply chain collaboration has proven difficult to implement although still has the potential to offer significantly improved performance*", This was mostly due to the lack of clarity of what organisations were collaborating over. Technology has been promoted to be a key enabler of inter-organisational collaboration (Barratt, 2004). Nowadays, technological innovations are everywhere within society, which makes supply chain collaboration once again relevant to organisations. The relationship between the individual partners of the supply chain is essential for maximizing sustainable performance as well as economic benefits (Gupta et al., 2019). Multi-layered collaboration offers opportunities for transforming corporations and their business models to more sustainable forms (Shrivastava & Guimarães-Costa, 2017). Meanwhile, the supply chain collaboration and integration positively affects Supply Chain performance and can also positively affect CE implementation (Gupta et al., 2019). The empirical evidence within the master thesis has indicated that the IoM can play an important role in facilitating collaboration when tracking materials or products and thus plays an important role in the transition of the CE (**interviewee 1 & 3**). For example, not only recyclers, but also other value chain players such as collection sites or sorting facilities can store data on materials into the IoM to increase transparency on materials flows. Supply-chain collaboration demands transparency of information (Cui et al., 2020). The IoT technology makes it possible to set up e-collaborative platforms to generate transparency of information and provide inter- and intra-organisational collaboration (Gnimpieba et al., 2015). The platform can provide data sharing capabilities and – when combined with the right sensors – enables the tracking and tracing of goods (Gnimpieba et al., 2015; Al-Fuqaha et al., 2015).

. In addition to recyclers, other players along the value chain, like collection sites and sorting facilities, can input data into the IoM to increase transparency on materials flows.

5. The Internet of Material

5.1 Conceptualizing the IoM

Paragraph 4.1 indicated that in order to reach the IoM objectives – Inform on *material tracking, material degradation, product redesign and quantified-self* – a combination of basic IoT technology; simple and advanced sensor technologies; and Machine Learning technology has to be configured (see Fig.10, p42).

The Basic IoT technology consists of three layers: a sensor layer, data transmission layer, storage layer (Gnimpieba et al, 2015). The complexity of the sensors in the sensor layer depend on the use-case. The transmission layer is responsible for the data transfer from and to the connected devices. The technologies which can be relevant to the transmission layer are the 3G/4G/5G, Bluetooth, WiFi, NFC, RFID, SigFox, ZigBee, and the Lora network. These technologies have specific features serving the best possible use-case and take into account the maximum power consumption and minimum network range (VI - Appx B, Fig.21). Cloud Computing enables the data storage in online data storage systems. Hybrid or shared cloud platforms have the possibility to collaborate with partners by simultaneously granting access to the data streams. The sensors which are used in the IoM, are identical to those used in the IoT. The main difference is that in an IoM configuration, multiple sensors are used at once to gather a more diverse range of data. An example of an IoM integration within a product would be a product that simultaneously pinpoints the GPS-location, measures temperature, measures humidity, identifies vibration, finds degradation spots and gathers user-data. Machine learning is often used to improve automation within organisations that use large databases. As mentioned in Paragraph 4.1.4.3, the variety of data types and speed at which new data arrives demand new solutions to process the data and perform analytics. These machine learning techniques are clearly more appropriate to capture hidden insights from Big Data (Dey et al., 2018). By integrating machine learning, the system becomes an autonome and self-analysing system (Lee et al., 2016; Adi et al., 2020). It is key to generate valuable data in this process to answer material related questions. The integration of IoT and IoM are similar in terms of generating data by binding technologies and connecting objects/ devices. The difference is that IoM focuses on generating data that can answer “material” related questions, by using Machine Learning algorithms. And thrives to find relationships that can aid in making products, machines or logistics more efficient and sustainable. Thus, the Internet of Materials is similar to the IoT but has a specific goal. In this case, IoT layers are used to generate data that can aid in optimizing IoM goals (i.e., product redesign, material tracking, identification of material degradation and the quantified-self). Therefore, machine algorithms need to generate insights and/or find a relationship in material/product use of 1) Customer products, 2) Manufacturing operations or 3) (Reversed) logistic operations.

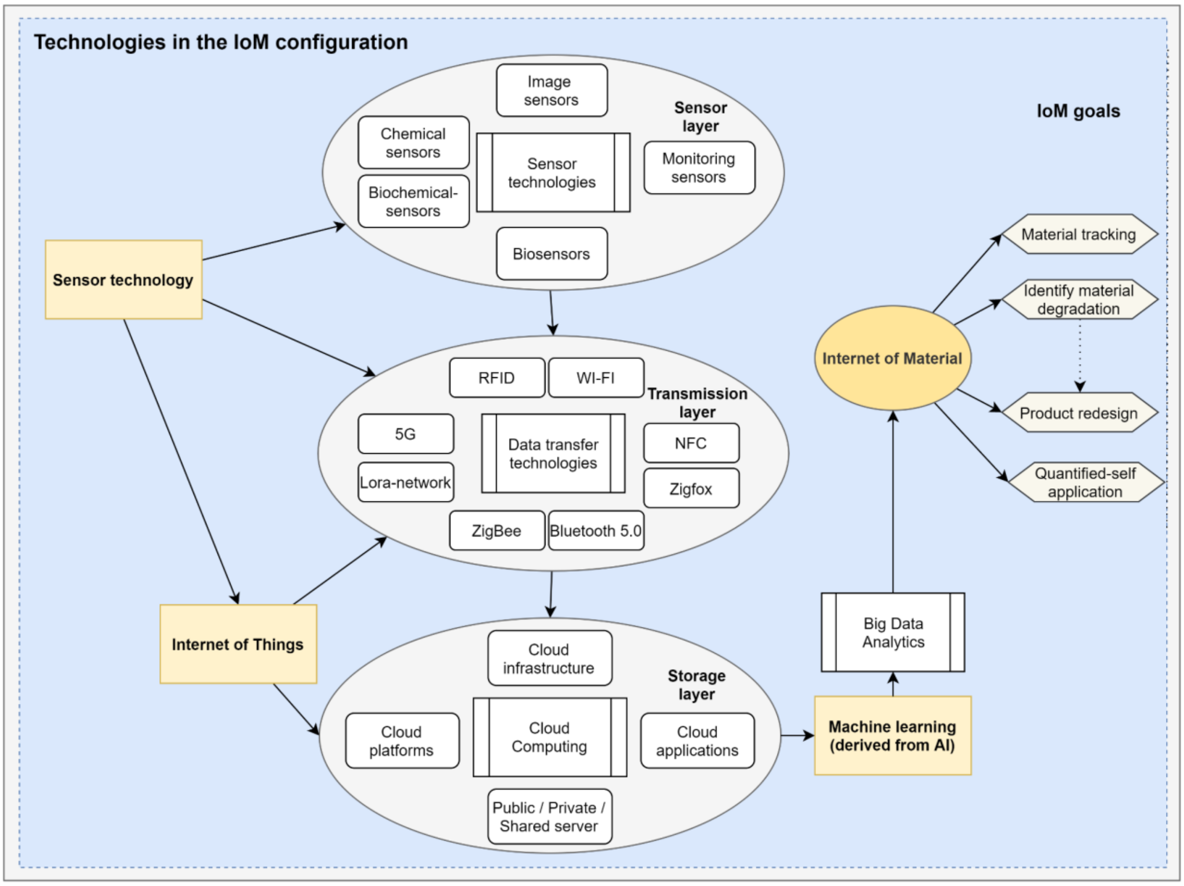


Figure 10. The IoM concept with all joint technologies (Produced by author: S.F. Gerards, 2021)

5.2 Combining the IoM with the CE

The three authors, Hosny (2015), Abowd (2020) and Liaskos (2020), unintentionally presented goals of the IoM that benefit circular strategies of the Circular Economy (Fig.11). The goals within each article can be redirected to the goals 'Material degradation, Product redesign, Tracking materials and Quantified-self application' which were formulated by this master thesis in paragraph 4.1.2. The first three goals can directly benefit the Circular Economy transition by improving transparency within the supply chain and by gathering data that can be used for data-driven or data-informed decision making. Quantified-self application benefits the CE through the ability to use its data to make human-object interaction models.

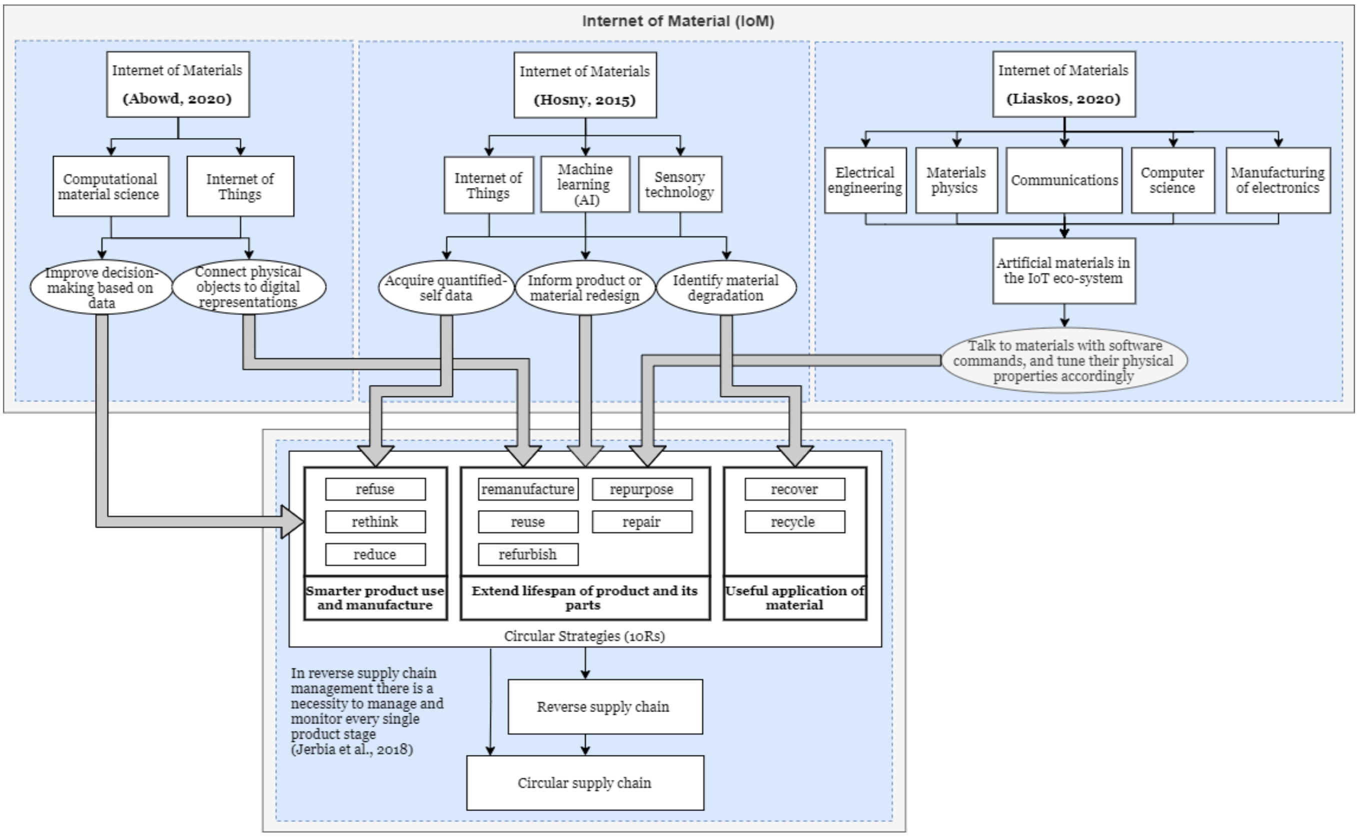


Figure 11. Connecting the IoM with the 10Rs Circular Strategies (Produced by author: S.F. Gerards, 2021)

By applying circular strategies, forward and reverse resource-flows can be monitored and waste can be minimized (Kumar & Putnam, 2008; Jonker et al., 2017). The application of IoM can constantly and automatically monitor products for reusability and failure by *"selecting each constituting components and testing whether it still works"* (Mboli et al., 2020, p8). By linking structural health monitoring with material informatics, it is possible to understand material degradation (Hosny, 2015) which can lead to material/product redesign, with the aim to lengthen the life cycle of a product or component (Fig.12).

The relationship between the individual partners in the supply chain is essential for maximizing sustainable performance as well as economic benefits (Gupta et al., 2019). IoT technology is identified as an enabler for inter-supply-chain collaboration (Barratt, 2004) through a platform for e-collaboration (data collection, storing & sharing in the Cloud). Meanwhile, creating opportunities for the transformation of more sustainable corporate business models (Shrivastava & Guimarães-Costa, 2017). In addition, adapting IoT technologies for IoM goals should improve inter-supply-chain collaboration and strengthen the integration of IoM. The promotion of inter-supply-chain collaboration is expected to have positive effects on CE (Gupta et al., 2019). More specifically, it can facilitate information transparency e.g. when tracking materials/products, which results in valuable insights to acquire a completely Circular Supply Chain (Gnimpieba et al., 2015; Interview 1 & 3). Witjes & Lozano (2016) emphasizes the need for new sustainable business models to improve CE (Witjes & Lozano, 2016). Circular business models have a different value creation and drive the supply chain into retention loops (Geissdoerfer et al., 2018). Human-object interaction models (enabled by IoM) can identify current and new trends benefitting the creation of new circular business models.

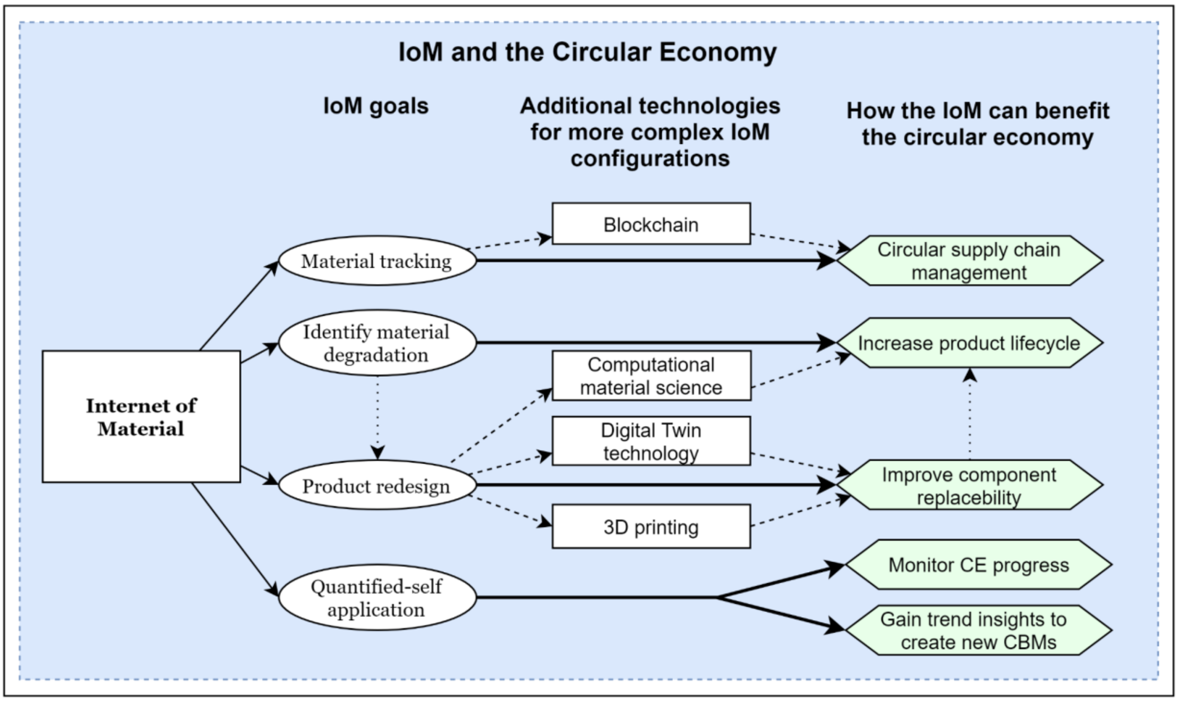


Figure 12. Circular benefit of the IoM (Produced by author: S.F. Gerards, 2021)

More complex IoM configurations to aid the CE

Basic IoT technology combined with other digital technologies can lead to more complex IoT configurations. Technologies such as Digital-Twin simulation, Blockchain and Artificial Intelligence can be relevant to the IoT depending on the use-case (i.e., IoM related questions). For example, Digital-Twin technology combined with the IoT, Artificial Intelligence (Machine Learning), and Software Analysis – including spatial network diagrams – can be applied in the manufacturing industry to create real-time digital simulation models (Chen & Huang, 2020), which can boost the Circular Economy by overcoming physical barriers regarding dismantling, reproduction and quality testing of an object, building or product; or either the storage and transportation of products or materials (van den Bosch, 2021).

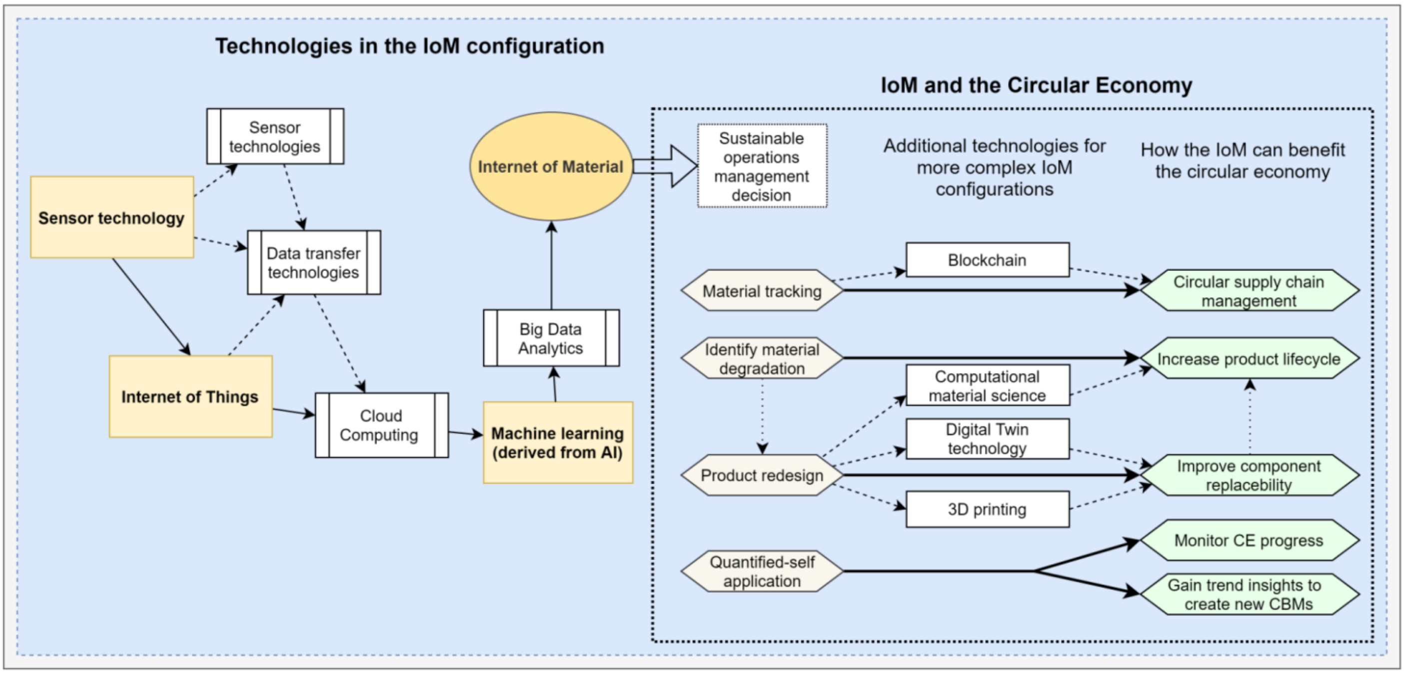


Figure 13. The two frameworks merged together (Produced by author: S.F. Gerards, 2021)

6. Discussion

This thesis has presented the technologies that are required for the initial formation of IoM technology as well as the explanation on how this technology can benefit the Circular Economy. The results from the academic literature search provide a clear understanding of the involved technologies along with the benefit of certain individual technologies for the Circular Economy. Meanwhile, the empirical data provides the opinions of technology experts in terms of how a combination of technologies can deliver additional benefits. In this chapter, the results are further discussed. First, the results of the academic literature and empirical data are reviewed. Then, certain suggestions for future research are given in context to the application of the IoM.

6.1 Discussion of the results

6.1.1 Practical Implications of the thesis results.

The results gave certain practical implications that can benefit organisations when applying the IoM. The following benefits will be discussed: IoM to overcome barriers; IoM to improve R&D (*Product improvement* and *Component replaceability*); IoM to aid with a Circular Supply Chain.

6.1.1.1 Overcome barriers

As mentioned in the literature review, the CE is being held back by specific barriers such as cultural and regulatory barriers (Hart et al, 2019). Other literature suggests that supply chain collaboration and integration positively affects supply chain performance and can also positively affect CE implementation (Gupta et al., 2019). This means that in order to benefit from better performance in the supply chain or a better CE implementation, inter and intra supply chain collaboration is important. As mentioned in the literature review, Kassen (2019) explains that e-collaborative platforms can enable cooperation between government and citizens, and boost public sector innovations. Thus, through the IoT and cloud computing platforms, the IoM can facilitate e-collaboration with the supply chain or with governments to overcome the cultural and regulatory barriers and improve SC performance and CE implementations.

6.1.1.2 Improve R&D - Product improvement

R&D departments are continuously searching to improve previous and develop next generation products. Among other things, the IoM provides the opportunity to gather data of the quantified-self and material degradation; and provide Big Data Analytics with Machine Learning techniques. Predictive analysis provided by the gathered quantified-self application can be useful to understanding future market trends (Dalhammar, 2016; Casarejos et al., 2018) and enables organisations to better understand how their products are or can be used (Wilberg et al., 2017). Data acquired from material degradation can be used to provide insight into the product's weakest components. With this information, R&D can focus on these aspects during product redesign which makes the product more durable thus lengthening the product life cycle.

6.1.1.3 Improve R&D - Component replaceability

Ever since the industrial revolution, products have been designed with a lower durability to break at a certain time to maximize profits (Friedel, 2013). This phenomenon is called ‘planned obsolescence’ and is a means to ensure continuity for organisations and long-lasting profits by eliminating the second hand markets (Iizuka, 2007). To improve the lifespan of products, repairing became more important but unfortunately, organisations reacted and made it harder to repair their product. Additionally, consumers who would repair their product at (often cheaper) independent repair shops, would risk losing the warranty since the product was not repaired by one of their certified partners (Svensson et al., 2018). These decisions led to a countermovement called the ‘Right to Repair’ has emerged. According to Hanley, Kelloway & Vaheesan, (2020, p3) the *“ Right to Repair activists has advocated for state-level legislation that would require manufacturers to make critical parts, tools, and software available to independent technicians and consumers ”*. Since people are becoming more aware of planned obsolescence, customers and new legislations are increasingly demanding to improve the component replaceability. The IoM can be used to be one step ahead of the competition by identifying how products can be designed to improve the replaceability of the weaker product components (which can also be identified through material degradation data of IoM).

6.1.1.4 Creating a Circular Supply Chain.

The rising population and increasing scarcity of natural resource availability forces organisations to adapt. Competition is becoming more fierce while the scarcity of natural resources drives up the prices. Circular changes in the supply chain can improve survivability of organisations. In order to implement circular activities, compliance of suppliers is required. Large multinational enterprises have the power to influence markets and societies (Geels & Schot, 2007) they can pressure suppliers to change but often experience a lack of tools to do so (Bai & Sarkis, 2020). Technologies can provide opportunities to ensure compliance and transparency across the supply chain (Johnsen et al., 2018). The IoT technology (integrated into the IoM configuration) can provide transparency by tracking and tracing the product throughout the entire logistic process and an online platform to enable inter-supply-chain collaboration (Gnimpieba et al., 2015).

6.1.2 Barriers and limitations of the IoM concept

The Internet of Materials can reach its full potential when government, top-management and individuals embrace data-driven decision making. Unfortunately, the concept also has its limitations and barriers. This paragraph discusses limitations and barriers that can emerge when the IoM is broadly implemented in society.

6.1.2.1 Managerial issues

Top Managers are responsible for both the return on investment and to realise a reduction of the environmental impact of products, manufacturing- and logistic processes (Yang et al., 2018; Elhabashy et al., 2019). A new business mind-set helps corporations to move towards sustainable developments (McDowall et al., 2017; Manzini & Vezzoli, 2003), as sustainable strategies and business models provide the basis for corporate contribution to CE (Witjes & Lozano, 2016). As mentioned in paragraph 4.1.4.1, there is a need to create changes in value chains, from product (re)design, new operational systems of production and consumption, and material recovery by restoring the value of used resources (Ghaffar et al., 2019; Geissdoerfer et al., 2017). Meanwhile, top managers struggle. First of all, there is a lack of (1) industry interest, (2) information on the life cycle of products, as well as a shortage of advanced technologies for cleaner production (Geng & Doberstein 2008; Su et al., 2013) (3) standardization of material reuse processes (4) interface design, difficulties in upgrading technology, and outdated models (Rajput & Singh, 2019). Thus, companies might experience great difficulties implementing IoM, as it encounters complex system design challenges that require coordination on many levels; technology, circular business models, funding, organisational change, and so forth (James et al., 2015; Hopkinson, Chen, Zhou, Wong, & Lam, 2018; Hart, et al., 2019).

6.1.2.2 Safety & privacy issues concerning data

It is essential to deal with privacy concerns concerning the rise of new technology (Monreale et al., 2010). To regulate information sharing between businesses within a supply chain and customs, the European Union installed the data protection law (among other laws). The law states that “everyone has the right to respect for their private life” (European Court of Human Rights 2010). This law makes product tracking trickier once it reaches the consumption phase. When multiple devices are connected to the internet, it also has more entry points to the organisational systems and thus giving it new areas to attack and/or new interfaces to exploit (Sen, 2015). To tackle safety and privacy concerns, organizations that use online cloud databases are increasingly finding the requirement to anonymize the acquired personal data (Sen, 2015). Through anonymizing, data is transformed in such a way that sensitive private information can no longer be retrieved (Monreale et al., 2010). Data Leakage Prevention (DLP) is an effective way to prevent data loss (Purohit & Singh, 2013). Specialists can secure databases in order to minimize the risks of security leakages (Ahmed & Hossain, 2014). The DLP protocol detects and prevents unauthorized attempts to copy or send sensitive data (Purohit & Singh, 2013).

6.1.2.3 Sensory issues

When organisations use sensors on their products in order to acquire data for decision making, the empirical data derived from the interviews (**interviewee 1, 4, 6, 7 and 9**) has shown that in practice there are multiple issues that come into play. Nowadays, organisations use sensors just for the sake of gathering data. They place the sensors and after a while they attract the information from the device or check the data acquired within a cloud platform. The cost of sensors, placing sensor devices on products, sending data to data storing servers and facilitating IT Infrastructures are the biggest limitations (**interviewee 1**). There is a possibility that the sensors did not acquire the right data; or that the sensors broke two weeks after placement. Instead, organisations need to have a clear goal of what they want to get out of the data and make a plan on how to acquire it. Continuous monitoring is essential but costs time and money. More advanced sensors are not always the best decision. A clear consideration has to be made about what quality and price range the sensor needs to have. Improved sensor capabilities and reliability is often equivalent to a higher sensor price and more advanced sensors often use more energy. When the products – equipped with sensors – are powered by battery-energy, high sensor energy consumption can become a problem.

6.1.2.4 Deep learning technology

Gartner describes hyper automation as one of the 9 strategic technology trends for 2021. *“Hyperautomation is the idea that anything that can be automated in an organization, should be automated” (Panetta, 2021).* Machine learning is often used to improve automation within organisations that use large databases. Deep learning technology is becoming the new trend and is a more advanced technique within Machine Learning. Deep learning technology is a useful technology to quickly react to changing business processes and requirements. It uses so-called ‘neural network algorithms’ that analyze large volumes of data allowing the system to automatically learn (Whiting, 2020). Unfortunately, there is a large downside to deep learning technology. The technology is data hungry, uses a lot of processing power and therefore consumes a lot of energy (**interviewee 9**; Marcus, 2018). The question remains whether deep learning's significant increase of energy consumption compared to previous machine learning techniques is counterintuïtive to the goals and objectives of the Circular Economy. Future research should shed light on this matter.

6.2 Limitation of research

Exploratory research brings along the limitation of only providing observations and insights into a specific topic. This means that it is often only generalizable for a small target group. In order for it to be generalizable to the population at large, additional research on the matter has to be conducted.

The aim of this master thesis was to achieve a thorough understanding of which technology combinations were relevant to the Internet of Materials meanwhile understanding the added value of these combinations to the Circular economy. Therefore, at the start of the research process, the decision was made from a grounded theory based on interviews with technology experts that were familiar with the concept of the Circular Economy. Unfortunately, this thesis was written during the '*Corona crisis'*, which made it harder for people to participate. Furthermore, it turned out to be difficult to find experts who are familiar with both subjects. Eventually, the decision was made to interview the technology experts within the field of Machine Learning, Internet of Things and Sensor technology. This led to insufficient primary data concerning the Circular Economy. The added value of the IoM to the CE was not really acquired through the interviews. To still obtain the necessary information to answer the question, valuable information was gathered from academic literature, government documents and organizational records. Due to a minimal sample size and time requirements, empirical data results were sometimes based on only a few interviews and made grounded theory formation within this thesis hard.

Qualitative studies have the risk of a participant or observer bias. Interviewees were contacted with an introduction text and topic description which could produce bias responses. To minimize biasities, interviews were structured with interview guidelines; interviews were recorded and transcribed.

6.3 Recommendation for future research

At first, this thesis only used a small sample size compared to academic literature papers, and thus might contain some biases. It is advised to replicate this research to strengthen the idea of an IoM. This can be done through new exploratory research and through confirmatory research when continuing on the ideas from this thesis.

Aside from the replicating research, new research can also be conducted to come to new or deeper insights. Below some of the future research suggestions are listed.

6.3.1 Identify actual benefits and costs of IoM technology in practice.

The application of IoM technology is technically possible, however, currently the added value of applying the IoM technology is no more than a theory. Future research should shed light on the actual value of the IoM technology in practice, which can be value in terms of profit, but also value in terms of achieving sustainable operational management decision making.

6.3.2 Investigate the added value of Deep Learning technology to IoM.

As mentioned in the limitation of this master thesis, deep learning technology is a newly used technology that cuts out human interaction within the process of data analysis. This can be a huge added value to the IoM, however, the deep learning technology is data hungry. It uses a lot of processing power and therefore consumes a lot of energy. Future research should investigate whether deep learning can be implemented into IoM applications. Furthermore, it should also shed light on whether deep learning's high energy consumption is counterintuïtive to the goals and objectives of the Circular Economy.

(Similar research suggestions can be made for what 'the tactile internet' or 'Fog computing' can mean to the Internet of Materials).

6.3.3 Impact of 5G and 6G on IoM

The current and still new 5G networks and in the near future the 6G networks can have a big impact on current technology implications (Kota & Giambene, 2019). *"This communication technology has progressed by generations but the next advance is seen as a paradigm shift" (Alsharif & Nordin, 2017).* It provides enhancements in bandwidth, flexibility, and intelligence and can and is two to three times as powerful as earlier 4G systems. With this improvement in mind, future research should investigate the impact of 5G and 6G networks to the Internet of Materials application.

7. Conclusion

Due to the linear economy, the earth can no longer sustain itself and disruptive changes towards a more sustainable Circular Economy are essential (Ellen MacArthur Foundation, 2015). Resource scarcity is becoming a reality for a large variety of materials (Pagoropoulos et al., 2017). Multiple closed-loop cycles of remanufacturing, recycling and of reuse, can make sure that raw materials retain their physical properties and value for as long as possible (Jonker et al., 2017). The closer corporations get to resolving or dismantling material wastage, the better the progress towards CE (Hart et al., 2019). Governmental incentives and corporate circular strategies have been insufficient due to uncertainty regarding cost, ROI and lack of standardization (Kristoffersen et al., 2019; Kristoffersen et al., 2020; Geng & Doberstein 2008; Su et al., 2013). As a result, the world is only 9% circular and the trend is heading in the wrong direction (Circle Economy, 2019). Literature on societal change has indicated that disruptive innovations can be used to establish or speed up the transition towards CE (Shin & Lee, 2011). The Industry 4.0 configurations, known for disruptive digital technologies, may have the potential to overcome important barriers to CE (Sousa Jabbour et al., 2018; Wilts & Berg, 2017). The rapid discovery of new technologies and the exponential growth of IoT applications are key to making the transition towards Circular Supply Chains possible (Lasi et al., 2014; Stock & Seliger 2016; James et al., 2015; Shrouf et al., 2014).

The findings from the literature review support the emphasis that IoM is a combination of specific digital technologies to acquire data-driven (business) decision making. This study has validated the accuracy of prior attempts by Hosny (2015), Abowd (2020) and Liaskos (2020) to conceptualise IoM. As the author agrees with the findings that IoM can 1) play an important role gathering data on materials to minimize *material degradation*. 2) IoM can use data insights for the purpose of *(re)designing products and* make it more durable or easier to repair; 3) gather interpretable data from the *quantified-self,* - which can be an added value for customer as well as manufacturer, 4) *monitor, track & trace materials/products,* in order to gain insights into the life-cycle of the product or material. It is also established that the IoM is a continuous process that consists of four phases: (1) (material) data generation, acquisition and storing; (2) (material) data sharing; (3) data analytics; (4) data-driven decision making. Phases 1, 3 and 4 are essential to generate useful insights. While phase 2 is essential to the inter-supply-chain collaboration. In order to collect and analyse IoM data, digital technologies such as IoT and Machine Learning are key. The aim of IoM is to provide businesses with valuable data on material use, in order to enable data-driven decision making. To collect data on materials (IoM), IoT technology is used that consists of three layers: 1) a sensor layer; 2) a data transmission layer; and 3) a storage layer (Gnimpieba et al, 2015). The complexity of the sensors in the sensor layer depend on the use-case. The IoM uses sensors simultaneously to gather a large variety of data types, making it more reliant on machine learning algorithms to perform Big Data Analytics. These existing and future machine learning techniques can be integrated into the IoT system in order to make it an autonome and self-analysing system (Lee et al., 2016; Adi et al., 2020). This is where IoT and IoM differ. IoM uses IoT technology to collect data, for the purpose of finding ways to lengthen the material life cycle of products or components. Thus, the main difference between IoT and IoM is that (different) algorithms are used to collect data.

To the Circular Economy, the value of IoM and Big Data is hard to deny since the performance of systems and processes can be optimized. When the digital (industry 4.0) technologies and Big Data Analytics are used in cohesion, key insights on material data (IoM) can identify efficient ways to redesign products, and contribute to (re)manufacturing- and (reverse) logistic operations. Meanwhile, support the applications of circular strategies and build a path towards more sustainable operation management. In addition, inter-supply-chain collaboration can improve organisational performance and drive a supply-chain to become circular through the implementation of cascading resource flows. Transparency in terms of data sharing is key.

To conclude, it is established that IoM has a positive effect on the transitioning towards a CE as IoM can accelerate business understanding of material degradation and produce more accurate predictive models. Organisations have expressed a need for guidance, tools and methods to extract insights and the IoM can lead the way by strengthening decision making during choice processes. In addition, circular business models and/or strategies with an integrated IoM system can deliver many attractive features for multiple parties, however to work, the IoM needs to be integrated within the entire organisation and preferably by the entire Supply Chain.

Steven Gerards (2021): "Internet of Materials is the future, not a fantasy!"

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VI - Appendix A

Interview guide

<table>
<tr>
<td>Deel 1: Introductie</td>
<td>
(introductie; kennismaking; uitleg van thesis; achtergrond van interviewee)

Introductie
- (Liever je of u?)
- Ondanks dat de scriptie zal in het Engels geschreven, zal dit interview in het Nederlands zijn.
- Toestemming voor het opnemen van het gesprek
*Ik zal vertrouwelijk met je antwoorden omgaan en zal gegevens anoniem verwerken in mijn rapport.

Mezelf voorstellen en introductie thesis
- Eigen naam
- Bedrijfskunde master Strategic Management
- Radboud Universiteit Nijmegen
- Werk naast studie bij adviestak van Radboud UMC.
-Ik heb een interesse in Dataficatie, IoT en blockchain

In het kader van mijn masterscriptie voer ik een literatuuronderzoek en een empirisch onderzoek uit met als doel om de twee verschillende onderzoeken samen te brengen. Op deze manier hoop ik ‘Internet of Material’ te introduceren, te verkennen en te conceptualiseren. Daarnaast wil ik ook een link leggen tussen een IoM en een Circulaire Economie. Uiteindelijk zal de scriptie drie frameworks bevatten

Dus tot slot, het doel van dit interview is om een beeld te krijgen wat er volgens jou allemaal komt kijken bij “Internet of material”. Ik ben in dit interview geïnteresseerd in zowel achtergrondinformatie als feiten als je mening over het onderwerp. Hou je dus vooral niet in.

Achtergrond van interviewee:
Woonplek, Studie, Werk en functie, Interesse(s)

Zou je zeggen dat je kennis hebt van alle drie de onderwerpen: Internet of things, sensor technologie en machine learning?

Heb je nog vragen over het interview?

Voordat ik uitleg wat ik, aan de hand van de literatuur, versta onder “internet of material”, zou ik graag weten wat
</td>
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<td>

Deel 2:

concept vorming

</td>
<td>

<u>Q1. “Wat is jouw eerste gedachte over wat een “internet of materials” eigenlijk inhoud”?</u>

Als we kijken naar de relatie tussen materialen en data dan zie je -– voor zover ik weet – twee verschillende relaties.

De eerste relatie is iets zoals “Structural health monitoring”. Dit wordt momenteel veel toegepast in de luchtvaart. Onderdelen van vliegtuigen worden gemonitord met als doel om een waarschuwing te geven op het moment dat er iets niet goed gaat. Het gaat vaak niet verder dan een waarschuwingssysteem en zijn hierdoor niet schaalbaar.

Je hebt ook de relatie waarbij de data uit van materialen wordt verzameld voor onderzoek. Denk hierbij aan “material informatics” waarbij data is verkregen om de ontwikkeling van materialen te verbeteren (bijvoorbeeld warmte-sensoren die data vergaren om de design van een laptop te optimaliseren) .

Als je deze twee relaties tussen materiaal en data samenneemt kom je bij een voorlopig concept van internet of materials.

Het doel van IoM is om met de data design continue te optimaliseren, terwijl de degradatie van materialen kan worden bijgehouden en ondertussen gebruiksdata kan worden vergaard (zoals hoe wij als mens met de voorwerpen omgaan). [SG1]

Goals IoM:
Inform redesign
Quantify fatigue
Promote quantified-self applications

Q2. Zou internet of material realistisch zijn

Q3. Vanuit een IT perspectief (van de machines), wat zijn volgens jou de stappen die nodig zijn om een internet of material te bereiken?

*Denk hierbij mogelijk aan de drie onderwerpen *Sensor technologie, Internet of Things en Machine Learning* en hoe dit in een Brede zin opgezet of ontwikkeld dient te worden.

Q4. Mogelijke toepassingen?

Q5. Vanuit een menselijk perspectief, Zou een internet of material op een grote schaal uitgevoerd kunnen worden?

(*wat zijn volgens jou de stappen om een Internet of material te bereiken?)

- Is het gemeenschap er klaar voor? gezien het feit dat het wel het privacy van personen tot een bepaald niveau zou kunnen aantasten.

</td>
</tr>
</table>

	Q5a. Het Nederlands kabinet heeft gesteld dat Nederland in 2050 een circulaire economie moet hebben. Kan "Internet of materials" volgens jou bijdrage aan deze circulaire economie? Zo ja, waarom wel? Zo nee waarom niet? **Q5b. Kan het ook helpen met de transitie naar een circulaire economie?**

Deel 3: Discussie van het theoretisch concept	**Pak het model erbij en kijk naar input**

Deel 4: Afsluiting	**(Indien nodig een samenvatting; Feedback van interviewee)** **Dankwoord** **Feedback vragen** **Ken je meer mensen die ik kan interviewen?** **Geïnteresseerd in het resultaat bij afronding van de masterscriptie?**

Interview codings

Title:	ATLAS.ti - Code Report
Project:	Internet of material
User:	steven
Date:	27-12-2020 - 13:18:25
Scope:	Show codes in any of the groups CE, Goals, IoM or Technologies

	Code	Grounded	Code Groups	Comment
▫	Analytics	8	Goals	
▫	Automatization	2	Goals	
▫	Barriers IoM	32	IoM	
▫	Buildingblocks	3	IoM	
▫	CE	4	CE	
▫	CE transition	5	CE	
▫	CE with IoM	16	CE	
▫	Costs	28	Goals	Cost of setting up IoM and IoM to save costs
▫	Deep learning	15	Technologies	Part of ML
▫	Degredation	7	Goals	
▫	First thoughts on IoM	6	IoM	
▫	Framework IoM	28	IoM	
▫	Functionality IoM	52	IoM	
▫	Insufficient knowledge	1	Goals	
▫	Internet of things	28	Technologies	
▫	long-term process	8	Goals	
▫	Machine learning	29	Technologies	
▫	Monitoring	3	Goals	
▫	Outsourcing	2	Goals	
▫	Purpuse of gathering data	13	Goals	
▫	Readiness of society	13	Goals	
▫	Redesign	5	Goals	
▫	Reliability	8	Goals	Both contains sensor reliability & reliability of data-driven DM
▫	Rules	1	Goals	
▫	Safety and security	2	Goals	
▫	Sensors	29	Technologies	
▫	Strategic management	2	Goals	
▫	Term IoM	31	IoM	

Table1. Codings gathered from the transcriptions with atlas.ti software

Operationalization of the research concept

Sensitizing concept	Dimensions	Aspects
Internet of Materials	Technology	Machine learning
		Internet of things
		Sensor technology
		Big Data Analytics
		Smart manufacturing
		Industry 4.0
	Goal	Degradation
		Data-driven decision making
		Automatization
		Redesign
		Circularity
		Product tracking
		Quantified-self
		Data sharing
		Intra-organizational collaboration
	Barriers	Costs
		Knowledge requirement
		Societal resistance
		Safety issues
		Legislation
		Technology
		Sensor reliability
Circular economy	Applications	Circular business model
		Circular Supply chain
		Circular strategies
		10Rs
	Technology	Machine learning
		Internet of things
		Sensor technology
		Industry 4.0
	Barriers	Cultural
		Regulatory
		Sectorial
		Financial
	Goal	Closing loop
		Slowing loop
		Intensifying loop
		Narrowing loop
		Dematerialising loop

VII - Appendix B

Industry 4.0 ecosystem

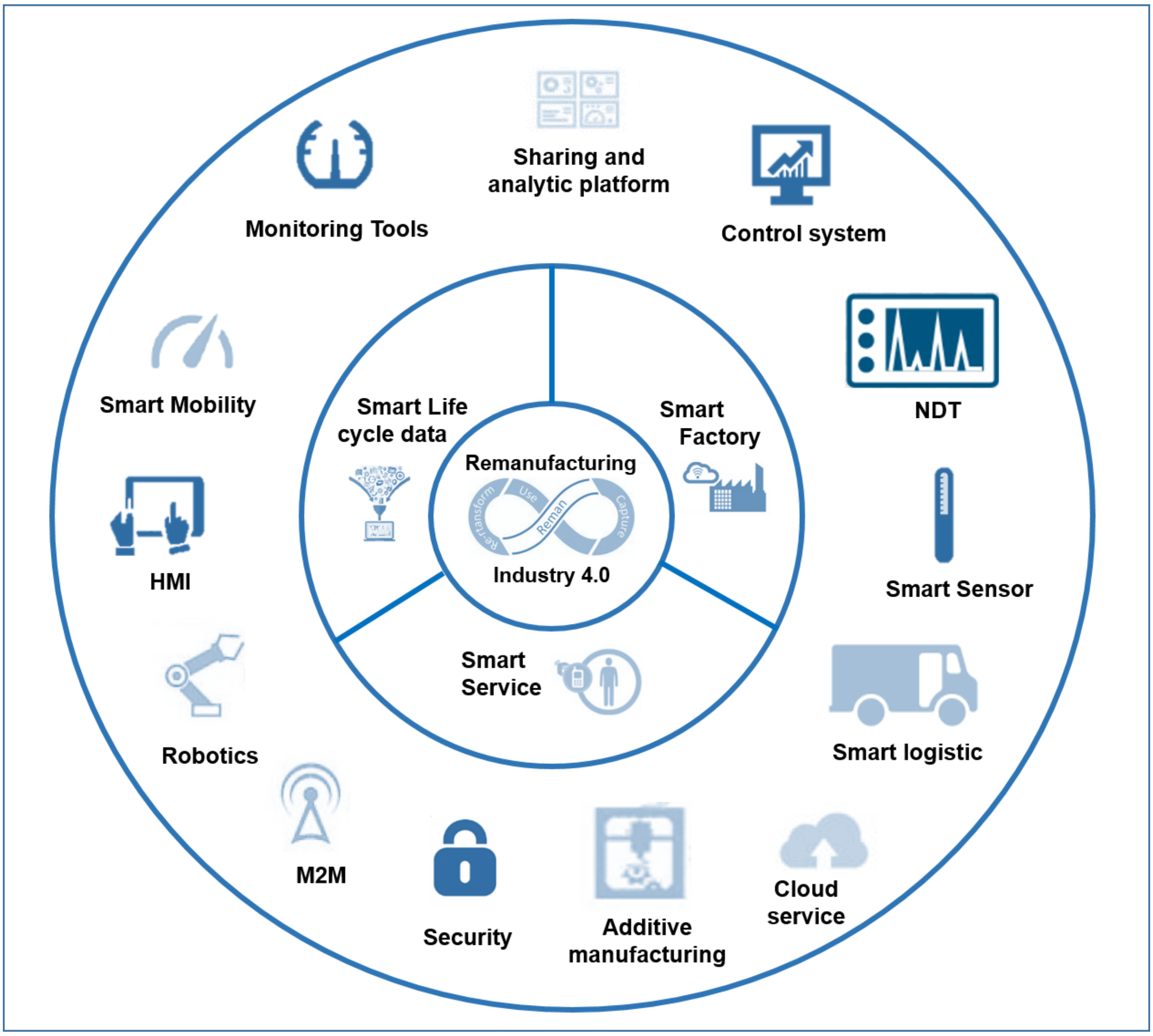

Figure 14. Opportunities from Industry 4.0 for remanufacturing, and its key enablers. Reprinted from: Yang, S., MR, A. R., Kaminski, J., & Pepin, H. (2018). Opportunities for industry 4.0 to support remanufacturing. *Applied Sciences*, *8*(7), 1177.

IoM process with the CE through the monitoring of material degradation

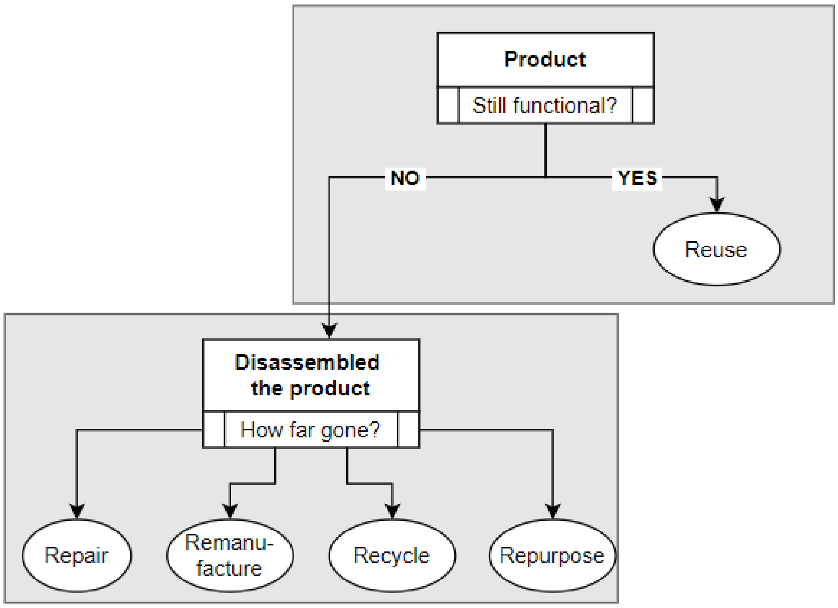

Figure 15. CE benefits of the IoM process through the identification of material degradation (adapted from Mboli, J. S., Thakker, D., & Mishra, J. L. (2020). An Internet of Things-enabled decision support system for circular economy business model. *Software: Practice and Experience*)

The 10 Circular strategies (10Rs)

1	Refuse means making product redundant by discarding its function or by offering the same function with a completely dissimilar product
2	Rethink means making product use more intensive
3	Reduce means use of lesser natural resources in manufacturing
4	Reuse means use of discarded product by another user which is still in working condition and the original functionalities are present
5	Repair means repairing and maintenance of defective product so that it can be used with original function
6	Refurbish means restoring an old product to bring it up to date
7	Remanufacture means use parts of discarded product in a new product with the same function
8	Repurpose means use discarded product or its parts in a new product with a different function
9	Recycle applies recycling for processing materials to obtain the same or lower quality of product
10	Recovering use incineration of material for energy recovery

Figure 16. The 10 Circular strategies (reproduced from Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the Circular Economy: An analysis of 114 definitions. Resources, conservation and recycling, 127, 221-232).

Circular Business Models (CBM)

BM type	Elements	Case study: Alpha	Beta	Gama	Delta
CBM	Closing loops	Development of partners to provide reverse logistics of used furniture and remanufacturing	High investment on R&D for product development	Low waste in the production stage	
	Slowing loops			Product design based on long usage stage	Internal product development and bike assembly to ensure long usage stage and facilitated maintenance
	Intensifying loops				Bike sharing intensifies use phase
	Narrowing loops		Partnership with clients interested in low carbon solutions		
	Dematerialising loops				Rent service instead of product ownership

Figure 17. Explaining the loops within Circular Business Models through case study examples (Reprinted from Geissdoerfer, M., Morioka, S. N., de Carvalho, M. M., & Evans, S. (2018). Business models and supply chains for the Circular Economy. *Journal of cleaner production*, *190*, 712-721).

The Vs of Big Data (5Vs)

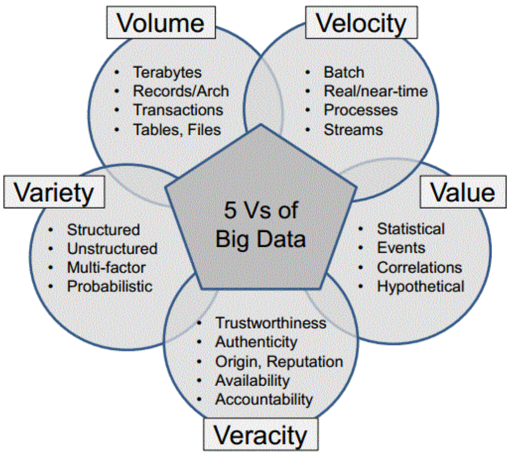

Figure 18. The 5 V's of Big Data from Perwej (2017) p16

Distinguish generated data

Big Data is generated by humans, machines or a combination of humans and machines. Data generation processes can be broadly categorized on the basis of the source and are distinguished between machine-generated, human-generated and organization-generated data (Ghotkar and Rokde 2016). When comparing the different type of data generation sources, each type can be distinguished by using the 3V-imperatives (volume, velocity and variety).

1. Data from machine-generated data is extracted through various instruments such as sensors, cameras, satellites, logfiles, bioinformatics, activity trackers, personal health care trackers and many other sense data resources. Machine-generated data has a high velocity Machines are capable of producing data at very high rates and the generation speed tends to be only limited by capital budgets (Monash 2014). These two features makes machine-generated data the largest source of Big Data.

2. Human generated data mainly comes from social media activities such as status update, tweets, photos, videos, etc. This generation method tends to be generated in average volumes but with an high velocity. The data is mostly semi- and unstructured and still has to be processed by using one of the data analytic tools.

3. Organization generated data are usually data in the form of records located in a fixed field or file and are trustworthy and highly structured in nature (Ghotkar and Rokde 2016). It has an average gathering speed and is gathered in relatively low volumes. The data is of a highly structured nature and is therefore --considered as trustworthy.

- **Machine-Generated Data:** The machine-generated data comes from several computer networks, sensors, satellite, audio, video streaming, mobile phone applications, and prediction of security breaches.
- **Human-Generated Data:** It can be collected by people, for example: identification details having their name, address, age, occupation, salary, qualification etc. Whereas, real streaming data can be generated by various files, documents, log files, research, emails, and social media websites such as Facebook, Twitter, YouTube, LinkedIn.
- **Business-Generated Data:** The volume of business data of all companies across worldwide is estimated to double every 1.2 years such as transactional data, corporate data, and government agencies data.

Figure 19. Domains of generated data (Saggi and Jain, 2018 p768)

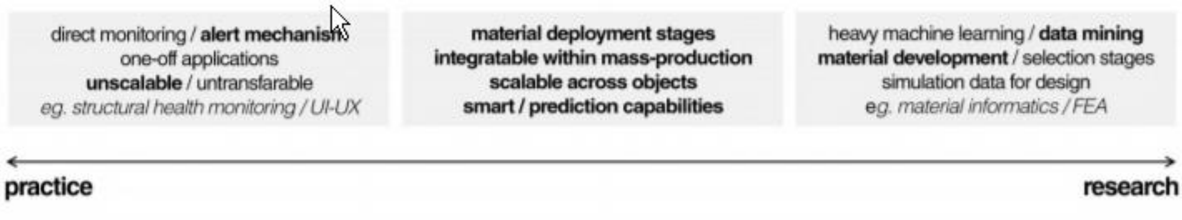

Figure 20. IoM - Linking practice to research (Hosny, 2015)

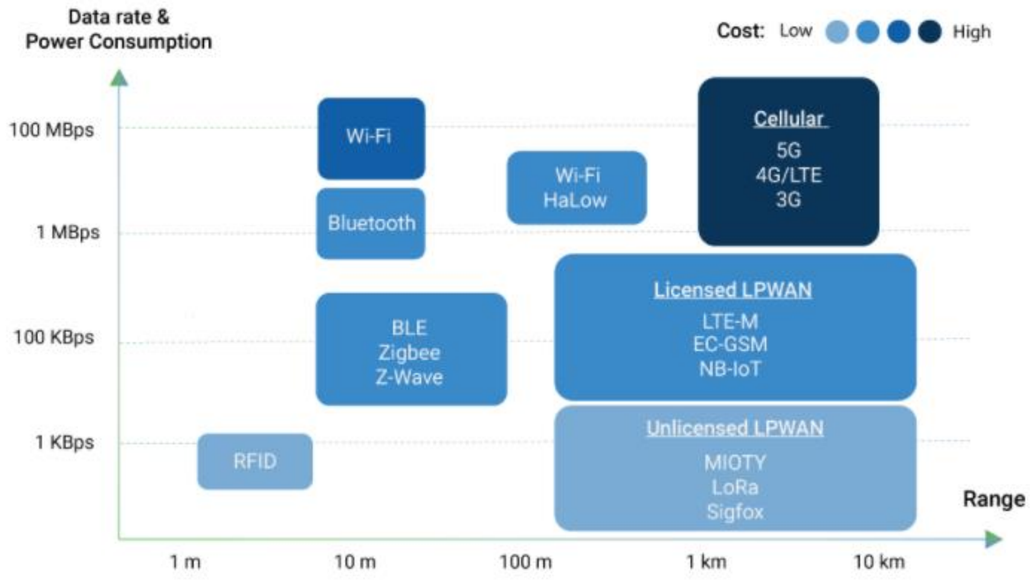

Figure 21. IoT data-transfer technologies .

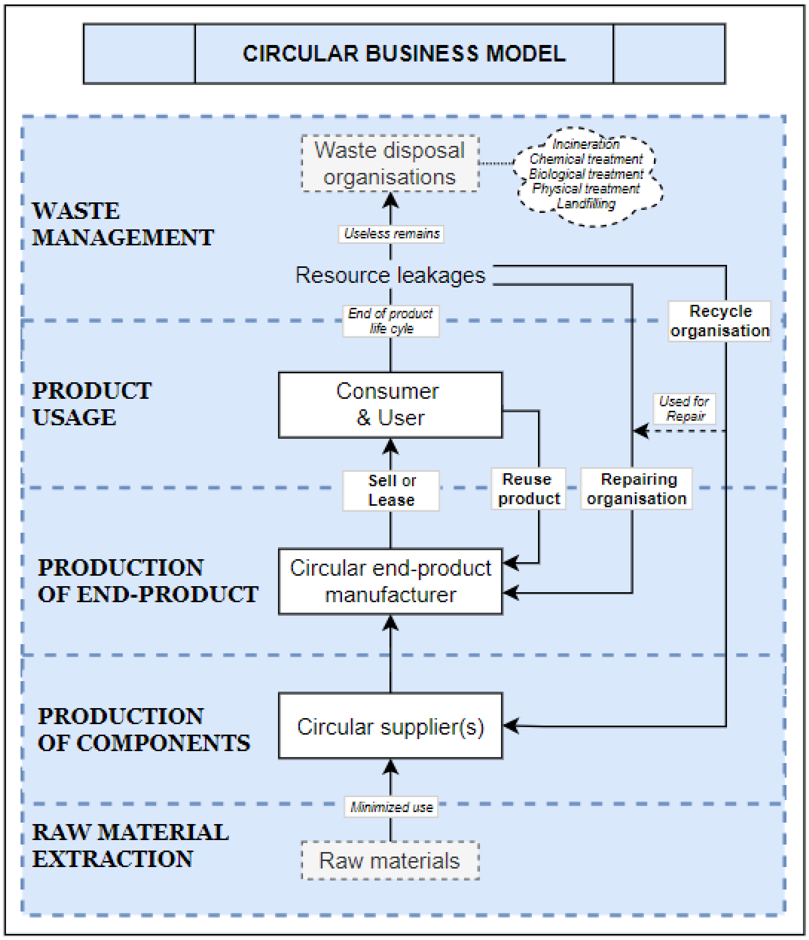

Figure 22. Circular business model with important components (by S.F. Gerards)