Doctoral Dissertation
Doctoral Program in Management, Production and Design (36th Cycle)

Technological Innovations for Sustainable Manufacturing

Concepts, frameworks, and supporting tools

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Abstract

For 10,000 years the Earth experienced an environmentally stable period, also known as the Holocene epoch, where human civilization have arisen and developed. Throughout the Holocene, natural environmental changes took place, and the Earth's carrying capacity preserved the conditions to enable human development. The Earth's carrying capacity can be represented by nine life support systems, in which each of them is controlled by specific quantitative variables. The threshold values of such variables represent the Planetary Boundaries (PBs) that define a 'safe operating space' for human development. The massive exploitation of resources by human activities over the years has significantly altered the natural functioning of our planet. In fact, to date, six out of the nine PBs have already been transgressed, and the Earth is in a quantifiably different state than before, corresponding to a new geological epoch, known as the Anthropocene. This highlights the urgent need to shift towards responsible and sustainable human development.

In this context, the manufacturing sector plays a critical role. During the second quarter of 2022, it accounted for 23% of the greenhouse gas emissions (GHG), which are a major contributor to climate change, within the European Union. Consequently, there is an increasing need for the generation of sustainable value and, in response to this challenge, the Circular Economy (CE) model has gained significant attention recently. The CE model is considered effective because it seeks to decouple economic growth from its environmental impact through a continuous reintegration of used products, components, and materials into value chains. However, implementing CE principles within the manufacturing context necessitates significant technological innovations across product, process, and system levels. At the same time, it is fundamental to consider the technological lifecycle when these innovations are delivered into the economy. In fact, the lifecycle of a technology is characterized by different phases that require different types of innovations, as affirmed by the Abernathy & Utterback's model.

The aim of this doctoral dissertation is to support sustainability-oriented technological innovation at different levels, i.e., at product, process, and system levels. It starts with the presentation of a sustainability-oriented technological innovation framework that effectively connects the innovation levels - namely, product, process, and system - with distinct phases of a technological lifecycle. The main purpose of this framework is contextualize the different types of sustainability-oriented innovations. In fact, it can serve as a valuable reference to determine the most appropriate timing for specific sustainability-oriented innovations. Additionally, it enables an evaluation of the suitability of the methods and tools proposed for implementing sustainability-oriented innovations in alignment with the technology lifecycle. Then, three different research activities are developed in line with such framework, which represent the core of the doctorate research.

The first research activity is focused on supporting sustainability-oriented product innovation, primarily applicable during the initial phase of a technology lifecycle, where early product design and development hold greater significance, and the product requirements drive the design process. Specifically, a decision-making tool for the establishment of product requirements for a CE is developed. This is achieved through the creation of a decision-making tool in the form of a decision tree. Such decision tree shows when a CE business model outperforms a linear economy (LE) model considering both economic and environmental criteria. Moreover, if the CE is selected, it further illustrates whether the product's components should be recycled, remanufactured, or reused. The decision tree provides a step-by-step graphical representation of the decision rules that must be followed to adopt a CE. Consequently, the decision rules within the tree can serve as a foundation for establishing product requirements for a CE business model. Moreover, the role of carbon tax on circular economy adoption is investigated. More in detail, carbon tax level curves are developed that show, for each product manufacturing cost and carbon footprint, which is the minimum carbon tax value that make include at least one environmental parameter in the decision tree and, hence, in the product requirements for a CE.

Then, the second research activity is focused on supporting sustainability-oriented system innovation, better suited in the second phase of a technology lifecycle. In fact, this research conveys greater added value when the dominant design of a technology has emerged, and, hence, the value chain configuration is well-established. In this context, the implementation of a digital product passport, meant as a digital information system that fosters value chain transparency, can result in considerable sustainability improvements. Therefore, sustainability-oriented data requirements for the digital product passport are proposed aimed at conducting a comprehensive evaluation of environmental sustainability that aligns with the Earth's ecological limits. These requirements are proposed by referring to the well-established Life Cycle Assessment (LCA) and the Planetary Boundaries (PBs) frameworks. Moreover, technical data to insert in the digital product passport are proposed with the aim of fostering the application of CE principles throughout the value chain. Furthermore, a framework based on Cyber-Physical Systems (CPSs) is proposed to facilitate the automated collection of both technical and environmental data.

Lastly, the third research activity focuses on supporting sustainability-oriented process innovation and it finds wider applicability in the final phase of a technology lifecycle, when sustainability improvements can be better achieved through process innovations. In this context, a case study is conducted on a manufacturing process that holds great opportunities in terms of sustainability enhancements. Specifically, the Resistance Spot Welding (RSW) process, widely employed in the automotive sector, is investigated. This process serves as the primary joining method in car-body assembly lines. It is characterized by significant uncertainty related to the electrode wear, as the degradation process encompasses several distinct phenomena, including mechanical, thermal, metallurgical, and more. Typically, car manufacturers perform considerable redundant welds (1000-1200 per each car-body) to account for the uncertainty connected with the electrode wear. If these redundant welds could be eliminated, it would result in significant resource savings, encompassing energy, time, and costs. Therefore, an experiment involving more than 1200 resistance spot welds was performed in this research. These welds were performed with the aim of inducing the electrode degradation and investigate its effect on the weld quality. The electrode degradation was induced through the repetition of the same welding cycle throughout the experiment so that the only phenomenon that could systematically alter the weld quality was the electrode degradation. Data recorded from sensors during the experiment are processed and used to feed a neural network (NN) with the aim of quantitatively computing, in real-time, the electrode degradation.