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Building Better Digital Twins for Production Systems by Incorporating Environmental Related Functions—Literature Analysis and Determining Alternatives

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Abstract: The digital twin solution is an industry 4.0 specific tool that has grown in the past decade, stemming from the modelling and simulation approaches that existed before, complemented by new sensor capabilities, cloud processing, big data analytics, and implementation mechanisms. As it is being used mostly in the present by manufacturing companies, the primary focus of the solution is to enhance productivity and reduce costs by optimizing processes and enabling real-time problem-solving, sometimes based on decision-making systems and artificial intelligence. However, as companies are being faced with an increasingly steep list of environmental requirements and regulations, ranging from the classical pollution control and waste recycling to full-scale economic models based on circular economy and transformative carbon dioxide elimination programs, the features of the manufacturing digital twins must also evolve to provide an appropriate answer to these challenges. In this paper, the authors propose a framework for building better digital twins for production systems by incorporating environmental-related functions. The demarches start from analysing existing solutions presented in literature from the point of view of environmental suitability, based on the use of the MoSCoW method for differentiating attributes (into Must have, Should have, Could have, Will not have elements) and determining development alternatives based on the employment of Multi-Criteria Decision Analysis (MCDA) for feature selection, and the TRIZ method (Theory of Inventive Problem-Solving) for application guidelines. The MCDA was performed within a focus group of nine production specialists from regionally successful sectors. We arrive at the conclusion that environmental-related functions are poorly implemented in the digital twins of the present (although more so in integrated solutions and custom-built applications) and that the development of the proper tools, databases, and interpretation keys should proceed immediately in the fields of production engineering, industrial ecology, and software development to support them.

Keywords: digital twin; digital production; production system; environmental management; multi-criterial decision analysis

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1. Introduction and Context

In the current economic and social context, manufacturing and production engineering are required to undergo significant changes to keep up with the developments of technologies and markets. Since its inception in 2011, the approach of Industry 4.0 has taken over the field of manufacturing, promising great benefits but also asking for great efforts to be undertaken by the companies. For more than two years now, and probably continuing into the foreseeable future, the COVID-19 pandemic has generated difficulties for the global supply chains and has determined countries to reverse their thirty-year-old industrial policies to re-shore manufacturing facilities back to the countries they have left in search of opportunities. An even more disruptive transformation that is approaching fast is generated by the global problem of climate change, which is already prompting producers to decarbonize their manufacturing facilities and processes, and to change their product designs.

Under Industry 4.0, machines, humans, and the environment co-exist in a complex interdependent relationship underpinned by big data, analytics, and machine-learning algorithms. Most companies are focused on increasing the productivity of the facilities, enhancing the quality of the products, and on responsive changes to the customization pressures coming from the market and the consumers. Within this situation, manufacturers usually focus on the operational benefits related to the digitalization of production, especially cost reduction and increased capacity. The environmental and social aspects, making up the sustainability strategy of a company, are not perceived as important in the context of company survival on the market.

When going beyond the initial stages of the digital transformation, a production firm usually combines data analytics, simulations, Internet of Things, and visualizations to become fully fledged smart factories, that adapt in real time to challenges and evolutions in their insertion environment. Digital twin solutions are evolving at a fast pace and there are many aspects and functions associated with their deployment that are not yet fully defined and clarified. The easy way out in this context would be to associate existing process and production system simulations to digital twins and reap the benefits of using this buzzword as a marketing tool. However, that would severely underappreciate the new functionalities and capabilities brought about by the scale of these solutions. More than just simulations running in parallel to production environments rich in sensor data, a digital twin has the ability to communicate in real time between the virtual and the real mediums and to enact two kinds of interventions: corrections and corrective actions to determine the system to stop generating a certain undesired result and preventive actions and improvement opportunities to determine the system to change for the better.

There are many challenges facing researchers and developers in the field of digital twins: the accuracy of the 3D modelling, the speed and precision of communication between the real and the virtual environment, the degree of user friendliness, the quality of the automated decision-making, etc. The authors have not identified in the literature digital twin functions directly aimed at the environmental issues regarding a production system, but rather indirect capabilities related to the sensor data generated by the system.

Sustainable production is a moving target and an ideal state that is hard to achieve. Moreover, since most changes required by sustainability go against the traditional flow of capital and resources to the most efficient possible state on a local level, the big picture of investing for environmental and social benefits can easily be forgotten from a digital twin solution aimed at a certain process, system, or even company. The most significant impacts in terms of sustainability come from an alignment of visions and objectives among the employees and management, among companies, and the emplacement in a certain locale managed by a certain government and populated by a certain community. For full results, these collaborations should also bring understanding among partners and competitors in a certain industry, and ultimately among global markets and national and supranational governments. This is especially true in the case of carbon emissions and the large-scale international effort to limit them, since CO_2 cannot be confined to a company, space, or impact.

The current paper analyses the existing features of digital twins through the lens of sustainability as a completement and enabler of productivity and not a deterrent to increased operational returns. Further, we propose an addition to what has been described until now in literature, namely that a fully functional digital twin solution for sustainable manufacturing should go beyond reducing environmental impact, employing clean technologies, and implementing the best green practices, and, in the future, allowing for possibilities to connect companies and data repositories among companies, in terms of elements with potential global impact. Manufacturing as a sector has an excellent window of opportunity to transform itself in the new digital world and occupy a position of environmental champion, not just to be digitalized because of societal pressures. The following five stages have been implemented and presented in this article, representing an original approach to meeting the challenges of sustainable manufacturing, that goes from conceptualization to implementation guidelines:

- A critical analysis of literature focusing on digital twins for manufacturing.
- A categorization of the attributes of these twins using the MoSCoW method.
- Proposals for environmental sustainability-related functions using brainstorming.
- Correlation of the functions and the attributes employing Multi-Criteria Decision Analysis using the MCDA software.
- Investigation of the achievability of the detailed results using TRIZ for innovative development.

2. Relevant Approaches to Digital Twins for Sustainability in the Existing Literature

When discussing digital twins, one should approach the topic from the point of view of research, but also from the point of view of developers and companies that cooperate to deploy practical solutions in manufacturing. While the first category of works addresses conceptual- and assessment-related issues of digital twins, the second category presents operational- and implementation-related aspects. We consider both sides to be of equal importance in further improving the contribution of digital twins to mature Industry 4.0 solutions.

2.1. The Conceptualization of Sustainability in the Case of Digital Twins

From a methodological point of view, article [1] addresses the need to implement a concurrent designing, modeling, and simulation as native approaches when creating digital twins, in order to be able to maximize the benefits of this system, which is also concurrent in nature. We believe this conclusion to be suitable for the case of sustainable manufacturing digital twins to an even greater degree, since the digital environment, the factory floor, and the local and global environment act independently and in parallel, and, at the same time, exhibits strong, model-altering interactions. In the same direction, after an extensive analysis of 192 papers, the authors of [2] propose an integrative framework called Function-Structure-Behavior-Control-Intelligence-Performance that aims to enhance the synergies of the technical components, the logical approach, and the human elements involved in the functioning of a digital twin for Industry 4.0 smart manufacturing. This work is relevant for our case too, as the analysis we undertake addresses the connections of these factors as enablers of sustainable results in intelligent production systems, more than individual environmental preoccupations or clean manufacturing technologies. Another important distinction that we observed is the one between traditional simulation approaches and the currently conceptualized bidirectional and proactive digital twins that act upon the process based on intelligent decisions reached by processing sensor data, described by [3] as they observed the limitations of CAD/CAM/CAE/CFD/FEM in achieving the same goals as a fully powered doppelganger. Another review that studied 123 papers, article [4] reinforces the role of modeling, simulation, and VR visualization, but also finds that big data analytics and cloud/edge computing are mandatory components of modern modular digital twins.

Based on a large body of literature of over 240 sources, article [5] proposes a complex approach to achieving sustainable intelligent manufacturing systems that seek to implement the virtual-real dichotomy in three directions: manufacturing system, manufacturing equipment, and manufacturing service. The novelty here is the identification of services and processes as a stand-alone component that can undergo digital transformation to answer to challenges in the environment, rather than them being used as the connecting bridge between the real manufacturing systems and its machines and the virtual environmental simulation. We consider this approach valuable for sustainability, as it facilitates its absorption as an integral part of digitalized factories.

Another paper [6] proposes five features that can be used to assess the usefulness and impact of using digital twins on the shop floor, namely realness, integration, dynamicity, visibility, and computability. By studying these attributes, we can also gauge the environmental footprint of a manufacturing system in order to support its sustainability-related efforts. Additionally, of high importance in this direction is the ability to perform advanced material management in a manufacturing system as presented in [7], because this is the source of most unwanted side-effects of production systems (e.g., waste, resource depletion, emissions, carbon dioxide). Still, in the meta-review performed by [8] using 29 review papers, the authors have not identified an exclusive approach centered upon the contribution of digital twins to environmental sustainability.

In a comprehensive understanding of sustainability in terms of economic, social, and environmental benefits, article [9] arrives at the conclusions that the digital transformation in a firm must be accompanied by a shift of focus from the needs of the enterprise to the needs of the user. On the other hand, the detailed influence of digital twins can go as far as optimizing process parameters to reduce carbon emissions, based on enhanced semantic real-time communication among the virtual and the real machines [10]. For these types of applications, many current technologies can be used, including radio tags, cyber-physical communication protocols, micro-sensors and micro-actuators, and others [11].

2.2. Particularization of Digital Twin Sustainability in Various Areas of Manufacturing

The focus on specific situations is a strong component of developing a suitable customized twin in high-tech industries such as aviation manufacturing [12], satellite assembly [13], missile production [14], electronics [15], the automotive industry, robotics and medical equipment [16], as well as intelligent home products [17,18], or more common domains such as the clothing industry [19]. There are also proposals for the generalization of the model to support enhanced performance at the level of product design and development [20], the production logistics system [21], the manufacturing supply chain [22], or the entire value creation chain [23].

Concerning certain domains to be addressed, the authors of [24] propose a smart manufacturing approach based on a digital twin concept relying on the quantitative green performance evaluation of the production systems and its outputs. The model introduces as priorities for the digital system important environmental, health, and social functions, which are then evaluated with the help of expert and stakeholder input in a comprehensive review. At the same time, the authors of [25], who analyse 52 scientific articles in the field, underline the need to track product and process data and to visualize the operations and interactions of the digital and real components of the twin. Additionally, the authors consider that energy consumption monitoring, which can signal operational efficiency and environmental sustainability, should be a main function of a twinning system. In the paper [26], the authors describe 12 potential benefits of data-driven maintenance processes as they can be implemented with the help of a digital twin, with a third of these being related to savings and safeguards in the area of environmental impact. The possibilities of supporting difficult decisions and projects of manufacturers working to protect nature are considerably enhanced in a digitalized approach based on twinning the real and the virtual environments.

The private sector is concerned with creating the most adequate strategy to deploy digital twins with minimal disruption [27] to increase the efficiency of complex technical systems as can be found in modern production systems [28]. The focus of companies is both on the impact and results of employing twins, and the operational changes required such as plant design [29].

2.3. Efforts towards Structured Development Frameworks

There are ongoing standardization and regulation efforts that seek to expand the benefits that can be obtained by deploying digital twins in firms. The standard ISO 23247 Digital Twin Framework for Manufacturing [30] is primarily focused on defining and managing the functional data layers of such a system, requiring one layer for collection and control, and one for processing and decision-making. The Digital Twins for Industrial Applications White Paper [31] proposes three main components: a visualization model (usually 3D/CAD/VR), a data framework, and a host of services to become available on the shop floor. The Draft NISTIR 8356 standard (as of 2022) Considerations for Digital Twin Technology and Emerging Standards [32] establishes the requirements for monitoring and controlling a digital twin in all of its possible states and for all possible functions. The report "Untangling the Requirements of a Digital Twin" [33] by the University of Sheffield distinguishes among supervisory systems, interactive systems, and predictive ones, in an increasing scale of capabilities. The Industrial Internet Consortium reviews all possibilities to create a digital twin structure, based on their interactions with the stakeholders [34].

An important number of authors studied the ways in which the growing field of digital twins [35] can be improved from a sustainability perspective [36]. Some of the current proposals in this domain include both theoretical contributions such as requirements discovery [8] and concept modeling [37], and applied approaches [38] that define actionable steps to be taken.

2.4. Literature-Based Feature Description

Next, the most important characteristics of the digital twins identified and discussed based on the literature survey above, have been sorted into categories according to the prescriptions of the MoSCoW method [39]: must have attributes, should have attributes, could have attributes, and will not have ones (Figure 1). They correspond to the following overarching definition and conceptualization that we have developed based on the literature study: digital twins are complex technical solutions that use Industry 4.0 technologies to achieve bi-directional real-time communication among a production system and its representations for the purposes of monitoring, adaptation, and intervention to internal and external factors. Thus, a clarification of the existing solutions can be achieved as a steppingstone to a more durable approach.

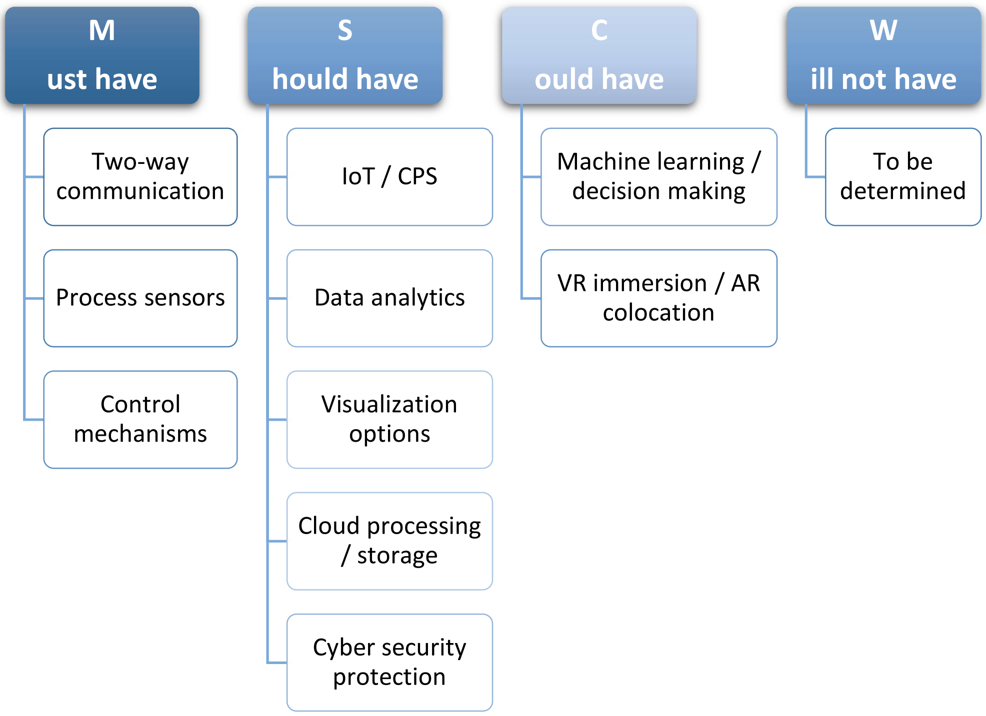

Figure 1. The main attributes and features of current digital twin solutions (own analysis).

The sustainability-related functions associated with digital twins have been defined by the authors through brainstorming based on experience (Figure 2). The brainstorming session was led by the principal investigator and took place over a limited period of 1 h, with each author being asked to contribute only concrete situations they have encountered during research or consultancy projects in manufacturing companies. Next, the data was processed, redundancies were eliminated, and the remaining functions were stratified in a chronological manner into classic functions (stemming from the original environmental movements from the 1970s to 1990s), modern functions (resulting from mature international treaties from 1990s to the 2010s), and a support function based on the European Green Deal [40], which is an advanced strategic approach applicable to the EU and its members.

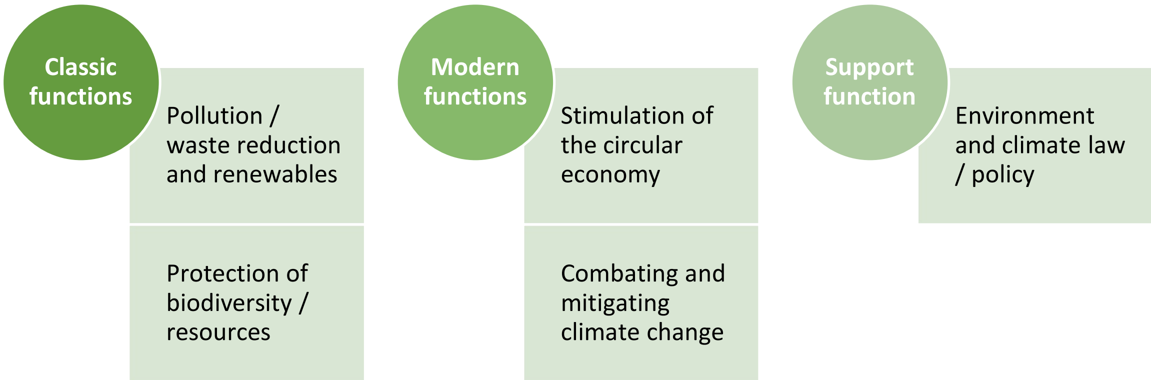

Figure 2. Environmental functions required for sustainable manufacturing (own analysis).

3. Proposed Framework for Determining Alternatives and Its Implementation

3.1. Context

In the context of the proposed research, the authors of this paper believe that sustainable manufacturing will soon become a pressing challenge in advanced and developing economies, as they will be pressured to re-shore their operations for strategic and workforce-related reasons, while they find themselves between sustainable energy producers and sustainable resource suppliers (using approaches specific to bio-economy/bio-based industry and the circular economy) on the one hand, and an ever-expanding customer base formed by Millennials and Gen Z consumers for whom the greening of the economy and society are embedded in their culture [41], on the other. At the same time, there is a strong trend to impose stricter environmental and carbon footprint regulations that limit the ability of the manufacturing sector to operate an outdated linear model of product lifecycle management that ends up with full landfills. There are currently many countries and cities that are experiencing a waste/trash crisis mostly due to increased consumption (including Romania and the city of Cluj-Napoca [42], where the authors of this paper are located). Per consequence, not only will production companies need to manufacture in a green manner, but they will have to decrease the material output that becomes waste and cannot be recovered, while generating near-zero carbon emissions. The approach to digital twin discussed in this paper and the proposals for its complete deployment and implementation in manufacturing companies considers all these requirements by using adequately structured product engineering and management methods in a coherent approach.

3.2. Methodology

The research methodology used in the practical portion of our study uses the MCDA method and its results as triggers for a TRIZ innovation proposal. The MCDA problem uses the envisioned environmental function as selection criteria and the existing digital twins' main functions as alternatives. The problem can be formulated as such: In which way and to which degree can we use, standalone and in combination, the features that are already implemented in digital twins to solve environmental objectives the production system should have?

The deployment of the digital twin attributes into functional environmental tools that embody a sustainable production approach has been established in a sound and traceable manner with the help of the Multi-Criteria Decision Analysis accessed through the MCDA v. 7.6 software created by ITES at Karlsruhe Institute of Technology (KIT) [43]. The method relies on the weighted sum model and proves to be reliable and easy to use. The mathematical formula uses the relative weight (on a scale of 1 to 10) of each criterion and the correlation score between the criterion and the alternative (also on a scale of 1 to 10) in the following way [44]:

$$PI = \Sigma_i (w_i * x_i) \quad (1)$$

where PI = performance index, w_i = weights, x_i = correlations, and $\Sigma_i w_i = 1$ and $w_i \geq 0$.

3.3. Implementation

The deployment was based on interviewing a focus group of 9 production managers/engineers, that can be considered specialists in the field due to the market successful results of the companies they work in the geographical region close to Cluj-Napoca (see Table 1 for details).

Table 1. Characteristics of the focus group interviewed during MCDA.

Industry Sector	Company Type	Research Method	Results
Electronics	1 small and medium sized	Open interview Contributions to ranking criteria Contributions to determining criteria-alternative correlations Achieving consensus	Relative importance of the proposed environmental functions Determination of the contribution each technical feature of digital twins has to achieving these functions Support during the interpretation of the results provided by the software
Metal fabrications	1 small and medium sized		
Furniture	2 small and medium sized		
Plastic components	2 small and medium sized		
Automotive components	1 large 1 small and medium sized		
Industrial machinery	1 large		

The results of this analysis are shown in Figures 3–6, below, together with the corresponding interpretations.

While implementing the analysis, the guiding constraints and requirements of digital twins identified in the literature survey have been observed. The 10 analyzed attributes of digital twins provide a measure of contribution to each of the 5 most-known environmental sustainability challenges (Figure 3) in the consulted sub-sectors of manufacturing.

The obtained scores for the correlations range from 0.2 to 0.85 on a subunit scale. Additionally, with scores forming 3 distinct clusters, we can underline the integrative character of the digital twin approach, as well as their discrete functionality based on the complexity of the issue resolved. The currently existing features should be supplemented by features that make use of synergies among technologies such as semantic web, mixed reality, sensor data fusion, and human technology interfaces, thus allowing for the higher-level functions related to sustainability to be deployed.

In Figure 4, the detailed representation shows data analytics and visualization options as frontrunners, while cloud processing/storage and cyber security protection rank the lowest. Additionally, the figure shows the contribution of each of the attributes to addressing the environmental topics in a proper manner.

It can be observed that the most relevant challenges addressed are pollution reduction, climate action, and environmental law, with biodiversity and resource protection approached in a light manner and requiring considerable future actions. There is a distinct separation in two categories, of very useful and beginning contributions, which we believe is due to the fact that current digital twin solutions are not geared towards achieving environmental functions, and this happens as a side effect of the attributes developed for managing and optimizing productivity and efficiency. We can infer that a digital twin based on the sustainability of manufacturing would reverse this trend and help achieve environmental and social cohesion first and operational issues in the background.

From the report generated by the MCDA 7.6 software for Figure 5 (and similar graphs for the other functions), we can deduce that combating and mitigating climate change is the most sensitive topic to be implemented in sustainability in the present. A mere 10% change in the perception for this function has the potential to determine a restructuring of the development effort. As society becomes more focused on combating climate change, the industrial sector is increasingly being called to come up with solutions and implement them quickly and with visible results.

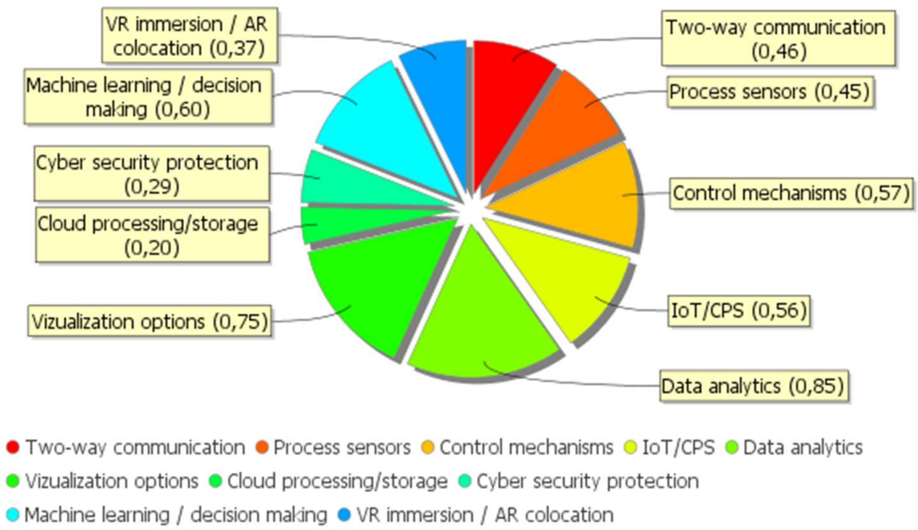

Figure 3. Sustainability contribution potential of the main functions of digital twins (subunit scale, compared elements indicated by color codes as provided by MCDA-KIT 7.6, own work).

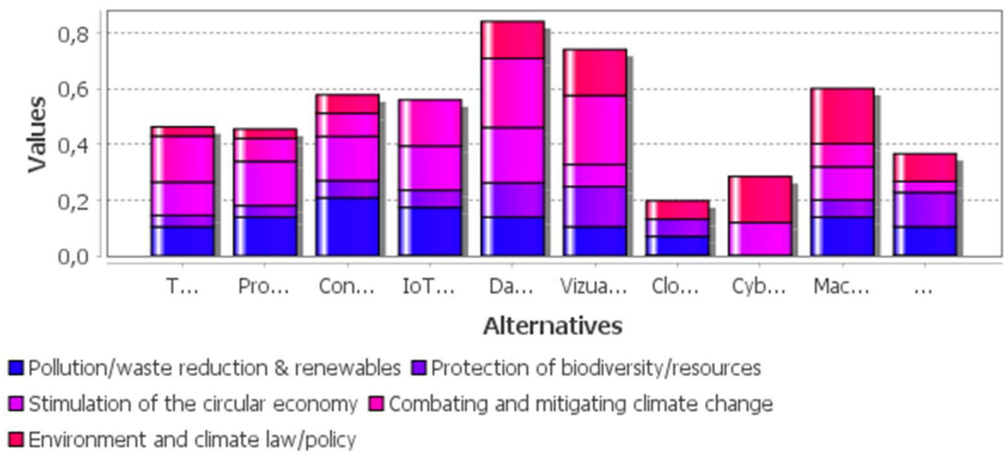

Figure 4. Contribution of digital twin attributes to the sustainability-related functions (subunit scale, compared elements indicated by color codes as provided by MCDA-KIT 7.6, own work).

Based on our study, we believe that developing functions specific to realizing sustainable manufacturing objectives and implementing them adequately across an important number of companies and production systems, will yield significant changes to the industry as a whole. Implementing tools to determine the carbon footprint of products and processes and data processing functions for cyber-physical sensors that measure CO_2 concentrations, as well as capabilities to report on a sectoral scale, will contribute significantly to achieving the international policy objectives in the field of climate change.

The last figure, Figure 6, details the contribution of each of the 10 attributes to the 5 functions mentioned.

One can notice that stimulation of the circular economy is being ranked first because of its industry-wide implications, and data analytics processes as well as visualization options can provide the most direct benefits in implementing the environmental-related objectives. Thus, these two areas form a lucrative development direction for software companies to address while working on the next generation of digital twins. Additionally, they can come to represent important areas for academia and researchers to develop new approaches, algorithms, and solutions that reveal results that are difficult to grasp, such as management system maturity [45].

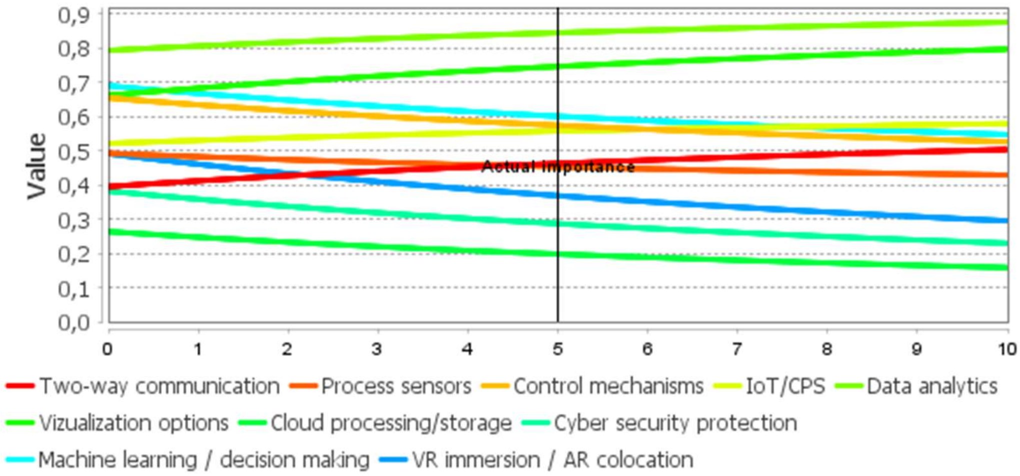

Figure 5. Sensitivity analysis for combating and mitigating climate change, showcasing alternative courses of action in digital twin development (subunit scale, compared elements indicated by color codes as provided by MCDA-KIT 7.6, own work).

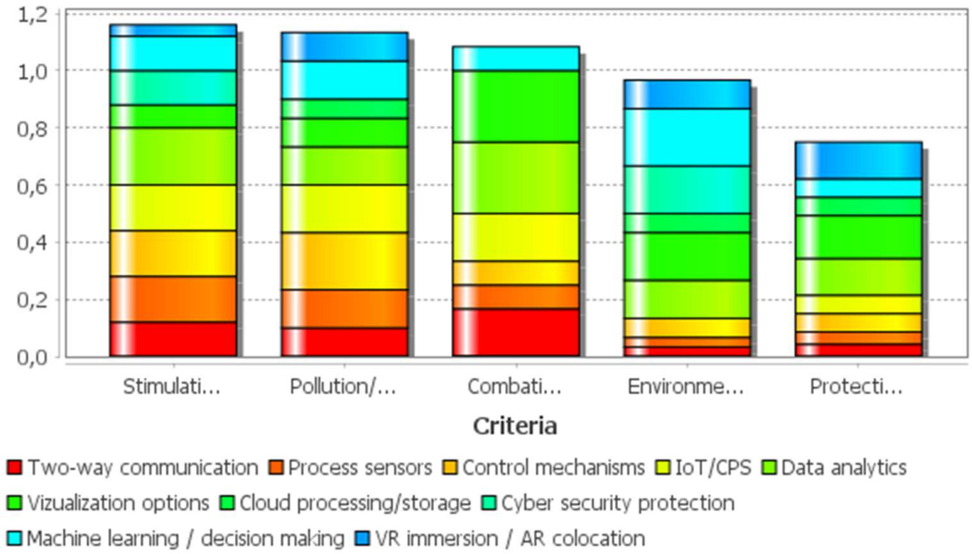

Figure 6. Impact assessment of digital twin attributes for environmental functions (subunit scale, compared elements indicated by color codes as provided by MCDA-KIT 7.6, own work).

In our approach, the software and hardware components of the twin are of similar importance to the architecture, the communication processes, and the key indicators used to assess results based on the collected big data from the actual production system. There should be a high degree of interchangeability in terms of the deployed solutions to allow flexibility and reconfigurability of the digital twin in line with the competitive constraints and the objectives of the company.

The authors hypothesize that a sustainability-oriented digital twin constructed on a structured technical concept can more easily undergo changes and upgrades in the future. This is critical for manufacturing in a more stringent way than in other sectors where digital twins are deployed (e.g., utility grids, climate modelling, or building information management) due to the need to control the variability of the processes. With very slim financial margins and growing competition, manufacturers rely on maintaining high volumes of production due to stable and capable processes, with as little variation as possible. Any twinning solution to be implemented should not change this situation, but it should be, at the same time, open to technological progress.

4. Discussion of the Alternatives

The authors of this paper believe that the research methodology employed is a robust and creative one that is capable of delivering sound and interconnected results that can be used in software solution development, applied research, and policy-making for the manufacturing sector. Each of the five steps of the demarche is underpinned by comprehensive and impactful instruments (a critical review of over 40 articles, two well-known idea management tools, and two software-based analysis/synthesis efficient implements). In this way, the intermediary and final results are kept aligned with the goals of supporting sustainable manufacturing and increasing competitiveness at the same time with protecting the environment.

Most of the requirements analyzed through the MCDA reveal the need to innovate in terms of the functions, attributes, and capabilities of the digital twin solutions, in such a way that they can deliver a sustainability-related impact by processing the proper types of data and implementing organizational, technological, and analytic changes within a company and its systems and processes. For achieving this result, the authors have used the TRIZ (Theory of Inventive Problem-Solving) method as it is implemented by the www.triz40.com platform (accessed on 25 May 2022) [46]. The method involved generalizing the conflicting attributes in terms of generic inventive principles, selecting the adequate response from the options offered by the database of the methodology, and converting it into proper changes to be deployed within the twinning solution. As mentioned in the analysis, the focus will be on the functions of the twin that can ensure its integration into large-scale initiatives intended to reduce the environmental impact of pollution, waste, discharges, and carbon emissions. This is due to the fact the resource consumption and energy efficiency, which are already connected to the economic aspects of running a digitalized production company, can be considered satisfactorily addressed by existing solutions, although some issues can still be improved: the length of the supply chains, the mix of renewable and fossil sources, the social implications of globalized business, etc.

The table below (Table 2) shows the results of the analysis of the main interactions studied and ranked attributes and their associated TRIZ parameters, together with the solution provided by the site from the contradiction matrix. As it can be seen, there is a number of 13 distinct solutions that can be implemented to achieve the desired transformation. They can respond to the conflicts between the ranked attributes of digital twins (which are technical in nature) and their observance during the implementation of the solution will yield environmental-related functions in an emergent manner, also responding to TRIZ generic features, which are used as guidelines. This process should be performed either upon the existing digital twins on the market (commercial solutions that are usually customized for each production facility) in a new development cycle, or it should form the basis when developing a local approach in a certain company with a specific production system, but with a strong orientation towards environmental performance (in-house dedicated digital twin solutions).

The following discussion will address the specific provisions of adapting the TRIZ solutions to the studied domain, through the lens of the steering feature:

- Solution 1 Segmentation and Solution 7 Nested dolls point to an open architecture of the digital twin platform both in the real and the virtual sides, allowing for adding various sensors and cyber physical devices in connection with the adequate software tools to process the data, and for reducing resource consumption, waste, and pollution;
- Solution 28 Mechanics substitution, Solution 32 Colour changes, and Solution 35 Parameter changes can be translated into reality by changing the functionalities of the twins from monitoring and informing human operators to fully automated systems based on machine learning and artificial intelligence, in real time and with a frequency of intervention suitable for obtaining the desired environmental performance in abnor-

mal and emergency situations, which are usually above the possibilities of a person to respond;

- Solution 15 Dynamics, Solution 21 Skipping, and Solution 34 Discarding and recovering must be implemented at the level of individual components of the twin to perform decentralized tasks, as is the case in fog computing devices and distributed sensor networks, which can help in implementing subsidiarity (i.e., solving the environmental issue as close as possible to its source);
- Solution 10 Preliminary action and Solution 11 Beforehand cushioning are related to the preparation process that is necessary for any digital twin deployment that should involve detailed determinations in the actual production system, which can include 3D scanning of the location, identification of equipment reliability issues, assessment of the process variability, and full material/substance balance, thus facilitating the tracking and reduction of environmental-impact-causing elements at system level, where impacts can suffer from compounding effects;
- Solution 13 The other way round, Solution 22 Blessing in disguise, and Solution 31 Porous materials also address the situations in which digital twins can be simplified to the state of ready-made solutions that can be implemented with minimal effort in any company; for example, in small- and medium-sized firms that might not have all the necessary know-how, but still need increased environmental performances.

Table 2. TRIZ40 Platform [46] solutions for the identified digital twin attributes contradictions (numbers indicate the reference generic feature or inventive principle).

Nr. Crt.	Conflicting Attribute 1 and TRIZ Association Feature	Conflicting Attribute 2 and TRIZ Association Feature	TRIZ Contradiction Matrix Solution Principles	TRIZ Feature Guiding the Digital Twin Environmental Function
1	Data analytics 39 Productivity	Visualization options 33 Ease of operation	1 Segmentation 28 Mechanics substitution 7 Nested dolls 10 Preliminary action	19 Use of energy by moving 20 Use of energy by stationary 22 Loss of energy 23 Loss of substance
2	Process sensors 37 Difficulty of detecting	ML/decision-making 38 Extent of automation	34 Discarding and recovering 21 Skipping	
3	Cyber security protection 30 Object-affected harmful	Two-way communication 35 Adaptability or versatility	35 Parameter changes 11 Beforehand cushioning 22 “Blessing in disguise” 31 Porous materials	27 Reliability 30 Object affected harmful 31 Object generated harmful
4	Control mechanisms 33 Ease of operation	Data analytics 39 Productivity	15 Dynamics 1 Segmentation 28 Mechanics substitution	24 Quantity/Quality of substance 15 Durability of moving object 16 Durability of non-moving object
5	IoT/CPS 28 Measurement accuracy	VR immersion/AR collocation 34 Ease of repair	1 Segmentation 32 Colour changes 13 The other way round 11 Beforehand cushioning	35 Adaptability or versatility 38 Extent of automation 39 Productivity

5. Conclusions and Outlook

Digital twins are a welcome development in the field of digital manufacturing, with many important and useful applications. Since environmentally sustainable requirements are increasing upon manufacturers, it seems fitting that digital twins should also transform to incorporate solutions for companies attempting to become greener in their approaches to products and processes. The work presented above investigates this correlation and the means to transform this potential into concrete solutions to be implemented by software companies that develop twins for real production systems, or firms that create their own local combinations.

By relying on such analyses, the results that can be accomplished will have an increased usability and will produce a faster return on the investment. The process of steering the development of digital twins in a strategically sound direction that makes use of advanced computing and sensor technologies, while solving important environmental issues, has the possibility to transform the manufacturing sector into one of the champions of the new net-zero carbon economy. The same idea holds true and is implemented on a large scale in smart cities and homes and in precision agriculture, with the production sector being forced to keep up with the new economic and social paradigm that is taking shape in the present.

Environmental issues are not yet in the focus of manufacturing, due to the competitive pressures on production companies to deliver quality products at lower and lower costs. Among the guidelines to be revealed by the study, we mention the following functions that can present interest to companies and, therefore, should also be approached by twin solution creators:

- Analysis and monitoring of material input and outputs.
- Real-time tracking of waste, emissions, and discharges.
- Product lifecycle management with live cloud database connections.
- Assessment of the circularity potential and achievements.
- Quantification of greenhouse-gas emissions, effects, and synergies.
- Reporting based on mandatory and voluntary schemes.

When combining the digitalization capabilities of digital twins with environmentally sound practices, the beneficiaries will gain the ability to diminish their impact on nature, which is one of the main challenges of our times. The work presented in this paper is meant to create the logic foundation for deploying advanced forms of digital twins in production companies, to achieve sustainable results, including both environmentally friendly processes and products, and robust contributions to global challenges, especially in the light of the current efforts to decarbonize the economy and to limit the effects of climate change induced by all economic sectors.

The framework developed builds upon the features of commercially and academically relevant solutions and incorporates synergy stimulation across industries and companies, helping to provide common answers to common problems, in line with the guidelines laid out in [47]. At the same time, the elimination of the technical elements as the driving force of the twining solutions fosters continued development and growth, as well as reduced variability and increased leanness of the manufacturing systems while satisfying complex stakeholder requirements.

As a consequence, the research presented in this paper will be further validated within the industrial context in which our host institution operates. The companies that we cooperate with, which are in the course of digital twin solution implementation, will be approached to become part of a pilot study dedicated to the addition of environmental functions. This process is expected to contribute to the refinement of the approach and to the capability to calculate and report upon concrete key process indicators, such as impact on productivity, cost vs. benefits vs. return on investment, and waste/pollution/carbon discharge from production systems.

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