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Digital Twin for Next Generation Manufacturing Company: From a Decision-Based Design Perspective

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Abstract

A successful high-tech design and manufacturing company should account for innovative technologies to improve product quality, meet the increased need for customized products, and reduce manufacturing time. To address the challenges faced in the manufacturing domain, a digital twin technology can be considered. This technology replicates the physical manufacturing process, which enables the designers to analyze the process efficiency and equipment health by considering real-time data. A digital twin can respond to changes at any stage of the process and deliver predictive outcomes, which aid in the creation of customized products. To enhance the efficiency of digital twins we can integrate them with decision-making approaches, which support continuous changes and adaptability to new technologies. This essay discusses how the use of a digital twin in conjunction with decision-making processes might potentially benefit futuristic manufacturing companies.

1. Introduction

For a manufacturing company to establish itself as a high-tech global company in the year 2040, it must have a clear understanding of the changing needs and technological advancements and keep abreast with changing needs and technological advancements. In a manufacturing company, a wide range of technological advancements and processes are used to transform raw materials into final products. Artificial intelligence, machine learning, automation and robots, data analytics, and the Internet of Things (IoT) are some of the more contemporary manufacturing technologies. With the advent of all these technologies a new era of manufacturing has emerged called Smart manufacturing [1]. The concept of digitalization and digital twin in the manufacturing domain has been enabled by the usage of many technological advancements like the Internet of Things (IoT), smart sensors, cloud computing, and machine learning [2]. The concept of digital twin has been in existence for decades [1], and adapting this concept to the manufacturing domain is still a challenge. A digital twin is a virtual representation of an actual physical model or process which helps to analyze the data and understand the performance of the product or manufacturing process [1]. They provide real-time data and predict the performance of the process or components and enhance adaptability and flexibility to changes. Some of the research challenges faced by the futuristic high-tech global company are mentioned below:

1. How effectively the process and equipment can be utilized in developing a product without affecting its quality.
2. To improve the maintenance of the tools or equipment and to effectively monitor their condition.
3. How to effectively facilitate new developments and innovations that are cost-effective.
4. How sustainably the resources are utilized.

In Figure 1. typical operations in the manufacturing company are shown, which includes deciding on raw materials, production planning, manufacturing process, quality control, assembly, inspection, delivery, and designing of the products.

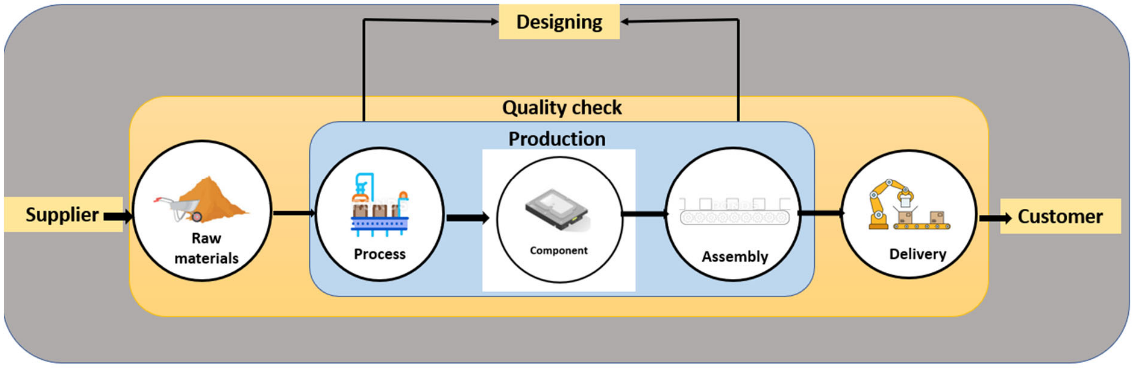

FIGURE 1. Typical Operations in Manufacturing Company

2. Need for digital twin in manufacturing company

In today's complex and evolving demands of customers manufacturing companies strive to meet the requirements with updated technologies. digital twins help accelerate new products or process development and monitor the condition of the equipment being used from real-time data acquisition. They can replicate any aspect of the process or component; they capture the data based on sensors in the physical product and process it with cloud or virtually augmented technologies. Using the digital twin in manufacturing helps improve the production process and understand the detailed performance of components from the individual component to the assembly stage. According to Shao and co-authors, [2] digital twin is a technology that depends on where it is being utilized and they called this a fit-for-purpose representation. This technology can be adapted at different levels of manufacturing like a component level, assembly level, integration level, or the entire process level. The representation of digital twins at different levels and characteristics that can be studied is shown in Figure 2.

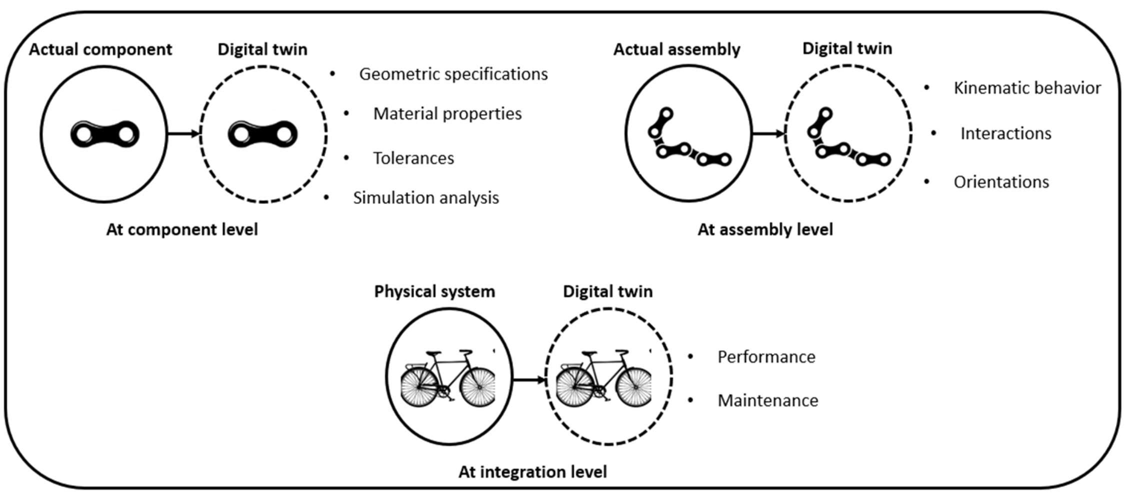

FIGURE 2. Digital twins at different levels

At the component level, the digital twin replicates individual components, this facilitates understanding the behavior of the component, and mechanical properties and forecasts the corrections required before finalizing the component. Assembly level consists of many components and employing digital twin at this level facilitates the understanding of component's interaction and how they behave under certain circumstances. At the integration level, a complete physical system is replicated to understand the performance of the product when finalized and how it affects its performance when it is subjected to changes. digital twin provides the flexibility to adapt to changes at any stage, enhance new product development, and helps understanding the product performance.

2.1 Integration of cyber-physical system with digital twin

Cyber physical systems are the one which connects physical systems with intellectual systems for accessing the information [3]. Using digital twins with cyber-physical systems enhances the efficiency of smart manufacturing. Smart manufacturing consists of IoT, Robotics and automation, cybersecurity, data analytics, and artificial intelligence.
IoT (Internet of Things): Sensors and actuators using IoT can be used to acquire the real-time data of the components which can be fed to the digital twin model. Facilitates the interconnection of the components and aids in understanding the data flow between the levels.
Robotics and Automation: When used in combination with digital twins they help understand which process needs to be repeated and reduce human errors and production time. Monitors the condition of robotics, and their behavior with the machinery, and optimizes the production process.
Cybersecurity: As the digital twin includes data communication between different components and levels, it becomes vulnerable to cybersecurity threats. It is necessary to ensure the data used is secured and encrypted to protect the company's integrity.
AI (Artificial Intelligence): The data collected from digital twin when integrated into AI algorithms provide predictive analyses of the equipment failure and the relation between the data across different levels. With the help of AI, the models can be modified over time to improve the performance or quality of the product or process.

3. Need for Decision-Based Design

A complex system of manufacturing consists of multiple interactions across different levels, conflicting design requirements and uncertainties in the system. There could be uncertainties in the system due to a variety of factors, including human error, flaws in the manufacturing process, or natural variability. The robustness of a system is defined as a system that is relatively insensitive to uncertainties. From a simulation-based design standpoint the challenges faced in complex manufacturing systems can be addressed from Robust design framework. Considering deterministic models in manufacturing does not provide the desired solutions with respect to real-world data, because in the deterministic approach, the randomness in the system is not considered. Manufacturing processes involving different types of uncertainties should always consider the randomness in the system to obtain a performance that is close to real-world data. Some of the of uncertainties that might occur are mentioned below,
Customer demands: Sudden changes in customer requirements may affect the planning and process of manufacturing, which must undergo many iterations to meet the demands.
Disturbances in the supply chain: The supply chain consists of vendors, suppliers, and logistics and these are connected if any disturbances at any level will interrupt every level.
Variability in the process: During the manufacturing of a component there might be variations in the process itself or variations in the raw material or conditions operated.
Sudden failure of equipment: When an equipment failure occurs, it disturbs the entire production and affects the company economically.

To manage all these unpredictable uncertainties, we need an efficient framework that addresses this issue. From a systems design standpoint, we see design as a decision-based, simulation-aided process. As a result, we adhere to the Decision-Based Design (DBD) paradigm, in which designers make choices based on the facts at hand [4]. The Decision Support Problem Technique in DBD [5, 6]. which is based on Herbert A. Simon's theory of bounded rationality [7], is the fundamental basis. A "satisficing solution" [8] is one that "satisfies" and "suffices" the needs of the designers for the conflicting design requirements. Given that the manufacturing process is a complex system, a robust framework is considered. The DBD framework consists of the following steps, *Step 1*: The design variables, constraints and requirements are identified. *Step 2*: Once the required factors and ranges are identified the next step is Design of Experiments (DOE), DOE is done to find the design points at which the simulation can be carried out. *Step 3*: Next the finite element analysis is carried out to generate the data for building surrogate modeling. *Step 4*: Surrogate models are the approximate models of the actual model and are used to get the design space for the system. *Step 5*: Next robust compromise Decision Support Problem (cDSP) is used with DCI (Design Capability Index) and EMI (Error Margin Index) constructs [9] to address the issue of uncertainties in design variables and the system itself. cDSP is a combination of goal and mathematical programming and consists of four key words Given, Find, Satisfy and Minimize. cDSP helps minimize the deviation function from the goals and different weight scenarios are exercised for formulating the cDSP. *Step 6*: Once the solutions are obtained from the cDSP the next step would be visualizing the solutions and identify the feasible solutions that meet the design requirements, a machine learning based visualization technique called iSOM (interpretable self-organizing maps) is used. In this essay, the digital twin concept for manufacturing companies is integrated with a DBD robustness framework. In Figure 3. the working of the digital twin in conjunction with decision-based design is shown. In this figure the physical system is connected with cyber-physical technologies, the data collected from these system is sent to digital twin where the digital replica of the physical system is developed which helps monitoring the system, and this integrated with decision based design to improve the efficiency of manufacturing process.

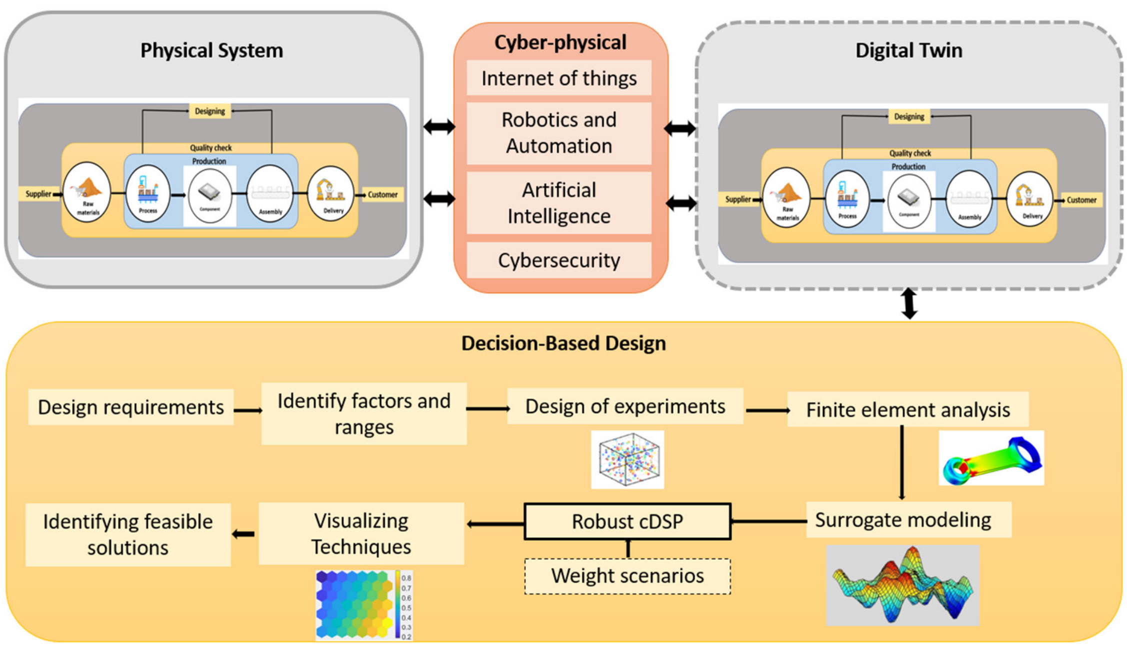

FIGURE 3. The architecture of digital twin with decision-based design

3.1 Advantages of integrating the digital twin with decision-based design framework

- As the framework addresses the robustness of the system and provides real-time data using digital twin, it improves the quality of the product and manufacturing process.
- Elevates the manufacturing process as it can be virtually prototyped with digital twin to understand the variation, find the feasible solutions through robust design framework where the variations do not alter the process.
- Eventually reduces the manufacturing time as the number of iterations of simulation is reduced.
- Can easily predict the performance of the product with the help of digital twin and address the variations occurred with the help of the robust design framework.

4. Futuristic composite manufacturing company – As an example

Composite materials are used instead of conventional metals in the aerospace, automotive and many other industries due to the demand for high-strength and lightweight properties. Composite materials are a combination of fibers (like carbon or glass) and resin matrix (like epoxy). Initially they were only used in secondary components, but now they are now used in core application components as understanding and development of the materials have progressed. In order to keep up with the demand for composite materials, the manufacturing company must become more productive and efficient. digitalization and cutting-edge technologies must be incorporated into the composite production process to meet the demands. As discussed in this essay there is need to implement the idea of using digital twins in manufacturing process along with the decision-based design approach. To begin, it is necessary to comprehend the characteristics of successful high tech Composite manufacturing company in the year 2040:

- Focused on sustainability as it makes sure that the manufacturing process employed reduces waste generation and increases recyclability.
- Operating as a worldwide manufacturing organization, improving technological partnerships and collaboration with other industries to broaden consumer reach.
- Increasing flexibility and customization to fulfill the diverse requirements of customers while also adapting to agile methodologies for market trends.

A Composite manufacturing company in 2040 must face numerous research challenges to keep up with innovation and remain at the forefront of the industry. Some of the potential research challenges are mentioned below,

- To increase the robustness of the materials without sacrificing quality, and to establish standards for material reliability, durability, and performance.
- Develop virtual prototyping to anticipate performance and employ improved composites process methods.
- Understanding the behavior of materials across different levels of manufacturing processes to improve performance.
- To enhance the automation for methods used in composite manufacturing to reduce human errors and increase mass production.

In the domain of composite manufacturing, prepreg (composite sheets in which the fibres are pre-impregnated with resin) fabrication is crucial since the component's quality, mechanical properties, and performance are all influenced by the fabrication process. Prepregs are commonly employed in composite manufacturing due to the numerous advantages like good mechanical properties, uniformity, and easy handling. Understanding the steps involved in composite manufacturing is crucial to comprehend the difficulties encountered in this process, and those steps are listed below.
Step1Prepreg Layup: First, the prepreg sheets are spread over the mold in various orientations depending on the component created, and this process demands a lot of human work and is entirely dependent on human skills.
Step 2 Vacuum bagging: This step entails removing the vacuum before curing to eliminate voids and maximize resin flow; this procedure also requires human intervention and might be repetitive.
Step 3 Curing: This step involves curing of prepregs and is carried out in autoclave to harden the composite and this done at specific temperatures and pressures based on manufactures requirement.
Step 4 Post curing: This is an additional step based on the component application, some components may need additional curing involving high temperature and pressure to enhance the properties of material.

The process of composites fabrication involves many challenges and uncertainties. To address these issues and provide robustness in the manufacturing process, the conjunction of digital twins (DT) with DBD is necessary.

Need for digital twins: Robotics and digital twin help speed up the tedious and repetitive hand layup process, which is very time-consuming and labor-intensive. Additionally, the virtual prototype provides details on the ideal fiber orientation to improve performance. During the curing process they present real-time data monitoring of equipment and component; they receive the data input from IoT utilizing sensors that can measure pressure and temperature. This aids designers in closely observing component performance and identifying required temperature and pressure values necessary for adjustment. They also simulate the curing process for different scenarios and evaluate the quality and performance of the component. With the use of digital twin, designers may continuously evaluate the state of the machinery and the curing process, look for any faults, and take necessary corrective measures when required.

Need for Decision based design approach: Finding satisficing solutions that meet the design requirements are frequently hindered by conflicting design objectives and uncertainties; however, using decision support tools and the EMI and DCI frameworks outlined above can help achieve the desired outcomes. During the process of hand layup there might be uncertainty in the material or the process itself, to address this issue we can use cDSP with mathematical constructs (EMI and DCI) to understand the variation of material properties at different levels of process and considering the variations in fiber uncertainties. During curing process variation might occur in temperature, pressure or curing time which effect the mechanical properties of the component, so there is need for robust curing process which still satisfies the design requirements even in the presence of certain parameter variation and this can be achieved using cDSP Decision based design approach. In Figure 4 the physical model consisting of hand layup and vacuum bagging process is connected to robotics system which automates the hand layup and vacuum bagging process to reduces the human error, the process then is virtually prototyped using digital twin to understand the features of the process like orientations of the fiber, how material properties vary, extent of tolerances allowed and analyzing the condition of equipment's. And next the process is integrated with decision-based design robust framework addressing the uncertainties in material or process. In Figure 5 the autoclave curing physical model is connected to Internet of Things through sensors which help in fetching the real time data from the material during the curing process and this data is used by digital twin to monitor the condition of the component and analyze the efficiency of curing process. Next, the process is integrated with decision-based design robust framework considering the uncertainties in temperatures and pressures during curing process. Using the decision-based design robust framework the feasible robust parameter values for temperature and pressure can be obtained, through which the efficiency of the curing process is enhanced.

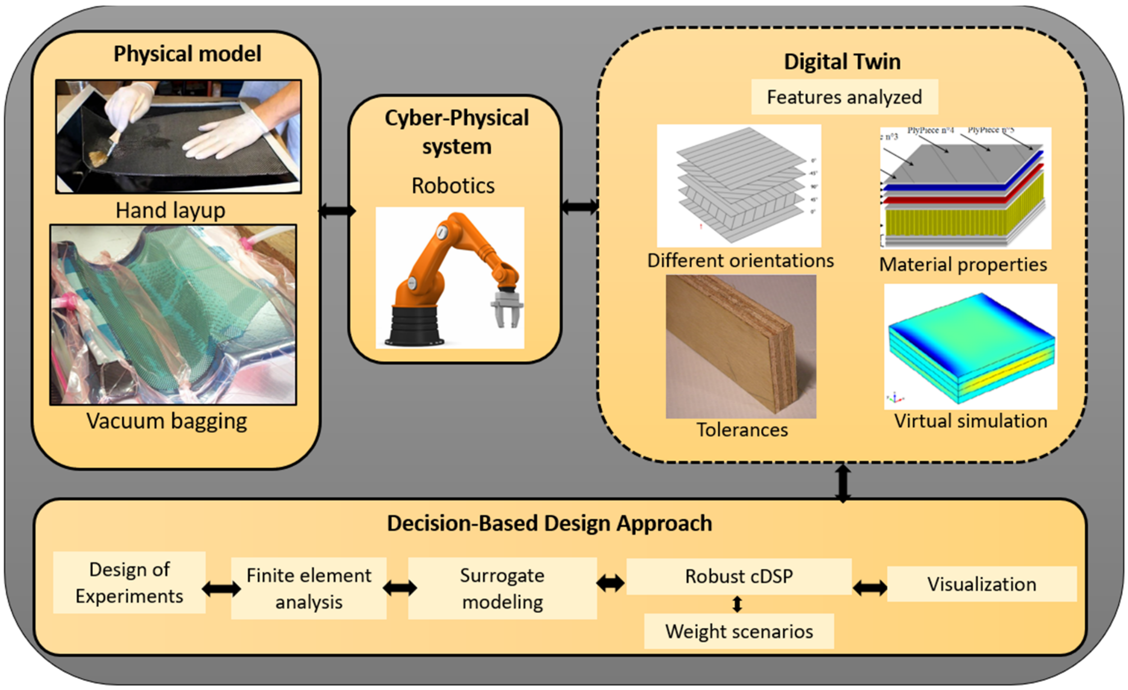

FIGURE 4. The architecture of digital twin with decision-based design for fabrication process

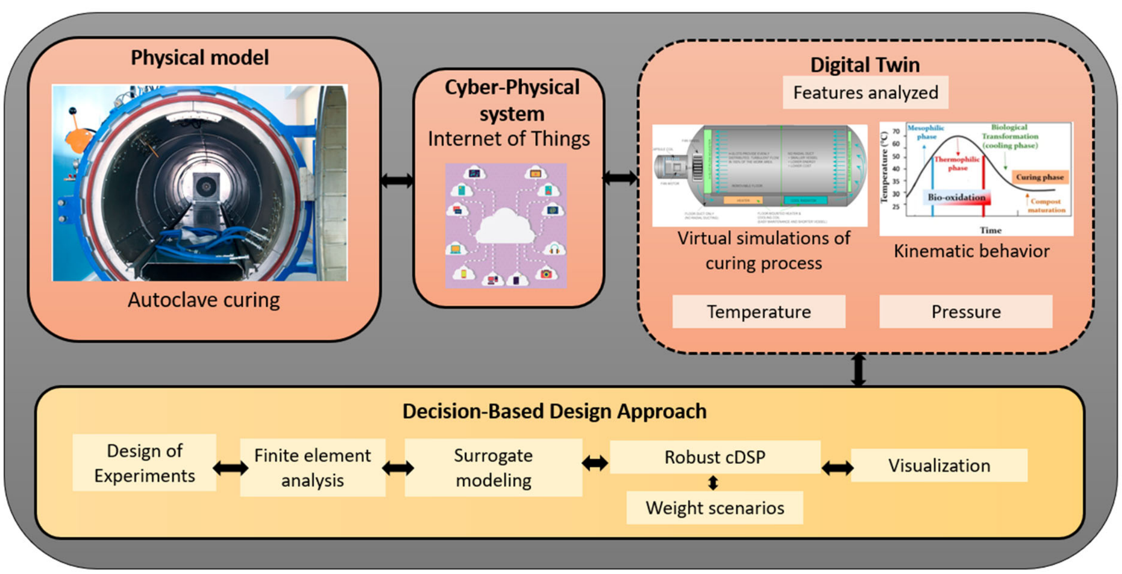

FIGURE 5. The architecture of digital twin with decision-based design for autoclave curing

5. Closing Remarks

A high-tech global manufacturing company should be ready to adapt to the advancements in the technologies and meet the diverse needs of the customers. With the increasing demands in the market the company should be open to collaboration with other companies to enhance the manufacturing process and quality of the product. Futuristic high-tech company should give importance to the agile technologies as it increases the flexibility of changes occurring at any stage of the manufacturing process. It is needed to emphasize sustainability and use environmentally friendly methods in manufacturing companies to reduce the negative impact on the environment. Additionally, increase the connectivity of the data across different levels to enhance the understanding of interactions within the complex manufacturing systems. Moreover, high tech companies should focus on enhancing the skills of the employees and keep them updated with innovative technologies. Finally, integrating the digital twin with a decision-based design robust framework allows a high-tech manufacturing company to improve its manufacturing process.

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