ADVANCING INDUSTRY 4.0 BY ENABLING SUSTAINABILITY AND CIRCULARITY IN INDUSTRIAL ENVIRONMENTS

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ABSTRACT

The first principle of circular economy (CE) is to eliminate waste and pollution[1]. Despite the intensive and continuous endeavors and the effort stressed in CE, less than 10% of global economic activity is circular [2]. EU's policy towards the industrial green and digital transition lies in enhancing the competitiveness of European industries, targeting in parallel to structure the optimal combination between climate neutrality and digitalisation pathways[3]. Digitalisation has the capacity to empower a sustainable circular economy by capturing and assessing critical information on the origin, availability, features and condition of products, while digital technologies such as Digital Twins (DTs) can boost the efficiency of industrial processes for waste minimisation, cost end energy reduction[4]. This research investigates the impact of industrial technological solutions focused on circular value chains, secondary raw materials management and monitoring, leveraging DTs technology and advanced tools such as Digital Product Passports (DPPs). The research focuses on the modelling of industrial production lines using interconnected models, both machine learning and first principles models of the industrial processes. The overall approach of the industrial value chain modelling is systemic and incorporates all key actors, their operability and interconnection. The key implementation steps of the technological solution include 1. The assessment of maturity of the existing traceability levels across the value chains, planning and monitoring, 2. Modelling of the industrial processes and supply chains as Digital Twin networks through the Process Simulation and Modelling Tool - PSM, a stand-alone tool developed by TUC, 3. Capturing and performing the full tracing path of the materials/products of the investigated value chain, applying end-to-end traceability, and creating the Digital Product Passports, and 4. Dynamic assessment of the circular value chain performance through the Circular Sustainability Balanced Scorecards. The delivered technological solutions are tested in real case studies and aspire to foster the Greek industrial sector towards its digital transition and to accelerate the industrial circularity, ensuring transparency and provision of information across the value chain to all involved parties: industrial actors, stakeholders, and customers.

KEYWORDS: Industry 4.0, circular value chains, resiliency, Digital Product Passports, Sustainability Balanced Scorecards

INTRODUCTION

Circular, sustainable, and innovative value chains are inextricably linked to sustainable development, as highlighted in the recently updated National Action Plan and the National Strategy for the Circular Economy[5], in line with the European agenda for sustainability and resilience, as reflected in the European Green Deal[6]. Under this framework, the life cycle analysis of a product, starting from design and manufacturing processes and moving on to energy consumption, reuse and recycling of resources and materials, has been redefined to move from the linear "take-make-use-dispose" model to a more efficient and climate-neutral model, with the aim of "closing the loop" to achieve circularity.[7], [8]

The green transition, joining forces with the digital transition, aims for climate neutrality, acquiring a dual character: environmental, through its impact on carbon dioxide emissions, and technological, by leveraging powerful tools such as Artificial Intelligence, Digital Twins, Data Analysis and Simulations, and much more[9], [10]. The present technological solution aims at the sustainable management of the circular value chains of industrial units, and their monitoring and evaluation, using innovative digital tools such as Digital Product Passports, management and evaluation tools such as Sustainability Balanced Scorecards, with an emphasis on circularity, as well as autonomous digital tools that offer personalised modeling, such as the Process Simulation Tool. The goal of this solution is the effective organization of circular value chains, incorporating traceability and transparency strategies, giving industries a competitive advantage and added value in the areas of sustainability (environment, economy and society), circularity and resilience. A dedicated technological solution for advancing the circularity and sustainability across the industrial value chains was followed the context of the project Greece4.0 under the framework of the National Recovery and Resilience Plan Greece 2.0, funded by the European Union – NextGenerationEU.

METHODOLOGY

Aiming at the transformation of the industry, in compliance to the principles related to Industry 4.0, the present solution includes the use of advanced technologies such as value chain modelling and the creation of digital twins, based on the layout and data under which the physical system (industrial units) is structured and operates, as well as advanced management and evaluation tools for the operation of the chains with a focus on sustainability and circularity, developing the corresponding application frameworks. The Technological Solution lies on three dedicated architectural levels (Figure 1).

1. Modelling of value chains in industrial units and simulation of individual processes using the PSM-Process Simulation Modelling tool,
2. Development of a tool to enhance circularity through product traceability and transparency, the Digital Product Passports, and,
3. Integration of management tools with the aim of facilitating industries to design and set strategic activities, the Sustainability Balanced Scorecards.

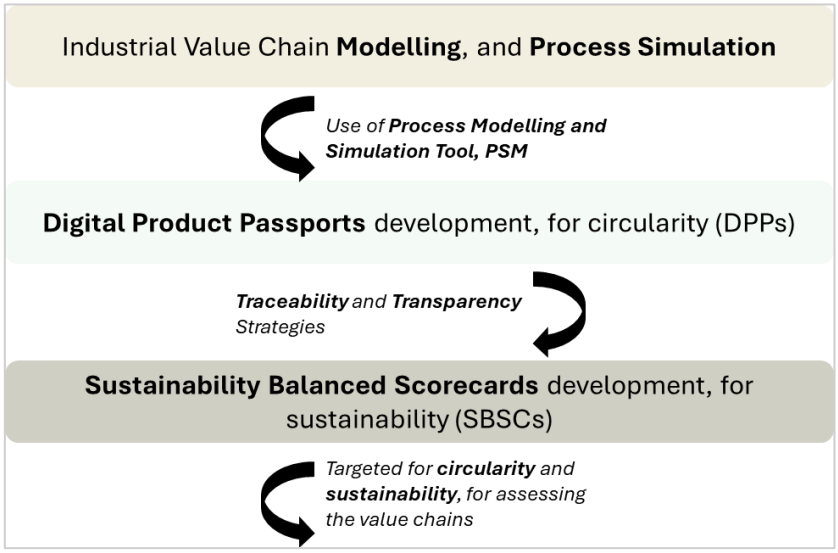

Figure 1. *Overview of the* Level of Architecture

Modelling of value chains in industrial units and simulation of individual processes using the PSM-Process Simulation Modelling tool

Production processes and supply chains will be modelled as networks of individual digital twins. The model-based digital twins will be created using the Process Simulation Modelling (PSM) tool, which was developed by the indigo team at the Technical University of Crete as part of European research programs. This tool allows for the creation of models of complex industrial units consisting of a multitude of processes and the simulation of their operation (Figure 2). PSM combines principles and methodologies within the framework of Material Flow Networks and Petri Nets to handle both continuous process industries and discrete manufacturing processes.

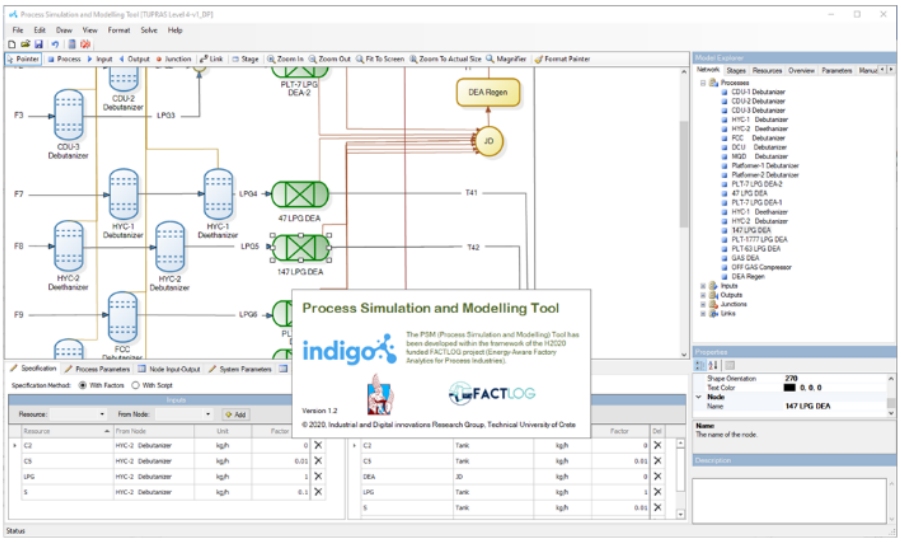

Figure 2. *The Process Simulation and Modelling Tool of TUC*

Development of Digital Product Passports for circularity

Digital Product Passports aim to enhance circularity, based on the principles of the Digital Europe Strategy, as introduced and presented in the Eco-Design for Sustainable Products Regulation. The creation of Digital Product Passports builds on traceability strategies, with the aim of covering all steps related to material procurement, production, and the supply chain, from product production to end-of-life. This detailed mapping of the product's journey and its individual parts/components will allow consumers, manufacturers, partners, and other potential stakeholders to have a complete picture of the specific product. DPPs can provide information on the origin, composition, repair, disassembly and/or reassembly of a product, as well as information on the recycling and reuse of its components. The creation and development of digital passports for a product aims to improve communication between the different actors in the value chains and to promote consumer decision-making and awareness, creating a new level of transparency and accessibility to information. The assurance of material quality and overall product quality throughout the product's life cycle is achievable through DPPs, especially in sectors critical to human well-being such as the food industry.

Development of Sustainability Balanced Scorecards

Sustainability Balanced Scorecards, or SBSCs, were originally created as a management tool to help industries design and implement strategic actions. SBSCs are based on the identification of four key pillars of a business: financial, customer, internal processes, and learning and growth. Starting from the definition of the business's core goal/vision and building on the goals of the four key pillars, a targeted, step-by-step implementation methodology is developed to create the SBSC for a business. The SBSC, taking data both from the modelling/simulation of individual processes that has been carried out through the PSM and from the product journey that is captured through the DPPs, evaluates the overall performance of the business in terms of sustainability (environment, economy, society), but also of internal processes and training, incorporating the appropriate key performance

indicators (KPIs).

Following the methodological framework presented below, the main implementation steps for carrying out the circularity and sustainability assessment tools were conducted. Four main steps were identified and implemented, as described below:

1. *Organizing, monitoring, and evaluating the current state of circular value chains, incorporating the traceability framework and the corresponding implementation steps.*

Reuse, remanufacturing, and recycling processes are among the key actions to minimize environmental impacts. However, the path to achieving sustainability and resilience in industrial value chains requires tangible actions and evidence of goal achievement. The answer to this purpose lies in traceability throughout the value chain, covering every process, collaboration, and stakeholder, according to the World Economic Forum. Traceability empowers companies to identify value chain strategy opportunities, innovate, minimize the impact of internal and external disruptions, and certify sustainable processes or products to meet standardization and certification standards. In this way, the principles of ethics, reliability, and related environmental impacts are ensured in value chains. The traceability framework incorporates the desired industry goals, available traceability solutions, and the key components that will play the role of enablers. The traceability framework encompasses practices and actions included in four critical steps, aiming to ensure success during implementation:

I. Linking traceability to business sustainability goals
II. Creating a collaborative ecosystem across the value chain
III. Understanding and developing traceability keys
IV. Transitioning from experimentation to transformation by taking a rapid testing and learning approach

2. *Modeling of manufacturing processes and supply chains as digital twin networks through the Process Simulation Tool.*

The interconnected models of individual processes model industrial production lines, incorporating both machine learning models (data-driven models) and physical principles models (first principles models). The methodology for developing a model in the PSM includes five key steps, as reflected in Figure 3:

1. *Model Creation*
2. *Registration in the system*
3. *Definition of a snapshot in the specific time frame*
4. *Flexibility in setting parameter values*
5. *Calculation of KPIs or objective functions*

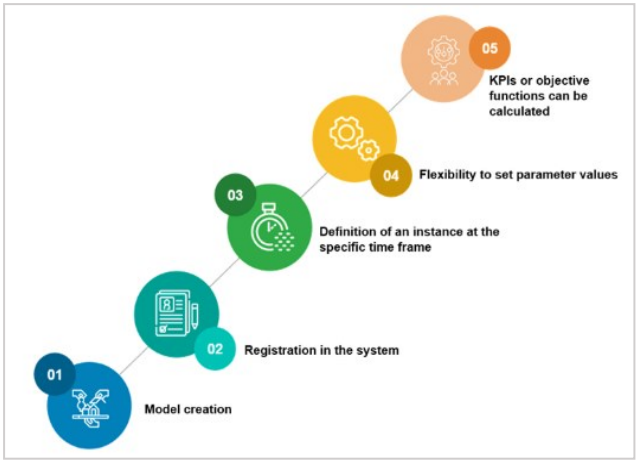

Figure 3. *Model-Based Digital Twin Engine - PSM Tool*

The input and output data at each stage/process are essential for creating a reliable model, by entering process operating parameters from sensors through APIs or manually, while the output includes the simulation results through APIs in JSON format, which are visualized in parallel through the autonomous PSM application (Figure 4).

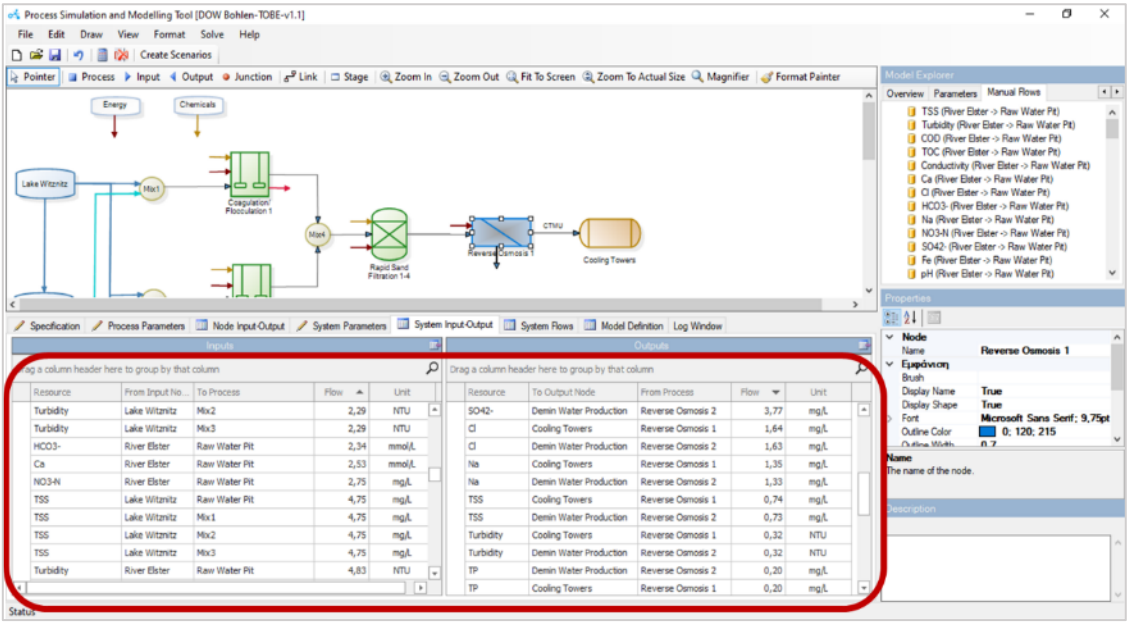

***Figure 4**. Visualisation of simulation and modelling results in the PSM UI*

3. *Mapping, tracing and pressing the traceability path of materials and products in the chain through the creation of Digital Passports.*

The development of a Digital Passport for a product or service incorporates the steps presented in the Traceability Framework, by adding information and data related to the product, its components, and their journey until they enter the value chain. Subsequently, information is incorporated related to the use or maintenance, but also options related to its management after the completion of its life cycle. These may include options for recycling, reuse, or other disposal methods that will minimize its environmental impact (as measured and evaluated through the Sustainability Balanced Scorecards).

The stages of development of the Digital Passport include:

a. Integration of basic principles and goals, as defined in the Traceability Framework.
b. Data collection, process line, and standardization activities that are followed in the industry under consideration.
c. Mapping and involvement of stakeholders, players, and partners who have a direct connection/involvement/collaboration/cooperation with the value chain.
d. Selection of technologies that will implement DPPs, such as blockchains or cloud-based databases.
e. Design of the User Interface of the Digital Passport, in a user-friendly, understandable, and direct way.
f. Data entry and integration, verification and creation of the first demo.
g. Continuous monitoring and evaluation of the DPP and its results/representations.

4. *Dynamic Assessment of Value Chains through Circular Sustainability Balanced Scorecards.*

As presented in the Architecture Levels section, Sustainability Balanced Scorecards were created to facilitate industries in making decisions and designing strategic plans, with the aim of evaluating industry performance in four key pillars: financial, customers, internal processes, and learning and development. The implementation framework of a Sustainability Balanced Scorecard includes a series of steps, starting with the definition of the industry's main goals and the vision for sustainability and resilience, as reflected through circular value chains.

The specific steps followed lead to the evaluation of the performance of the production process in terms of the environment, society, the economy, the life cycle analysis of products, but also specific measurable targets (KPIs) that the industry may set (Figure 5).

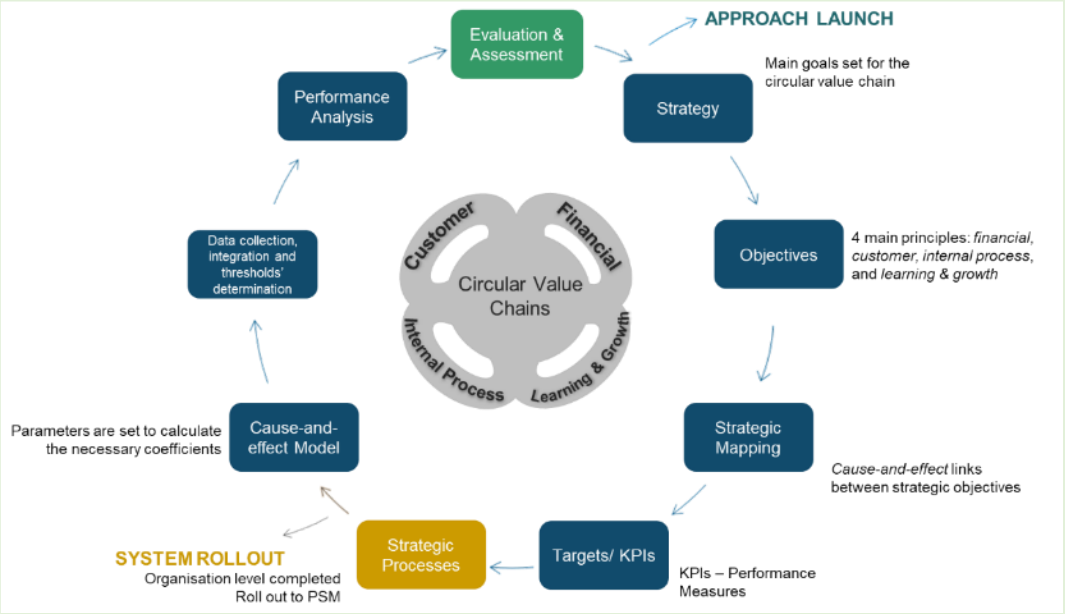

Figure 5. *Sustainability Balanced Scorecard framework and implementation steps*

RESULTS AND DISCUSSION

The application of this specific solution aims to enhance the circularity of industrial processes, following strategic and technological solutions with the goal of traceability, sustainability, and circularity of processes. The mapping of the complete path/origin/composition of products or/and secondary materials, and the representation of this information through digital product passports, provides immediate and transparent access to all product-related information, which can be directly accessed by consumers-citizens, potentially involved stakeholders and potential partners, as well as authorities responsible for legislative control and monitoring of compliance with regulations.

Consequently, the development of circular sustainability balanced scorecards as a tool for assessing the impact and evaluating the product and the individual processes of the value chain, in terms of their environmental, economic, and social performance, evaluates the product/service in terms of its sustainability and circularity, providing a comprehensive picture of the products produced, to consumers, potential partners, and investors.

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REFERENCES

[1] Ellen Macarthur Foundation, “Eliminate waste and pollution”, available at: https://www.ellenmacarthurfoundation.org/eliminate-waste-and-pollution

[2] European Investment Bank, Circular Economy Overview, 2023, available at: https://www.eib.org/en/publications/20230157-circular-economy-overview-2023

[3] European Commission, “Making Europe's businesses future-ready”, available at: https://ec.europa.eu/commission/presscorner/detail/en/ip_20_416

[4] Kalaboukas K., Rozanec J., Kosmerlj A., Kiritsis D., Arampatzis G. (2021), *Implementation of cognitive digital twins in connected and agile supply networks-an operational model, Applied Sciences*, 11, Issue 9.

[5] Ministry of Environment and Energy of Greece, “Circular Economy, the New Action Plan of Greece”, November 2021.

[6] European Commission, ”EU whole-of-government” approach, available at: https://commission.europa.eu/strategy-and-policy/sustainable-development-goals/eu-whole-government-approach_en

[7] N. Bocken, C. Bakker, I. Pauw, “Product design and business model strategies for a circular economy”, *Sustainable Design & Manufacturing Conference, Seville*, 12-14 April 2015.

[8] European Investment Bank, “Focus on the circular economy, Closing the loop”, available at: https://www.eib.org/en/publications/interactive/sustainability-report-2017/focus-on-the-circular-economy-closing-the-loop/

[9] European Commission, “The Green Transition”, available at: https://reform-support.ec.europa.eu/what-we-do/green-transition_en

[10] European Commission, Directorate-General for Structural Reform Support, “Technical support for implementing the European Green Deal”, July 2020.