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Digital Twins: Enhancing Circular Economy through Digital Tools

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Abstract

In the drive towards sustainable design, the push for products with greater longevity, reparability, and recyclability has never been more crucial. Central to this is the integration of eco-design principles within manufacturing processes. However, there is a gap: manufacturers lack both standardized processes and digital tools to support them, even though the promising digital product passport largely focuses on product lifespan. Key Performance Indicators (KPIs) are paramount, serving as benchmarks for both the manufacturing process and environmental sustainability of a product. These KPIs encompass factors like energy, water, compressed air, and material resource consumption. To emphasize the importance of these metrics, Europe is vulnerable to supply disruptions due to its high dependence on raw materials from non-EU countries.

This paper discusses the state of the art of digital twins and presents a digital shadow—a comprehensive digital tool design to support manufacturers during the product design phase. Drawing from a case studies in the automotive sector, this tool not only aligns with recycling and sustainability objectives but also mitigates risks associated with raw material dependencies.

Keywords: digital twin; digital shadow; eco-design; digital product passport; manufacturing; sustainability

1. Introduction

The European Circular Economy strategy [1] as part of the European Green Deal is a comprehensive approach aimed at transitioning the European Union (EU) towards a more sustainable and resource-efficient economy. It centers on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems. The strategy seeks to minimize the environmental impact of production and consumption, while promoting economic growth, innovation, and job creation.

Historically, the circular economy has mainly focused on recycling and reintroducing materials into the production cycle. It has not extensively explored designing products in a manner that facilitates easier, more cost-effective, and energy-efficient recycling from inception. This concept, known as "Design for Sustainability," emphasizes the creation of products that last longer, are easier to repair, and inherently more recyclable. While adopting this approach requires substantial investment, it represents a significant milestone in Resource Efficiency and Waste Reduction. Enhancing resource use efficiency across sectors and curtailing waste generation will undoubtedly be a pressing challenge for the EU manufacturing industry in the coming years.

Unfortunately, today's product design engineering tools are not ideally designed for this paradigm shift. While they often emphasize cost-efficiency and other performance metrics, they typically overlook the imperatives of sustainable design, e.g. the repairability. Traditionally, manufacturers have not created their products as part of their ongoing supply chain, once sold, products seldom return to their origin. However, a transformation is underway. Manufacturers are increasingly recognizing used products as valuable resources in their own supply chain.

This evolving perspective demands a rethinking of product design as eco-design: considering how materials and

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components can be efficiently repurposed. Furthermore, the pressure surrounding resource procurement, especially given that a large proportion of raw materials are imported from non-EU countries, cannot be ignored. Recognizing this, the European Union's Critical Raw Materials (CRM) [2] initiative is addressing the sustainable and secure provision of essential raw materials crucial for industries ranging from electronics to renewable energy. The CRM initiative promotes recycling, resource efficiency, and responsible sourcing to diminish dependency on imports and minimize ecological repercussions. Proposed strategies are in favor of domestic production, refining recycling methods, encouraging research and innovation, and building alliances with resource-abundant nations.

Today, there is – besides Life Cycle Assessment – neither a standard process nor hardly any digital support tool available to guide the manufacturer to design products for a reuse or recyclability right from the beginning. As it is nearly impossible for manufacturers and consumers to overlook all necessary and important developments for sustainable resource management, digital tools play a crucial role in advancing the European Circular Economy [3] strategy.

The present paper discusses the main Key Performance Indicators (KPIs) to serve as a benchmark for the sustainability of a product and assesses digital twins as a solution for the stated problem. This tool is not just aligned with recycling and sustainability goals but also serves to reduce risks linked to dependencies on (critical) raw materials and as a nice side effect supports energy efficiency.

2. Background and related work

The European Green Deal [4] is a comprehensive action plan introduced by the European Commission aimed at making Europe the first climate-neutral continent by 2050. This initiative encompasses various measures, ranging from cutting greenhouse gas emissions, promoting renewable energy, improving building insulation to increasing biodiversity, and transitioning to a more sustainable food system. The Green Deal's primary objective is to boost the efficient use of resources by transitioning to a clean, circular economy and stop biodiversity loss. As a consequence, Design for Sustainability is entering the design division of most companies to use materials in a most efficient way.

Design for Sustainability (DfS) is a multi-dimensional approach that covers the environmental, social, and economic aspects of product and system design with the objective of reducing negative impacts throughout a product or system's lifecycle. Traditional design focuses primarily on aesthetics and functionality. In contrast, DfS seeks to ensure that products and systems are resource-efficient, durable, repairable, and produced with the least possible environmental harm [5]. However, this is not a new approach, as there was already a guideline for “Recycling-oriented product development” known as VDI 2243 from 2002 in Germany.

The United Nations has emphasized the importance of DfS in the context of global sustainable development. According to a report [6] by the United Nations Environment Programme (UNEP), DfS not only addresses environmental challenges such as waste reduction and energy efficiency but also incorporates social considerations. These include fair labor practices, well-being, and equitable socio-economic outcomes. The UNEP highlights that truly sustainable design goes beyond merely being "eco-friendly" and puts effort into broader commitments to social justice and economic viability.

Adopting DfS offers numerous benefits. Beyond environmental advantages like decreased waste and pollution, sustainable design practices can provide economic gains through cost reductions, enhanced brand reputation, and tapping into new market opportunities. Furthermore, as regulations and consumer preferences shift more and more towards sustainability, DfS is not only becoming an ethical choice but also a must for businesses. In this evolving landscape, companies that integrate DfS principles are better equipped to anticipate regulatory shifts, meet growing consumer demand for sustainable products, and ensure their long-term success in an increasingly sustainability-conscious global market [7].

In both, this study and our prior research, we align with Kritzinger et al.'s [8] definition, which describes a digital twin as a digital depiction of a physical system. The authors differentiate between three categories: a digital model, a digital shadow, and a digital twin. In the digital model, information transfer between the physical and digital domains is manual in both directions. For the digital shadow, while the transmission from the physical to the digital is automated, the reverse is manual. In contrast, the digital twin is characterized by automatic bidirectional information flow. Furthermore, the digital twin is also defined in the ISO guideline 23247-1:2021 [9].

Dalibor et al. [10] conducted a comprehensive review of 356 digital twins’ publications to understand their distribution across various domains. They identified 20 unique application domains, with a notable 70% of the analyzed work being concentrated in the manufacturing sector. These digital twins serve as tools for monitoring and control, either to refine the design process pre-production or throughout the product's lifecycle. The central objective is to minimize expenses and time, all while enhancing comprehension of the system in focus.

The research presented here is a part of a broader project aimed at creating a robust tool: a sustainability digital twin, digital shadow respectively. In an earlier study [11], we introduced a framework tailored for evaluating sustainability within various production stages. This framework utilized sensor data captured during distinct manufacturing phases. This initial endeavor not only served as a proof-of-concept but also highlighted the substantial potential for energy efficiency and sustainability enhancements through the use of a digital twin.

Building upon our prior work, this current research takes a slightly different trajectory. While the previous research predominantly centered on the practicality and potential of sustainability assessment, our current focus narrows down on the capabilities of digital twins within the Circular Economy paradigm. More specifically, this study considers the development of digital twins and digital shadows for the principle of "Design for Sustainability" within the manufacturing sector. The aim is to find out how these digital tools can be used most effectively to advance sustainable design and thereby promote a more resilient and circular manufacturing ecosystem.

3. Data acquisition

Data collection and analysis is important, not only during the manufacturing phase but in a holistic approach. Digital technologies enable the collection and analysis of vast amounts of data related to resource consumption, production processes, and waste generation. During product manufacturing, raw materials are involved, where most materials are derived mainly through mining and less through recycled material. Primary raw material mining is associated with a variety of issues ranging from price fluctuations, material availability to access to minable stocks. Consequently, access to and exploitation of secondary resources has become an obvious need. While the recycling of paper, glass and steel are established concepts, considering urban spaces as a source to recover strategic and often critical materials like Lithium, Gallium, Phosphor and Rare Earth Elements is a more recent development. Urban areas provide resources through, for example, waste landfills and dumps, building stock (residential, industrial, infrastructure, construction and demolition material), end-of-life vehicles, municipal solid waste, electronic waste, sewage and biomass. However, data on secondary resources are still poor today. But this data informs policy decisions and helps identify areas for improvement. In essence, digital tools enhance the implementation and monitoring of circular economy practices, enabling more efficient resource use, reduced waste, and a shift towards a more sustainable economic model.

Data collection builds the foundation of a digital twin with the aim to enhance circular economy. In order to know which data needs to be obtained, the production company needs to develop a clear understanding of the objectives of the DfS for the product they want to produce. Thus, it is necessary to not only define requirements for the functionality of the product but also of the performance of KPIs in the environmental, social, and economic aspects of the product.

The digital twin for circular economy needs to encompass a variety of different data sources. This may include but is not limited to:

- Environmental databases like Ecoinvent
- Life cycle assessment results and key performance indicators (KPIs)
- Data from the production process, i.e. the resource consumption of each production step and the necessary production steps for each combination of product features
- Geopolitical data like World Governance Index or Herfindahl-Index
- List of all possible materials and their impact
- Data about repairability and recyclability

Ideally, all of the above data sources are present in the digital twin. However, it is unrealistic to assume that all necessary information about the production process or all possible materials can be known now. In this case, reasonable assumptions have to be made. However, when the digital twin consists mainly of assumptions, it will not be realistic and thus, rendered useless. Therefore, the data acquisition should become a priority, even though it is time-consuming. The more accurate the data, the more effective the digital shadow will be, as the consequences of design choices can be seen more accurately. For example, the information about the impacts of certain materials from an environmental database is mainly accurate but averaged. If this information can be obtained from the supplier directly, the information will represent the real conditions. In addition, if different suppliers can be compared with each other, the digital shadow will be more useful. As result, it will not only be able to compare different materials for one component of the product (e.g. housing) but also different suppliers. Consequently, the product designers can make sure to comply with the set of requirements.

In some industries, it is easier to get this information. For example, in the automobile sector, the bill of materials is available through the IMDS data base [12]. However, this is only shared within the automotive supply chain.

Another important type of KPI is those that help mitigate geopolitical risk. Geopolitical changes could heavily limit or disrupt the supply chain. Indicators of geopolitical stability are therefore essential in ensuring supply chain integrity. While some geopolitical events cannot be predicted, knowledge of geopolitical trends can limit this risk. In addition to geopolitical stability knowledge of the concentration of material production to single countries is also valuable so that materials might be substituted, or suppliers changed to mitigate risks of supply chain disruption.

The initial list of data needed for a specific use case can be reverse engineered from the list of KPIs that can be derived from the requirements for the product. It is necessary for each company to set an aim for each KPIs so that product designers know which trade-offs to choose. It is highly unlikely that there exists a product feature combination that will achieve perfect ratings in all KPIs and perfect capability for reparability and recyclability. Instead, because of complex interdependencies between choices and circular economy aims, there will always be a trade-off.

The data for recyclability and repairability can be obtained through case studies and expert knowledge. Norms like the DIN 45553 or DIN 45554 can be used to determine the ease of disassembly. Depending on which kind of logic is used [13], experiments might be useful to give an estimate of repair time for different product feature combinations. The recycling potential is dependent on the material composition as not all materials in a component can be recycled in one step. A product designer should therefore have the information if a material combination is not ideal for recycling.

As the digital twin and digital shadow combines many different data sources some kind of data management will be necessary. Some KPIs can just be derived from a single data source, but some KPIs need to be recalculated for each version of the product design and are based on a combination of different data sources. Furthermore, data sources need to be able to be updated or replaced by more recent or accurate data sources.

Our case study for this digital twin to enhance circular economy emerged from the EU-funded CIRC-UITS project. Here, we use two use cases of components in the automobile sector to research how we can implement the digital twin to enhance circular economy and how it will help product designers. For that, we are strongly collaborating with sustainability and recycling experts as well as the product engineers to build a strong link between the different disciplines. KPIs that will be calculated include the CO2, H2O, overall process energy, the abiotic depletion potential, repairability and recyclability KPIs (see Figure 1). The aim is to include all KPIs that might be relevant once all necessary KPIs have been identified. For a fixed product design, these KPIs can then also be used for the digital product passport (see Section 4.2). The repairability potential is determined by dismantlers.

4. The path towards digital twins for Circular Economy

A significant shift from traditional physical towards data-driven models marks the contemporary era of technology. Physical models were once key for understanding complex systems, but they struggled to keep up with fast changes. Now, with big data and advanced computing, the focus has shifted to models based on continuously changing data. These new methods are more detailed and flexible, allowing for precise predictions and quick adjustments. They also help to find detailed insights in large amounts of data. As the world turns digital, this shift to data-driven models reflects the need for accuracy, quick response, and adaptability in a constantly evolving environment.

4.1. The Digital Shadow: A Precursor to Digital Twins

According to the definition this work adopts, we consider our research to be in the stage of a digital shadow. It is important to discuss the concept of the digital shadow. Representing a static digital imprint of systems, the digital shadow offers a snapshot of the current state.

Kritzinger et al. [8] consider digital shadows the extension of a digital model, where a change of state in the physical object leads to a change of state in the digital object, but not vice versa.

Brecher et al. [14] define digital shadows as a concept that centers on gathering, consolidating, and simplifying manufacturing data to facilitate informed decision-making. By ensuring domain-specific data streamlining, the process remains computationally efficient. Digital Shadows incorporate diverse data types, such as measurements, simulations, and models, sourced from various origins. This data is then selectively condensed and merged based on the specific application to meet its objectives. Consequently, these digital shadows provide a foundation for activities like process refinement and data exploration.

Brecher et al. [14] call attention to the fact that, even though digital shadows promise tremendous potential to reduce time and cost in manufacturing, they are normally designed for specific applications. Therefore, they conceived a conceptual model of Digital Shadows that can guide their engineering, combination, and reuse. Digital shadows have great potential, yet they are less complex than Digital Twins.

An advanced example of transformative digital tools is the Digital Twin. By designing precise digital replicas of products, materials, or even entire processes, they pave the way for simulations and predictive testing of circular strategies, thereby minimizing potential failures and maximizing desired outcomes. For instance, the effectiveness of digital twins lies in their potential to revolutionize Circular Economy and sustainable resource management across Europe. They enable stakeholders the ability of virtually modeling and simulating products, materials, and processes. Consequently, designers and engineers are able to virtually model and refine diverse scenarios prior to physical production. The outcome are products that are meticulously designed for longevity, enhanced recyclability, and minimal waste.

The digital twins' versatility is present across the entire product life cycle, influencing products, production processes, and even socio-technical impacts. Their utility includes:

- Preemptive requirements engineering and model-driven developmental stages, even before the physical twin's inception.
- Monitoring and regulation during the cyber-physical system's testing and operational stages.
- Predominant requirements monitoring and capturing end-user innovation during the usage phase.
- Implementing ongoing learning methods and planning for "Re-technologies" (like reusing and recycling) as a product nears the end of its life cycle.

A closer look at many studies shows that small and medium businesses are not really using digital twins, and there are not enough unbiased studies comparing them. In summary, digital twins and digital Shadows are becoming key tools in Europe's effort to lead in Circular Economy and smart resource use. They provide deep insights, allow complex simulations, and help in making data-driven improvements. Digital twins/shadows are important for reducing waste, using resources more efficient, and driving innovation in many areas. The overall goal is to develop a strong, sustainable, and resilient economy.

4.2. The Role of Key Performance Indicators

As concept for a digital shadow we propose a product centric approach. All information that goes into the product is captured in the digital shadow, as shown in figure 1. With the linkage to the recycler or dismantler, information on the reparability and recycling is received. This enables the manufacturer to adjust the product throughout the whole life cycle to reach the highest circularity of the product. Even this setup needs a few years to be established, it is the time now to set it up. The digital passport plays an important role in this case study as it shares the information of the product not only with the manufacturer but also with the recycler of the product's supply chain.

The reason for sharing information on a product with other partners in the supply chains helps to create the supply chain more resilient as the product itself could close the supply chain. A product that can be repaired, remanufactured or "only" recycled can lower the pressure on primary resources. Which can reduce potential disruptions in the supply chain caused by geopolitical events, or the reliance on those primary resources with questionable origin and potential human rights infringements. How can a company decide how to make a product more sustainable? Where and how are fewer resources used and how can I make a product easier to repair? As there are no "ready-to-go" tools available, we need to develop new systems.

In General, we want to achieve two principles: a) achieving the necessary high level of collaboration between the different parties within the supply network [15]. Only then can supply chain risks be identified at an early stage during operations and be jointly managed. A key role is played by the exchange of information, which eliminates uncertainties and thus promotes resilience; and b) this principle suggests agility in order to achieve resilience. A supply chain should be flexible enough to react quickly and correctly to unexpected situations, such as changes in demand and supply, within an uncertain environment. This so-called supply chain velocity requires full visibility of the up- and downstream flows of information, goods, materials and finances in the supply chain [16].

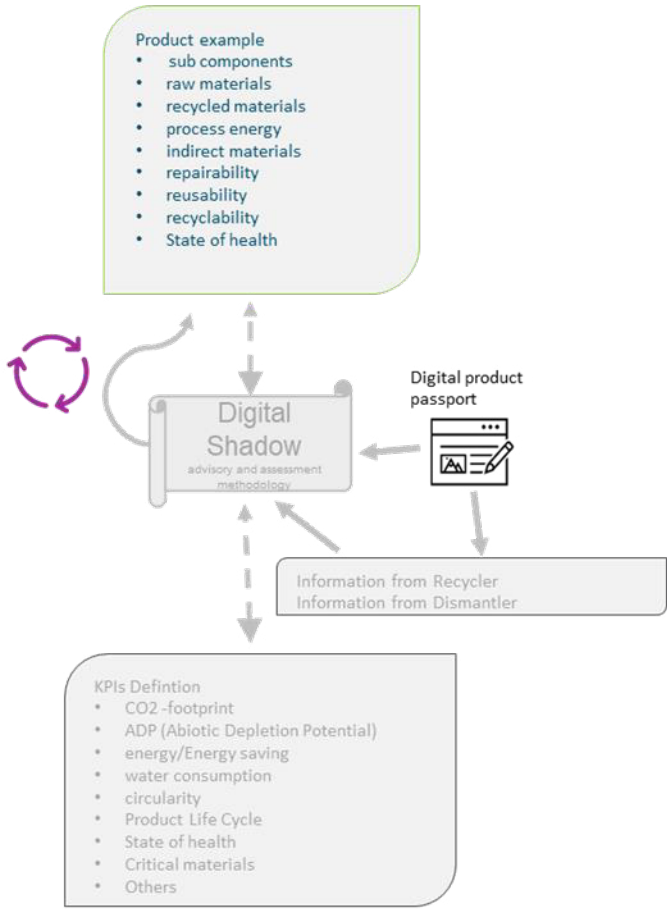

Fig. 1. Concept of the Digital Shadow approach including KPIs

During operations within manufacturing nearly all data needs to be available close real-time so that adaptive measures can be quickly devised in case of unexpected disruptions. But the decision regarding products manufactured in a better circular economy approach is often not relevant in real time. For example, recycling quotas of raw materials or the criticality of raw materials are often a long-term issue. Therefore, the digital shadow must be able to evaluate KPIs in real-time and long-time. For a product designer, this means that he can use the digital shadow to test and adapt different variations of the product. In our case a product inside a car can be improved by the access of all stakeholders to one data base, as the manufacturer provides the list of materials, the user can assume the life time of the product and the dismantler can assess the reuse or repair success. In the long run this information might be available through a digital product passport by the end of this decade. In addition, the dismantler can act as supplier back to the original manufacturer, who might be able to repair the product easily and bring it back on the market as remanufactured or repaired product. This would increase the circular economy and decrease the pressure on raw materials.

Overall, resilience of this whole supply chain can be strengthened by building a supply chain risk management culture at every organizational level. Risks that have their origin outside the organization are often overlooked or underestimated. Consequently, risk management for supply resilience must include the entire supply chain and its environment.

5. Summary and Conclusion

In practice Digital Twins are already extensively applied to the manufacturing phase and most commonly used for internal company tracking and training. However, applying digital twins for cross-company activities in production and supply chains is still very rare, in both industry and academia. Given their rarity there is still hesitance to implement the bidirectional information exchange necessary for the digital twin. Therefore, implementing a digital shadow will eventually increase confidence in the concept and be the first step towards a digital twin. The digital shadow proposed in this work has the potential of being less complex then a digital twin while still sharing information throughout the supply chain and addressing more stakeholders than the manufacturer itself without sharing company secrets. However, the outstanding feature of the digital shadow presented is that it can also be used as a design concept for manufacturers. In addition, end-of-life stakeholders are also included in the concept and can also implement the product circular economy more successfully through recycling and repair. This research is still in the beginning and shows only the interim result of the concept. More information is still gathered and the digital shadow will be implemented within the manufacturing soon.

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