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Enabling sustainability and resilience in industries through the value chains' circularity and digitalisation

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Abstract Living for the last decades in a linear world has emerged the necessity for resources reduction, reuse, and recycling, leaving behind the "take-make-waste" economic model and jumping over towards a cyclical ecologic system. Especially for the industrial environments, the efficient management of resources, the need for prevention and the circular designing and planning, have shown the path towards alternative approaches, new technologies and services, and cutting-edge solutions. Digitalisation technologies (Digital Twins, big data analysis, etc.), secondary raw materials, circular supply chains, integrated sustainability frameworks and standards, Digital Product Passports, are some of the solutions, services and tools that assemble to facilitate a green and digital transition, considering the circular economy aspects, and targeting to resiliency and sustainability. Under this scope, three industries focus on transforming their supply chains into circular, green and sustainable ones using advanced traceability approaches. The ordinary supply chains of a citrus juice company in Greece, the processes of managing Waste Electrical and Electronic Equipment (WEEE) for magnets and Carbon Fiber Reinforced Polymer (CFRP) for drones, are assessed using the Sustainability Balanced Scorecard, to empower the business opportunities, to enhance traceability and lead to sustained value chains.

Keywords: industrial value chains, sustainability, resiliency, circularity, digitalisation

1. Towards circular, digital and sustainable value chains

Circular, sustainable, and innovative value chains are assuredly connected with sustainable growth, as outlined in the recently updated European Circular Economy Action Plan (CEAP, 2020), a fundamental component of Europe's agenda for sustainability and resiliency, the European Green Deal (EU Green Deal, 2019). Under this scope, the overall life cycle of products, starting from designing and manufacturing procedures, and going further to energy consumption, reuse and recycling, is being reanalysed to switch from the linear pattern of "take-make-use-dispose", to a more efficient and climate-neutral approach, aiming to close the loop, for achieving circularity.

The green transition, as being reinforced by circularity, is called to accompany the digital transition towards climate neutrality, a target that has been underlined as a key requirement in the EU's green agenda (Digital Europe, 2022). Digital solutions, in relevance to carbon emissions, have a bifold character; they may provide a vast potential to minimize emissions and enhance sustainable growth by exploiting powerful tools such as artificial intelligence, digital twins, and others, but they can also create a significant environmental burden since their manufacturing and operation demands a significant number of resources. To this end, the inseparable connection of green and digital transition can lead to a win-win situation, by overcoming challenges in relevance to energy and resources consumption and efficient management.

Recently, many industries worldwide embraced new business models for disrupting the linear settings in value chains by adopting a pattern based on circularity, sustainability, and efficiency. The circular economy paradigm encourages the shift towards waste reduction, reuse, recycle, based on the effective resources' valorisation (Carraresi, Broning, 2021), empowering the concept of secondary raw materials and highlighting their exploitation potential within an industrial value chain. Specifically, for the Balkan and Mediterranean territories, considerable progress has been made over the last years regarding the level of circularity in the industrial symbiosis and waste management field, but they are still lagging behind the EU countries, indicating the need for extensive efforts towards circularity (Angelis-Dimakis et al., 2022).

Secondary raw materials (SRMs) are a product of recycling, and they can replace (fully or partially) virgin raw materials in manufacturing processes. As the JRC reports, the SRMs can be technically identified as materials able to be recycled and returned to the process and financial activities as new raw materials (EU Science Hub, 2016). The importance of SRMs in supporting the circular economy in each step of the value chain (production, consumption, repair and manufacturing, waste management, etc.) has been defined since 2015 through the Action Plan for Circular Economy, although the EC has outlined a strategy to ensure the sufficient access to raw materials on three pillars; access to raw materials on world markets at undistorted conditions, foster sustainable supply of raw materials from European sources and reduce the EU's consumption of primary raw materials (COM/2008/0699). SRMs can be classified as scraps and by-products of industrial and mining processes, such as waste from electrical and electronic equipment, which is the sector presenting the fastest-growing waste stream in the EU (Eurostat, 2020).

On the other hand, Europe foresees achieving both a green transition and digital transition during the Digital Decade, focusing mainly on high energy-consuming industrial facilities towards a net-zero industries concept. Digitalisation has the capacity to empower the sustainable circular economy by providing and assessing critical information on the availability, location and condition of the products. Digitalisation can boost the efficiency of industrial processes, minimise waste, energy consumption and costs. A combination of available systems and tools can provide major opportunities for sustainable industrial value, such as cyber-physical systems, Big Data, data analytics, Internet of Things. Traceability and transparency of a product throughout its lifetime can be supported and enhanced by the use of artificial intelligence or blockchain technology (Antikainen et al., 2018).

The circular value chains concept has been investigated thoroughly in numerous companies and industrial processes such as plastic (Johansen et al, 2022), textiles and clothing (Alves et al., 2022, Sanci et al., 2022), agriculture (Toop et al., 2017), food (Genovese et al., 2017), bioproducts (Jain et al., 2022) and many other applications. Systemic eco-efficiency assessments have outlined the contribution of eco-efficiency towards a greener economy by studying the production chain, the water supply chain and the background system (energy, raw materials and supplementary resources) in three industrial cases; a bottling plant, a textile dying industry and a dairy industry unit (Georgopoulou et al., 2017).

Digital technologies are a fundamental component in all these applications since they can support the circular economy principles throughout an industrial process for increasing efficiency, reducing wastes and costs, exploiting scraps, and enabling the shift towards industrial sustainability (Chauhan et al., 2022). Despite their popularity and extensive use, the adoption of digital technologies in the context of circular economy products and supply chains is still at an infant stage, presenting indisputably a great potential for future exploitation in the circular value chains.

One of the main contributors that can provide incredible opportunities in the fields of manufacturing, healthcare, smart cities, automobile and others, is the Digital Twins (DTs). DTs are a virtual representation of a physical model or an object using real-time data to model, but also improve its overall performance (Tsinarakis et al., 2022), (Susila et al., 2020). Digital Twinning technology is capable of providing accurate information for the circulation of materials and products and making it available to the proper stakeholders and actors, for enabling tailored decision-making. This process inevitably influences the level of economic and environmental success of a supply chain (Preut et al., 2021). Digital Twins are considered a core enabler of Industry 4.0 in manufacturing, enclosing the overall depiction and management of the value chains and their optimisation through the identification of anomalies and disruptive events in production processes, establishing also a connection between resilience and cognition (Eirinakis et al., 2022). The technology has been used to develop process modeling and simulation framework for discrete industrial systems aiming to optimise the industrial systems and perform reliable evaluation by mirroring the behaviour of the physical system for monitoring, control limitation and correction purposes (Tsinarakis et al., 2022).

Within the context of the circular economy, the digital twins have proved to be a key success factor for the supply chains' agility and resilience, especially in manufacturing companies forcing them to promptly respond to dynamic changes (Kalaboukas et al., 2021). Moreover, Cognitive Digital Twins (CDTs) – digital twins with cognition capabilities that ensure proper monitoring and optimisation – have been studied within a holistic governance approach integrating the aspect of business and sustainability, data governance and cognition models governance, aiming to model supply chains following different circular strategies of its critical components, towards the sustainable enhancement of supply chains through agility and resilience (Kalaboukas et al, 2023).

2. Demonstrating a digital circular value chain framework

The methodological approach for "closing-the-loop" in industrial value chains has been based on a solid sustainability framework that consists of governance models and the Sustainability Balanced Scorecard Framework.

The Governance Framework incorporates *Business Governance,* for operational and procedural aspects and applicable waste treatment strategies, *Data Governance,* with regards to data inputs/outputs, confidentiality principles and a FAIR treatment of data, *AI Models Governance*, for addressing how AI (cognitive) models on top of the CDTs ensure trustworthiness and in line with ethics principles.

The Sustainability Balanced Scorecard Framework targets to create a quantitative impact assessment approach, for assessing the circularity potential and impacts, based on knowledge of the inter-relations among waste/scrap and the performance of each of the product enables.

The methodology has been developed on the Design Science Research approach (Hevner et al., 2004), focusing on traceability data and digital services for waste management and optimised use of Secondary Raw Materials. The methodological approach incorporates 4 layers of solutions:

1.Reference processes and operating models for waste management
2.Interconnected digital services and coordination
3.Circular process waste reduction through optimal material use
4. Assessment and solutions scale up

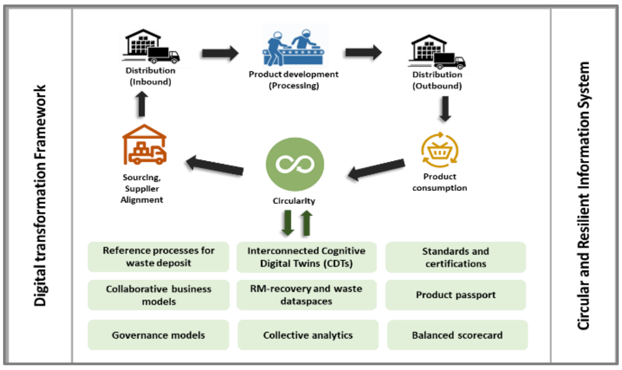

Figure 1. Methodological framework approach

The main objectives derived from this methodology are the establishment of a digital transformation framework for the circular value chain, the development of a Digital Twin platform to support circularity in industrial processes, and the creation of a Circular and Resilient Information System for real-time monitoring and decision-making. To validate the methodological approach, three diverse case studies from the industrial sector will be assessed and deliver policy recommendations and standardisation activities.

3. Integrating sustainability framework and digital solutions in three real use cases

Three pilot demonstrations have been selected for assessing their performance, not only as supply chains and industrial processes use cases, but as business cases targeting to achieve sustainability and resiliency in 4 main pillars: environmental/resources, social, economy, and governance.

Carbon Fiber Reinforced Polymer (CFRP) for drones

The global demand for CFRP has increased about 10,1% from 2019, to 2021. This demonstration involves the production of drone CFRP components, the supplier of CFRP waste, the drone manufacturer and the elaborator of the procedure to extend the self-life of waste, in order to represent adequately the full supply chain of CFRP and increase its recycling and reuse. As a result, a drone passport on materials and standards will be produced, accompanying the product until the end of its life, facilitating in parallel its recycling potential.

Waste Electrical and Electronic Equipment (WEEE) for magnets

Electric vehicles and green energy technologies have forced the increase in permanent magnets (PM) demand by over 7% annually. This pilot use case involves the magnets producer, the recycling plant and the recycling PMs processes, focusing on increasing the reuse of NdFeB and Strontium-ferrite (Srferrite) permanent magnets (PMs), recovered by WEEE from magnet products. A new industrial activity by "closing the loop" (reuse of residues, leftover and disposed magnets) is designed, to extend the marker of PMs.

Citrus processing waste for juice by-products

A citrus processing plant and a food LCA expert are engaged to manage the essential oils' distillation, molasses condensation and animal feed production process from Citrus Peels Waste (CPW), to accurately estimate the quality and characteristics of products, fine-tune the processes' conditions in real-time and minimising raw materials loss. Moreover, to address the high costs of the environmentally friendly disposal processes that are implied by the EU Directives of the European Parliament and Council. To achieve this, the citrus processing supply chain will integrate the tools of Product Passport on the final products, the Balanced Scorecard and circularity index on the products and the ingredients used, and the product configuration and monitoring to track the specifications of by-products and their compliance with regulations and standards.

4. Achieving resiliency and circularity in industrial value chains – Discussion & Results

Digital technologies are used for demonstrating the increase in waste reduction and for optimising the use of secondary raw materials in the value chains. The CFRP waste for Drones pilot aims to demonstrate a 67% reduction of prepreg disposal and a reduction of Existing Unused CFRP waste in the production of composite materials. The WEEE for new bonded Magnets pilot focuses on reducing by 35% of WEEE landfilled for bonded materials, and on a significant increase in the recycling rate from leftovers and disregarded magnets from 60% to 75%. The Citrus processing waste for juice by-products pilot targets to decrease by 10% the production waste and to demonstrate a significant decrease (>40%) in the volume of waste that goes to biological treatment. Moreover, The CFRP waste for Drones pilot aims to use CFRP waste from the production of new composite materials to be re-used in the production of drones in the value chain (+20%). The WEEE for Magnets pilot uses WEEE to extract PMs (bonded NdFeb and Sr-ferrite, and sintered Sr-ferrite), which are used (as SRMs) in the production of new magnets, aiming to increase their usage by at least 30%. The Citrus processing waste for juice by-products pilot uses the waste from the production of orange juice to recover EO and then produce by-products such as animal feed, high-quality molasses for the food industry, and d-Limonene for the cosmetic industry. The final target is to increase the usage of waste by 60%.

5. Conclusion

Integrating circularity, resilience and sustainability into the industrial supply chains is a rather challenging undertaking. Manufacturing companies can benefit from the circular economy model, managing their constantly increasing need for scarce resources, and turning over towards efficient use of resources. Moving from linear to circular production schemes, prioritizing the recycling, reuse and exploitation of by-products as raw materials to re-enter the production processes.

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