Chapter 45
Remanufacturing Towards Circularity in the Construction Sector: The Role of Digital Technologies

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Abstract Among the different circular strategies, remanufacturing proves to be particularly interesting since it aims to maintain the value of building components overtime extending their lifespan by guaranteeing multiple consequent cycles of use, overcoming in this way the most common down-cycling logics. However, unlike other industrial fields which already benefit from remanufacturing, the construction sector delays to adopt this practice due to barriers of different nature, namely organizational, information, technical, regulatory and economic. Among these barriers, the first two can now be addressed more effectively thanks to the support of Information and Communication Technologies. The latter offer the possibility of real-time monitoring, remote communication and scenario modeling, opening up to innovative solutions for remanufacturing. Hence, the paper aims to investigate how the application of ICTs can support the cognitive and organizational processes related to remanufacturing of building components. In particular, the paper explores the application of sensing technologies, digital twins and information platforms and assess their potential to support the implementation of circular service-based remanufacturing models in the construction sector.

Keywords Circular economy · Construction sector · Remanufacturing · Building processes · Information and communication technologies

45.1 The Role of ICTs Towards Circular Remanufacturing Models in the Construction Sector

The last decade has witnessed the rapid spread of Circular Economy (CE) principles in several industrial fields at the global scale, strengthened by the introduction of the UN Sustainable Development Goals (SDGs) advocating Sustainable Production

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and Consumption (Goal 12) (UNEP 2022). The CE concept promotes the development of sustainable technological and business solutions able to guarantee value creation while reducing the resource throughput (Ness et al. 2019). Unlike traditional linear models, in which components are fabricated, built, used and demolished, CE approaches have emerged as sustainable alternatives following the closed-loop strategy, i.e. material components are fabricated, built, used, disassembled, reworked and reused. Hence, circular models aim at promoting closed cycles based on multiple re-uses of materials, components and products, minimizing in this way the creation of waste. In this context, the construction sector—representing one of the most crucial economic industry—is responsible of the 30% of all the waste generated in EU (ECSO 2019) with 923 million tons of waste produced in 2016 (Eurostat 2017). Indeed, based on volume, Construction and Demolition (C&D) waste represents the largest waste stream in the EU, equal to one third of all waste produced (European Commission 2016). Being one of the most resource- and waste-intensive economic activities, the construction industry counts a share of 38% of the total global energy-related CO_2 emissions (UNEP 2020) and 40% of all material consumption (Ness et al. 2019). To address such environmental issues, in the last decades the construction sector mainly focused on down-cycling and recycling practices as alternatives to material transfer to landfill.

However, recycling processes for converting waste into new products often imply the consumption of large amounts of water and energy, as well as the related generation of greenhouse gas emissions (Rios and Grau 2020). Hence, if on one hand the recycling practices contribute to the conservation of raw materials, on the other hand they result in high resource consumptions, generating significant environmental impacts (Rios and Grau 2020). Going beyond down-cycling and recycling practices, in recent years remanufacturing has emerged in several industrial fields as a strategy for closing the loop, extending the lifespan of products by restoring them at the end of their use-cycle for starting a subsequent new one, thus preserving embedded resources and limiting environmental impacts. Through remanufacturing processes, used products are returned to "as new" with a limited waste of materials, water and energy. Several industrial fields, such as for instance automotive, aerospace, machinery, electronics, rail, marine (Parker et al. 2015), already benefit from circular business models based on remanufacturing, in which components are disassembled, remanufactured and reused multiple times in closed-loop cycles.

Unlike these industrial fields, the construction sector delays to adopt this virtuous practice due to barriers of different nature, i.e., organizational, information, technical, regulatory and economic. Among these barriers, the first two can now be addressed more effectively thanks to the support of Information and Communication Technologies (ICTs), especially Internet of Things (IoT). As evidenced by ICT-based remanufacturing practices consolidated in the above-mentioned industrial fields (Butzer and Schötz 2016), the application of ICTs has the potential to support circular business models by improving cognitive and organizational processes. With reference to the construction sector, ICTs and IoT offer new capabilities of real-time monitoring, remote communication and scenario modeling, opening up to innovative solutions for remanufacturing. IoT is meant as a digital network of connected physical objects that are equipped with a variety of identifying, sensing, communication and processing technologies, becoming the so-called “smart products”. These novel abilities open up to the development of innovative smart circular systems within building practices. Based on these premises, the present paper proposes an overview of digital technologies that can contribute to solve the bottlenecks of current practices, supporting the spreading of reuse and remanufacturing within the construction sector. In particular, addressing remanufacturing as a key strategy for achieving long-term manufacturing sustainability in the construction sector, the next paragraphs explore the potential of sensing technologies, digital twins and information platforms.

45.2 Sensing Technologies for Supporting the Provision of Service-Based Business Models in the Construction Sector

Supporting circularity within the construction sector, Internet of Things (IoT) and its sensing technologies (e.g. wireless sensors, actuators, RFID, smart tags, mobile devices, etc.) and digital wireless networks (e.g. Wi-Fi, NFC, Bluetooth, etc.) currently offer virtual identities and real-time communication capabilities to physical products, that acquire the so-called “smartness” becoming “smart products” (Wang et al. 2020). By equipping products with a unique identifier, it is possible to collect data during the product use phase, allowing a real-time IoT-enabled traceability. Moreover, through the empowerment with sensing and communication capabilities, smart products can monitor and report their own condition and they can communicate over the Internet with other devices or/and with people by means of data visualization tools and digital smart interfaces. These new capabilities of products are unlocking new ways of value creation by allowing information gathering and analysis after the construction products leave the production site or the distribution facility (Alcayaga et al. 2019). Especially, these capabilities enable the transfer within the construction sector of Service-Based Models (SBMs), already consolidated in different business sectors with proven benefits (Bressanelli et al. 2021), allowing an increase in resource efficiency and a reduction of the overall life cycle costs, contributing to the transition towards a circular economy. SBMs imply a paradigm shift towards practices no longer oriented to the sale but rather to the offer of products “as a service”. According to this new vision, the ownership of products is not transferred to the customer but it is retained by the supplier. Hence, the customer is no more the buyer of a physical good but it becomes the purchaser of a service, shifting from being the “owner” to become the “user” of the product. Hence, SBMs allow to decouple the value creation from the resource throughput, since the value is linked always to the same product that is sold as a service for several use-cycles (to the same user or to different users), preserving the resource-embedded value over time. In this perspective, the adoption of the IoT facilitates the implementation of SBMs within construction practices, supporting the collaborative consumption of products by offering advanced information management functionalities (e.g. remote monitoring, dynamic data storage, data processing and analytics). The IoT-based SBMs experimented in recent years are varied and characterized by different contractual terms and payment systems (e.g. rental, leasing, sharing, outsourcing, performance-based, functional result, etc.), however they all require the implementation of product-lifecycle-extension smart strategies, namely: smart use, smart maintenance, smart reuse, smart remanufacturing (Table 45.1) to guarantee the value creation overtime (Alcayaga et al. 2019). Table 45.1 introduces these smart strategies for circular IoT-based SBMs in the construction sector, highlighting the needed enabling technologies and their role towards an effective product and information management.

In particular, it is possible to classify the SBMs in three main categories, according to different delivery strategies and value retention approaches, i.e.: product-oriented, use-oriented, result-oriented SBMs (Alcayaga et al. 2019; Bressanelli et al. 2021). In particular:

- *Product-oriented* SBM refers to the selling of the product as a service plus a set of "quality services" (Alcayaga et al. 2019) (e.g., preventive maintenance, periodic quality testing, condition monitoring, sub-component upgrading, etc.) during the product use-cycle. The set of additional services enables to guarantee the steady availability and reliability of high quality products.
- *Use-oriented* SBM includes leasing and renting contracts (the same product is used sequentially by different users) and sharing approaches (the same product is used simultaneously by different users) (Alcayaga et al. 2019). Instead of the traditional single payment method, the use-oriented SBM involves new pay-per-use or pay-per-period formulas.
- *Result-oriented* SBM involves contracts based on the results, thus on the product performance. The user relies on global service outsourcing strategies. Hence, the supplier delivers a performance result (agreed with the user) and there is no particular technical or aesthetic specification expressed by the user about the product that supports the service delivery (Alcayaga et al. 2019). Result-oriented SBM involves payment systems based on the results, i.e., pay-per-performance methods.

According to this classification, Table 45.2 shows the suitability of the IoT-based strategies (introduced in Table 45.1) with respect to the three different typologies of SBMs.

Albeit still in their ancillary investigational phases, some experimentations of SBMs in the construction sector have been recently carried out at the European level, such as the virtuous case of smart façade leasing developed by TU Delft (Azcarate-Aguerre et al. 2022). The project focuses on the development of two full-scale Façade-as-a-Service (FaaS) prototypes and the related circular business model (Azcarate-Aguerre et al. 2018). The service-based model proposed by TU Delft is based on the use of the façade as performance-delivering tool: instead of purchasing the façade panels as products, the customer pays for their performance,

Table 45.1 Enabling technologies for circular SBMs in the construction sector. Adapted from Alcayaga et al. (2019)

Smart strategy	Execution frequency	Enabling technologies	Improvements towards circular models
Smart use	Constant during product use-cycles	• Smart products • ID tags, sensors, actuators • BMS and IoT • Visualization tools	• Remote monitoring to collect data on product use-profiles for improving product efficiency and safety • Data accessibility though a digital information system with dynamic database to store and access overtime product data • Analysis of product usage data for estimating product residual lifespan
Smart maintenance	Regularly during product use-cycles	• Real-time monitoring systems • BMS • Dynamic databases • Visualization tools • Data analytics	• Diversification of the service offer and availability of new ICT-based services • IoT-based preventive maintenance strategies: maintenance is performed adaptively according to product behaviors (increased product availability, reduced expenditures and downtimes) • Interventions for product lifespan extension
Smart reuse	After a use-cycle	• BMS • Data visualization tools • Dynamic databases • Data analytics tools	• Estimation of product residual performance and evaluation of the reusability potential of smart products • Data availability to support the decision-making related to the possible reuse and remanufacturing actions • Increased efficiency of reuse processes, e.g. reduction of materials losses and logistic costs by accessing reliable product data (location, technical features, use level, etc.)

(continued)

Table 45.1 (continued)

Smart strategy	Execution frequency	Enabling technologies	Improvements towards circular models
Smart remanufacturing	After multiple use-cycles	• BMS • Data visualization tools • Dynamic databases • Data analytics tools	• Advanced estimation of product residual performance • Improved ability to estimate and simulate the performance of remanufactured products • Reduction of the uncertainty related to the remanufacturing processes in terms of timeframes, costs, waste generation, etc. • Availability of data for improving the design process of new products (design for remanufac-turing/disassembly strategies)

Table 45.2 IoT-based strategies for product-, use- and result-oriented SBMs

Smart strategy	Addressed SBM type/s	Possible payment systems
Smart use	All the three types of SBMs (Product-/use-/result-oriented)	• Pay-per-use/performance/period formulas • All inclusive (product plus services) payment • Fixed fee with incentives/penalties
Smart maintenance	Marketed in all-inclusive formulas or as extra service in use-/result-oriented SBMs	• All inclusive (product plus services) payment • Fixed fee with incentives/penalties • Pay-per-performance
Smart reuse	Suitable for use-oriented SBMs but it can also address the other two SBM types	• Pay-per-use or pay-per-period formulas • Fixed fee for the product preparation-to-reuse activities, such as cleaning, logistics
Smart remanufacturing	Suitable for product- and use-oriented SBMs but it can also address the result-oriented SBMs	• Pay-per-use or pay-per-period formulas • Deposit/credit or buy-back formulas • Fixed fee for product preparation-to-reuse activities (cleaning, logistics, etc.)

outsourcing their management and upgrade to the supplier/manufacturer. According to the project team (Azcarate-Aguerre et al. 2022, 2018), the adoption of this business scheme can guide to a wider market adoption of circular products as well as reuse/remanufacturing practices, limiting environmental and economic impacts.

45.3 Digital Twins for Promoting Design-for-Remanufacturing and Life Cycle Cost Estimations

The term Digital Twin (DT) refers to a 3D digital copy of the actual physical asset. The DT represents a virtual model of the product matching the real geometry, structure, physical characteristics and functional attributes (Wang et al. 2020). By implementing this digital-physical one-to-one correspondence, the DT opens up to new opportunities to simulate remanufacturing interventions and estimate the related needed time and costs, reducing in this way the uncertainty on remanufacturing feasibility. The DT can also be digitally integrated with smart sensors, IoT technologies, artificial intelligence, machine learning and big data analytics in order to (i) replicate the specific behavior of the real product and automatically updating the 3D model when changes in the physical world occurs, (ii) detect the real-time use conditions of assets and analyze their maintenance status, (iii) plan data-driven predictive maintenance interventions to be carried out to extend the lifespan of products. By means of these capabilities and exploiting the physical-digital bi-directional data flows, the DT can support the delivery of the SBMs introduced in the previous paragraph, with particular regard to product-oriented (preventive maintenance services) and result-oriented (real-time monitoring of product performance) models.

Moreover, the adoption of DTs has the potential to facilitate the integration of Design for Disassembly and Design for Remanufacturing criteria (Table 45.3) within current building product design practices. Design-for-D/R practices aim to ensure the disassemble-ability of the built assemblies with the final goal of facilitating the maintenance, repair, remanufacturing and reuse of their components.

By being the initial stage of the product lifecycle, the product design directly affects the subsequent phases (i.e. manufacturing, delivery, use and end-of-life). Hence, the development of a proper and accurate DT in the design stage has the potential not only to optimize the design processes but also to support the operational management of (i) maintenance intervention during the product use-cycles and (ii) remanufacturing interventions at the end of each product use-cycle by identifying the most sustainable and cost-effective solution, performing scenario simulations and what-if analyses. In the long run, Design-for-D/R approaches can contribute to a more efficient use of material resources and energy, reducing the life cycle cost of buildings and contributing to environmental savings.

Table 45.3 Examples of design-for-D/R criteria for supporting circular SBMs. Adapted from Denis et al. (2018)

DfR/D criteria	Design verifiers
Accessibility	The element is free to move according to the disassembly direction
Transportability and move-ability	Maximum dimensions and weight of the element for transportation and movement
Modularization	Standardization of dimensions
Reversibility of connections	Connections can be unfastened without damaging the elements
Disassemble-ability	Ease of disassembly and limited time to disassemble
Sequential dependency of disassembly actions	The order of the disassembly actions (sequential dependency) is easy to be recognized

45.4 Information Platforms for Facilitating the Creation of Remanufacturing Supply Networks and Digital Marketplaces

Information Platforms (IPs) are increasingly recognized in literature as promising tools towards circularity in the built environment. IPs exploit the novel capabilities of data management offered today on the market by ICTs and IoT for the creation and management of stakeholder networks, so that the various actors involved in Service-Based Models (SBMs) can share and exchange data and information.

By facilitating a long-term multi-stakeholder engagement, IPs support the overcoming of main communication barriers to the uptake of SBMs within the construction sector. In particular, the development of IPs can contribute to face some key challenges for SBMs implementation related, firstly, to the lack of stakeholder collaboration and communication tools and, secondly, to the lack of tracking and displaying tools able to visualize the demand-offer of available remanufactured/to-be-remanufactured products. In this regard, on the one hand, IPs support the relationship between manufacturer, remanufacturer, service provider and customer, facilitating their interaction (e.g. through smart apps, queries on shared databases, communication interfaces, mobile devices, real-time notifications systems, etc.). On the other hand, digital platforms can be used for the development of online brokerage websites of e-commerce for the purchase and sale of goods and/or services (digital matchmaker marketplaces), facilitating the demand-offer matching and reshaping the traditional way of selling products. Specifically, Marketplace Platforms (MPs) or Transaction Platforms are aimed at facilitating the online buying and selling by creating an e-commerce for B2B or B2C transactions of products and/or services, according to different procurement features. Although sharing the intent, MPs features may vary in relation to the following aspects:

- *Product categories*. MP can be mono-product or multiple products;
- *State of use of products*. MP can sell only remanufactured ready-to-use products or they can sell only/also products to be remanufactured;
- *Broker role of the platform*. MP can play a significant role in the relationships between buyer and sellers, by defining contract terms and payment modalities, or they can merely act as a virtual place for demand-offer matching;
- *Geographic market scale*. MP can act worldwide or they can focus on few neighboring countries or they can act only in a single country;
- *Type of contract*. MP can offer sales contracts and/or renting contracts;
- *Accepted stakeholders*. MP can accept only companies for B2B contracts or they can only/also accept single buyers/sellers for B2C or C2C relationships.

With respect to SBMs, MPs can be considered as a "new virtual stakeholder" (Moro Visconti 2021) that connects conventional partners (manufacturers, construction companies, service providers, customers, spare-parts suppliers, etc.) increasing their interaction skills and expanding their ways of communicating.

45.5 Conclusions

Contributing to overcome inefficiencies in the management of both product-related information and supply chain relationships, ICTs and IoT can reduce the high uncertainty that still characterizes remanufacturing processes in the construction field.

The paper outlined the contribution of digital technologies in supporting the implementation of circular SBMs based on remanufacturing in current construction practices. Firstly, sensing technologies and ICT-based monitoring systems can efficiently track building components and products and collect information on their levels of use and degradation during their use-cycles, useful to outline their residual performance and to understand possible remanufacturing actions to carry out. Secondly, digital twins and data analytics tools enable to assess the usage conditions of the products to be remanufactured allowing the estimation of the number and entity (time and cost) of the required rework operations to be performed. Lastly, information platforms and cooperation tools facilitate the implementation of collaborative remanufacturing process by connecting stakeholders, supporting new collaborative businesses and facilitating the demand-offer matching. The adoption of service-based business scheme (SBMs), empowered by the use of these digital tools, represents a booster for a faster market uptake of reused and remanufactured construction products, allowing to limiting resource consumption and environmental impacts, while reducing the initial investment for building owners. Indeed, business schemes focused on the performance delivery rather than the product sale, if properly supported by ICTs, can prove to be successful approaches for initiating circular practices, reducing the economic risks that currently hold back construction industry stakeholders.

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