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Circular Product Design Strategies, Principles and Guidelines for the Metal Sector

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Abstract: The rapid depletion of finite resources used to create short-life products and resource sustainability issues has generated profound global concern. Design in the existing linear economy (LE) has been identified as a major contributor to these problems as well as a crucial component in the transition from the LE to a circular economy (CE). Due to the unique material properties, manufacturing processes, and recycling issues of metals, the metal sector requires specific circular product design strategies (CPDSs), circular product design principles (CPDPs), and circular product design guidelines (CPDGs) to make long-lasting metal products. These metal products are to be designed to enable the circular flow of material resources, particularly aluminium and steel in a CE. There are currently no comprehensive set of CPDSs, CPDPs, and CPDGs for the metal sector to design long-lasting metal products that will enable circular flow of metal resources. This study, a project of the CircularMetal research centre, addresses these concerns with the identification of product design strategies, principles and guidelines from eco-design, mechanical design, and circular product design. These were adopted/adapted and systematised into a comprehensive set of clearly defined CPDSs, CPDPs, and CPDGs that were previously unavailable for the metal sector. They are then clustered around the various product lifecycle phases of the developed Circular Design Strategy Wheel, an adaptation of the Eco-design Strategy Wheel. The circular product design guidelines include aspects such as metal manufacturing processes, robotics, and other processes which enable the design of long-lasting metal products and circular metal resource flow.

Introduction

Resource sustainability issues poses significant challenges for both present and future generations, especially considering that the global middle-class population is projected to reach approximately 5 billion by 2030, more than doubling its size from 2015 (Ellen MacArthur Foundation, 2015). The ways in which finite resources have been used irresponsibly to make short lifespan products to meet the needs of rising population over many decades, and for economic growth which is dependent upon material and energy consumption in the current linear economy (LE) has caused social, economic, and environmental problems (Hilson, 2010; Desing, Braun, and Hischier, 2020). These short lifespan products which have been designed with obsolescence as an inherent part of their design and manufactured from depleting finite raw material resources are mostly disposed after use (Allwood et al., 2011) with significant loss in material value and damage to the environment. These issues have generated an alarming global concern with individuals, academia, industry, non-governmental organisations, and both national and local governments including the United Kingdom (UK), seeking actively to provide solutions to these problems through diverse initiatives. Design has been determined to be the primary or a major contributor to the issues of resource sustainability (Papanek, 1972; Bocken et al., 2016) and identified as a key element in the transition from the existing LE to a circular economy (CE) whose advocates includes Stahel (2016; 2010), Murray et al., (2017), the Ellen MacArthur Foundation (2015), and Geissdoerfer et al., (2017). This has led to the development and implementation of various product design paradigms including product eco-design to enable long-lasting and sustainable product design, manufacturing, and behavioural change in consumption (Vezzoli et

al., 2015; Ceschin and Gaziulosoy, 2016; 2019). Aluminium and steel are the most used and important engineering materials in the UK metal sector. They support other important industrial sectors including construction, automotive, aerospace, and other manufacturing industries. The uniqueness of their material properties, production and manufacturing processes, recycling challenges, and associated energy consumption, requires specific circular product design (CPD). However, a comprehensive body of CPD knowledge is lacking to address the issues of resource sustainability and circularity. Despite the availability of several generic product design and eco-design strategies, principles, and guidelines which exist to foster the design of long-lasting products and resource flow in a CE (Franconi, Ceschin, and Peck, 2022), there is still a lack of systematic CPD knowledge. Additionally, the available CPD knowledge is limited in scope and requires adaptation to address the design and resource sustainability issues associated with short-lived products that are discarded after use (Kirchherr et al., 2018) This research aims to fill this gap in knowledge in support of the UK government's aim to enable transition of the UK metal sector into a metal circular economy by 2050. As part of the CircularMetal research centre (one of the five CE research centres funded by the UK Research and Innovation), this study addresses the following research question: "What are the circular product design strategies, principles and guidelines that can be applied in the metal sector?"

Methodology

Literature Review

A literature review was undertaken to identify existing traditional mechanical design, product eco-design, and circular design strategies, principles, and guidelines. The process of identification of these design strategies, principles, and guidelines utilised key words and strings including "Design for longevity", "Design for disassembly", "Design for remanufacturing", and "Design for circular supply chain". The literature search was done with host of synonyms in the strings using two search engines, namely Google Scholar and Brunel University's library which incorporates Scopus: the world's most comprehensive database of peer-reviewed literature that spans over every known and established discipline including design in both academia and industry.

After the relevant data had been collected, the classification, adoption and adaptation and systematisation of the circular product design strategies (CPDSs), circular product design principles (CPDPs), and circular product design guidelines (CPDGs) was undertaken.

2. Classification of existing design strategies and principles into eco-design, general design, and circular design categories

It was identified in the literature that strategy, principle, and guideline are terminologies which are often used indistinctly, and this causes some contextual ambiguity in product design. Therefore, it was necessary to provide definitions for these terminologies which are given below to make a distinction amongst them and avoid ambiguity in this study.

A product design strategy is a plan of activities or processes which are intended to achieve a desired design outcome.

A product design principle is a basic idea which serves as a proposed rule that when applied to the design of a product or system results in actions which help to solve a design issue or achieve a desired state or function of a product or system.

A product design guideline is a prescriptive recommendation or suggestion which aids the application of design strategies, principles or guides a course of action in the design process of a product or system.

The existing product design strategies and principles were classified into three categories: eco-design, circular design, and general design. This classification was done in two stages. The first stage involved categorising the product design strategies and principles into these three categories. The second stage involved correctly defining the terminology used in the literature and classifying the product design strategies and principles into their respective categories using the given definition and a Product Design Terminology Classification and Identification Matrix. Product design guidelines were not categorized, as they are prescriptive recommendations intended to help implement relevant circular product design

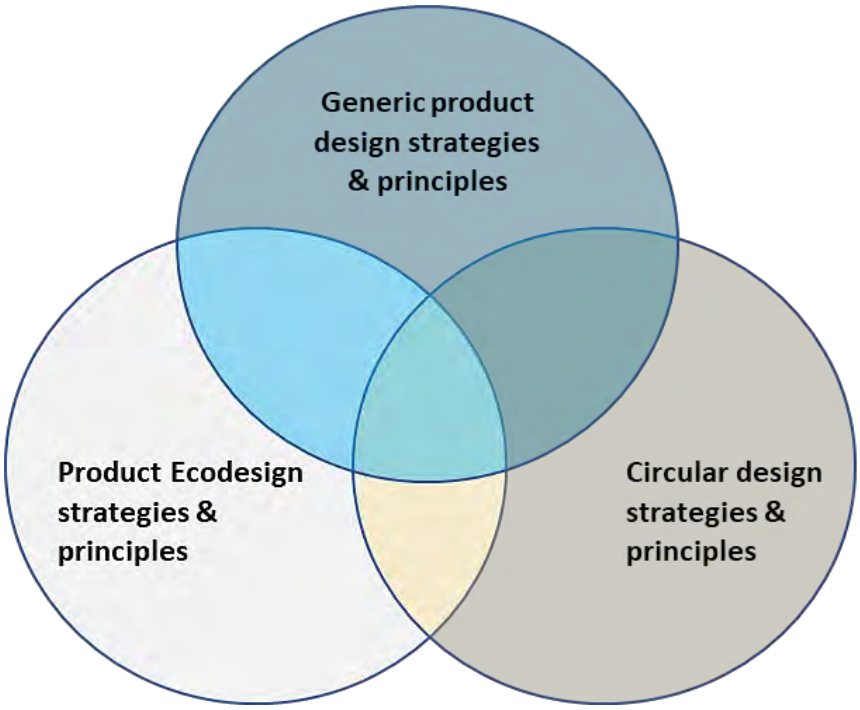

Figure 1. Schematic of the categorised product eco-design, general design, and circular design strategies and principles.

strategies and principles when designing long-lasting metal products.

Adoption and adaptation of existing traditional mechanical design and product eco-design strategies, principles, and guidelines into circular product design strategies, principles, and guidelines for the metal sector

Since circular design is a recent idea in the evolution of design, it encompasses several aspects of other types of design approaches including eco-design and its design strategies and principles as indicated in Figure 1. Nonetheless, circular design has its unique distinction from other types of design as it takes the ideal approach of eliminating waste through the superior design of materials, products, and systems (Ellen MacArthur Foundation, 2013). Thus, the characteristics or traits that promotes material circularity must be present in all chosen and modified product eco-design strategies, principles, and guidelines. For instance, a design strategy, principle, or guideline for product design that advocates decomposition cannot be seen as one that fosters the circular flow of metal resources. Hence, all the relevant aspects that foster waste, short product lifespan, undesired or early obsolescence, have been eliminated.

Systematisation of Circular Product Design Strategies, Principles, and Guidelines for the metal sector:

The systematisation of CPDSs, CPDPs, CPDGs includes the development of a hierarchical structure of the Circular Design Strategy Wheel which is derived from the Eco-design Strategy Wheel (White, Belletire, and St. Pierre, 2013; Brezet and van Hemel, 1997). It has been used as the model for the development of the Circular Design Strategy Wheel because it is a product design tool that provides a logical or systematic approach to address product design issues. It presents product design knowledge in a simple format with various levels of detailed product design strategies, principles, and guidelines which span the entire product design lifecycle phases. Product eco-design is also the design framework that shares the most common and comprehensive product design strategies, principles, and guidelines with circular product design. Those that are not common between the two design frameworks are easily adapted to CPDSs, CPDPs, and CPDGs. As such, the Eco-design Strategy Wheel represents the best

available model to develop the Circular Design Strategy Wheel. To fulfil the aim of achieving full metal circularity, three approaches; slowing, narrowing, and closing material resource loop were adopted by the CircularMetal research programme. They were combined with the research programme's aim, CPDSs, CPDPs, and CPDGs to create the Circular Product Design Pyramid (Figure 4).

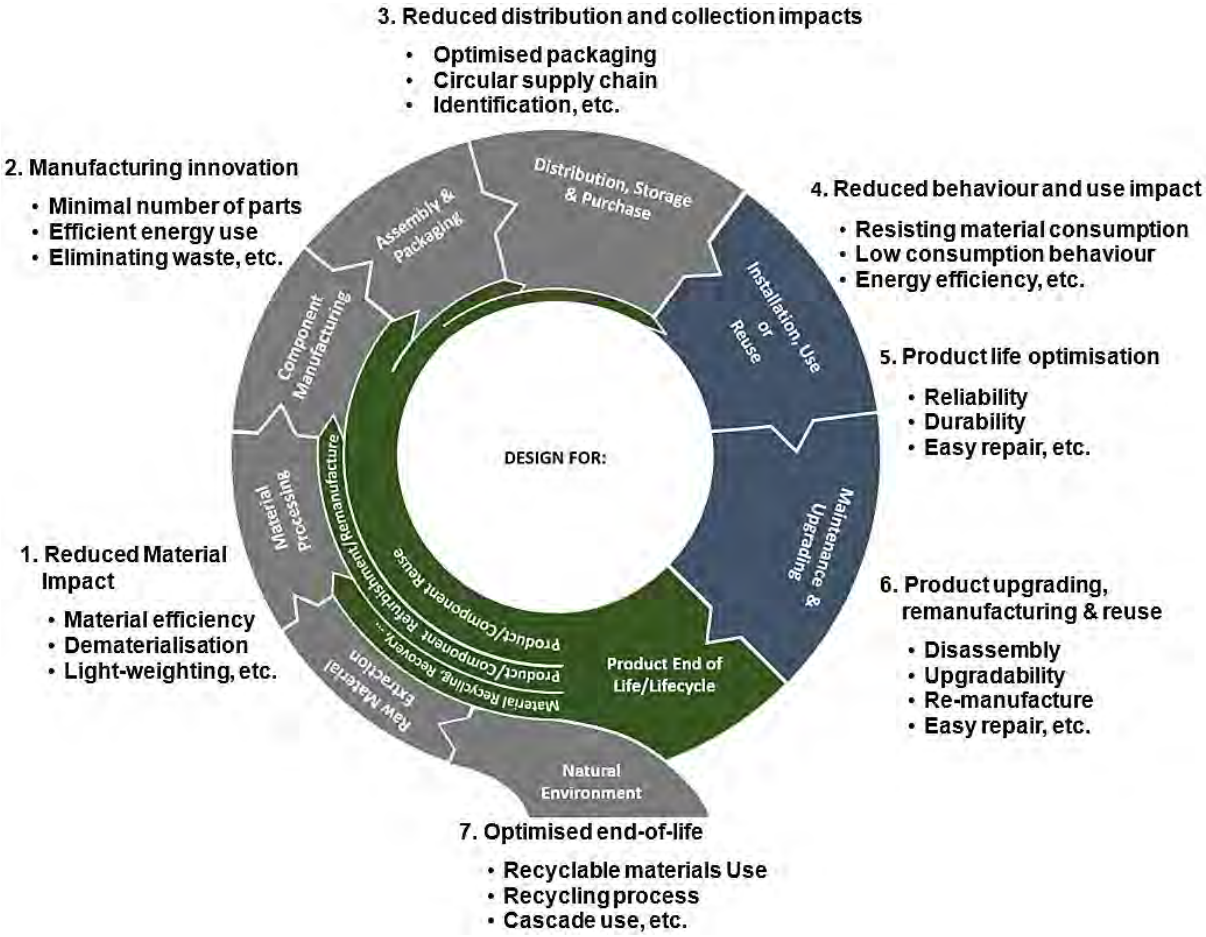

Figure 2. Circular Design Strategy Wheel with examples of circular product design strategies and principles. Adapted from Eco-design Strategy Wheel (White, Belletire, & St. Pierre, 2013; Brezet & C. van Hemel, 1997).

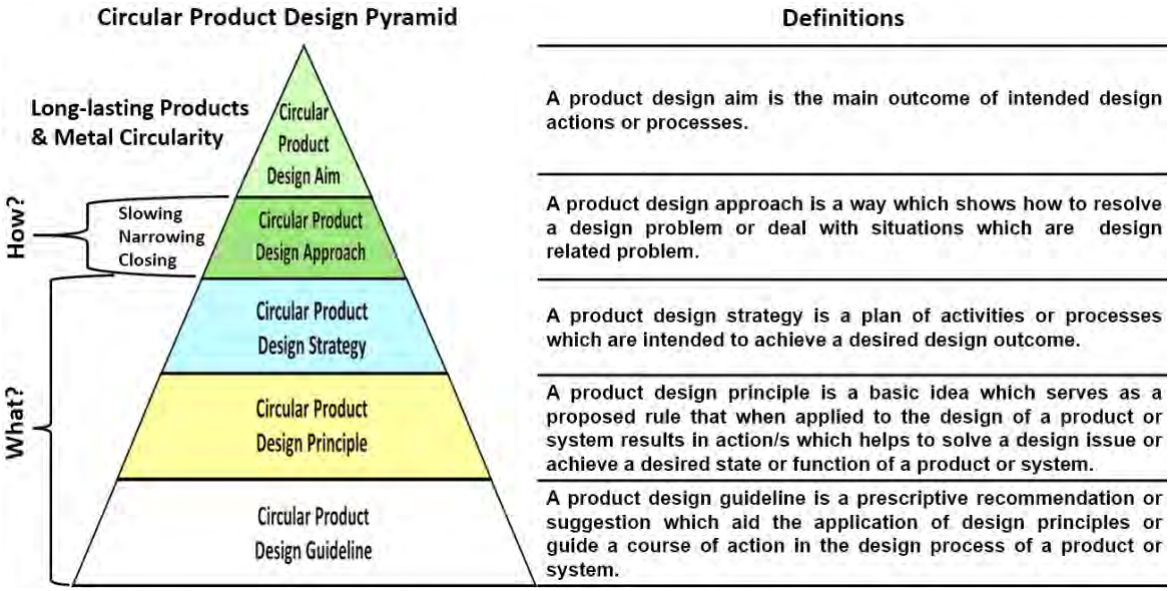

Figure 3. The circular product design pyramid with definitions (right) of its various constituent design elements.

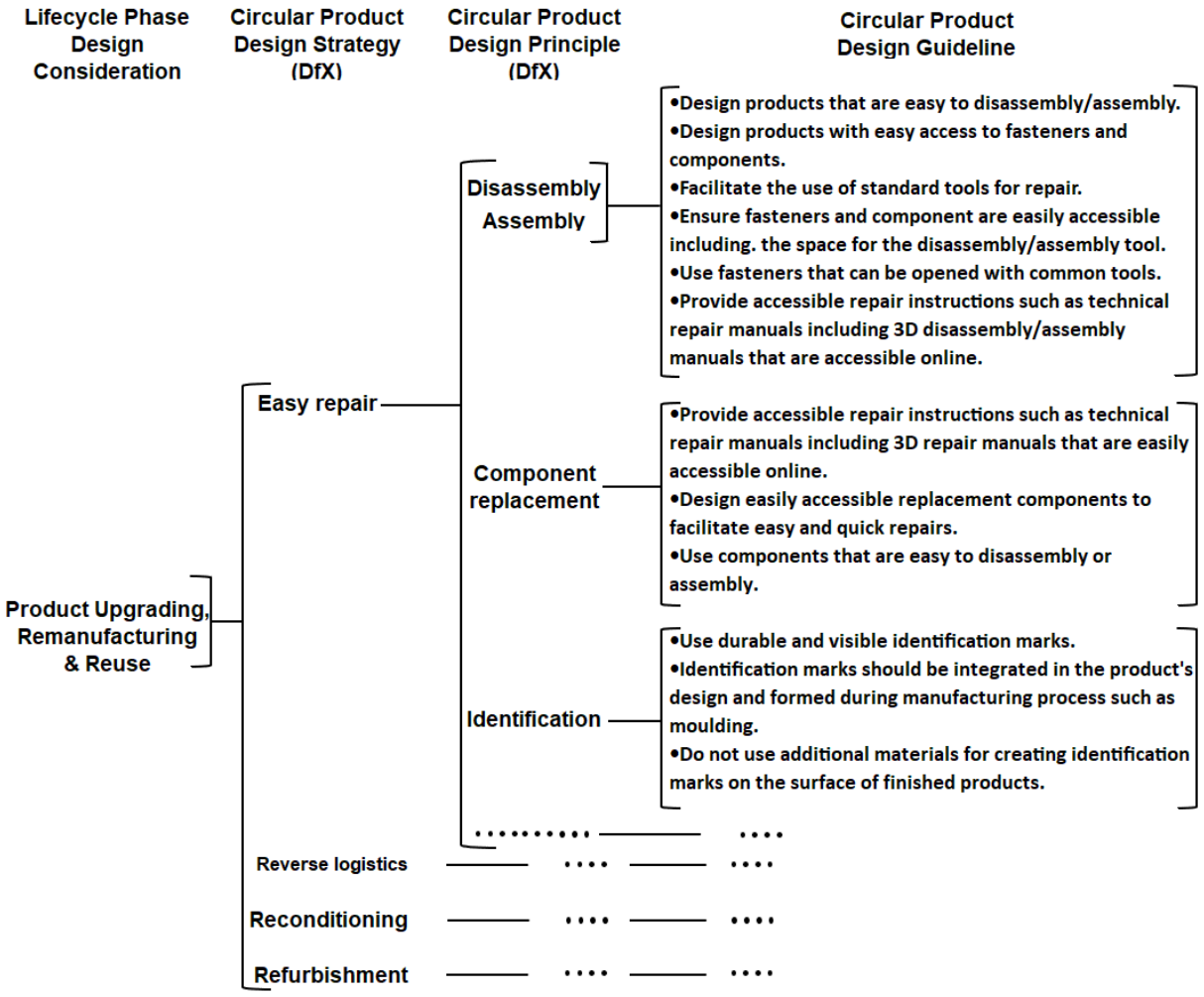

Figure 4. An example of a tree diagram of the various levels of the circular design strategy wheel.

Results

The work done in this study resulted in the systematisation of clearly defined and comprehensive circular product design strategies, circular product design principles, and circular product design guidelines. As part of the Circular Design Strategy Wheel, they form the most import aspect of the current study. They were defined from the adoption and adaptation of the existing traditional mechanical design and product eco-design strategies, principles, and guidelines. Those which were adopted possess inherent circular product design characteristics. The ones that have been adapted lack circular product design characteristics completely or in part, e.g., minimise manufacturing waste is adapted to design for eliminating manufacturing waste. This adaptation aligns with the focus of metal circularity which is concerned with eliminating waste instead of minimising it. Also, new CPDSs, CPDPs, and CPDGs were also integrated into their respective categories and proposed specifically for the metal sector. The product design guidelines are comprehensive and span over the different lifecycle stages. They include aspects such as metal manufacturing processes, new and developing technologies, robotics, artificial intelligence, and other processes which enable the design of long-lasting metal products and circular flow of metal resources.

There are currently 32 CPDSs, 46 CPDPs, and 161 CPDGs. Some of the CPDGs also consist of a total of 277 detailed recommendations which are called circular product design guideline considerations. They enable the easy application of the relevant CPDGs which require multiple product design considerations to support the implementation of CPDSs and CPDPs in circular product design. The results also include the definitions which are given for product design strategies, principles, and guidelines to make a clear distinction among these terminologies which in the literature are sometimes used indistinctly. The distinction among these terminologies serves the purpose of eliminating any form of ambiguity when they are used in the context of product design.

Furthermore, the work undertaken resulted in the development of the Product Design Terminology Classification and Identification Matrix which is used to classify the circular design strategies and principles into their respective categories. It is also used to identify CPDSs and CPDPs which are related to each other. The identification of relationship between CPDSs and CPDPs is made possible by matching their relevant attribute. The related CPDSs and CPDPs can be sub-design strategies of a higher-level product design strategy, and sub-design principles of higher-level product design principle. As such, the Product Design Terminology Classification and Identification Matrix enable the formation of a detailed tree diagram hierarchy (Figure 4) which reflects the various levels of the Circular Design Strategy Wheel (Figure 2). The Circular Product Design Pyramid (Figure 4) was also created as tool to show the various levels of hierarchy of the CPDSs, CPDPs, and CPDGs.

Discussion and Conclusions

Potential Benefits for Designers to use the Framework and related Strategies, Principles and Guidelines

There are potential benefits that can be derived from using the Circular Design Strategy Wheel with its associated CPDSs, CPDPs, and CPDGs. They may be considered significant, primarily the positive impact on the environment and the availability of metal resources for future generations. Designers or the metal sector can utilise this framework to design long-lasting metal products of different types of metals. This framework and its related CPDSs, CPDPs, and CPDGs not only addresses present product design challenges for the metal sector, but also future ones. They encompass the entire product lifecycle phases and include aspects such as artificial intelligence, robotics, new and developing technologies and metal manufacturing processes. Its wide scope and framework allowed for its further development to include new CPDSs, CPDPs, and CPDGs in line with technological advancement and metal product innovations of the future. It should be noted that there is the potential to include more CPDSs, CPDPs, and CPDGs as this research project continues. The Product Design Terminology Classification and Identification Matrix will also enable the further development of the Circular Design Strategy Wheel with the addition of new CPDSs, CPDPs, and CPDGs.

Summary of achievements

It must be noted that outcome of the various CPDSs, CPDPs, and CPDGs can produce contrasting results. For example, lightweight

designs might not be durable enough for product longevity as the reduced material input affects structural stiffness and reduced loading cycle. However, there are CPDGs that suggests the use of ribbed designs to increase the strength of lightweight metal components or products for long-lasting use. Also, guidelines that deals with material selection including the use of multi-principal element alloys enable the design of long-lasting metal products that fosters circular flow of metal resources. As such, the application or purpose for which the metal product is design for will determine the appropriate trade-offs that can be made or accepted by the product designer and product user respectively. The trade-offs also will also affect the longevity of the metal products. Nonetheless, the inherent circular product design characteristics will certainly enable the circular flow of metal resources if the CPDSs, CPDPs, and CPDGs are implemented in the design of the long-lasting metal products and in the right conditions of a CE. Designing long-lasting products does not necessarily guarantee circular flow of materials as there are other external factors such as human behaviour that can influence circularity of metal resources.

The perceived or actual value of the CDSW and its CPDSs, CPDPs, and CPDGs for the metal sector cannot be used to determine its adoption by design practitioners in both industry and academia. The reasons for any undesired lack of adoption by practitioners may not be associated with its practical usefulness in the design of long-lasting metal products or circular flow of metal resources. But, it may be due to reasons that hinders the adoption of eco-design including logistics information and supply chain issues (Eijk, 2015), lack of skilled technical workforce (Rizos et al., 2015), high start-up cost (Kirchherr et al., 2018; Eijk, 2015), consumer value preference (Bey, Hauschild, and McAloone, 2013) and business attitude towards change of investment (van Hemel and Cramer, 2002). Therefore, it should not be a surprise if its adoption is not significant in proportion to its value or potential contribution to circular product design.

The Circular Product Design Pyramid illustrates the hierarchical organisation of the CPDS, CPDPs, and CPDGs. It also includes the aim and approaches at the higher levels of the pyramid's hierarchy. This work provides value to both academia and the metal sector. It can be useful to support future research in circular product design and integrated in design tools such as CAD software packages to aid design practitioners design long-lasting metal products that enable circular flow of metal resources.

Next Research Steps

Further work is required to be done including the validation of the Circular Design Strategy Wheel, CPDSs, CPDPs, and CPDGs. Other work includes the integration with circular business model archetypes which are developed in another stream of this research project. These will be applied to three case studies in the metal sector. Practitioners and the metal sector will benefit from such through knowledge gained in experiencing the use of Circular Design Strategy Wheel to design long-lasting metal products.

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