Benefits of Digital Twin Applications used to Study Product Design and Development Processes

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Abstract. Fast-paced technological advancements and ever-growing demand for customized products trigger the need for a transition from traditional manufacturing to intelligent manufacturing. This review paper focuses on identifying the benefits of Digital Twin applications for the theme of product development processes. Benefits are analyzed according to the 10 knowledge areas defined by the Project Management Institute's project management body of knowledge (PMBOK). Classification by knowledge area helps to understand where benefits can best be found according to desirable product characteristics and corporate goals. This paper analyzes which PMBOK knowledge area has proven, practical applications and sound theoretical underpinning, thus indicating the likelihood of a successful implementation of Digital Twin.

Keywords: Product Development Process, Digital Twin, Digital Twin Benefits

1 Introduction

Transition to intelligent manufacturing has become a priority for various enterprises due to the advancement of technologies such as Digital Twin (DT), artificial intelligence, cloud computing, and the internet of things [1]. The advent and development of DT technology as a tool to facilitate the shift to intelligent manufacturing has gained remarkable attention in recent years [2]. Moreover, there is irrefutable growth in the application of DT in the manufacturing industry [3]. However, the use of DT brings many challenges such as IT infrastructure requirements, quality data requirements, privacy and security, trust, lack of a standardized modeling approach, and more importantly, financial feasibility studies of DT applications [4]. Therefore, the current paper focuses on the benefits of DT applications for decision-making.

The rest of this paper is organized as follows. The background on DT applications in product development processes (PDPs) is given in Section 2. Section 3 has the method for article selection. Section 4 discusses findings and the relationship between DT application benefits and the Project Management Institute's project management body of knowledge (PMBOK). Finally, Section 5 presents conclusions. The main contribution of this paper is to identify the benefits of DT applications in the manufacturing and mapping the benefits to different knowledge areas to assist managers in dealing with challenges in shifting to smart manufacturing.

2 Background

In Sub-Section 2.1, a generic summary of the PDP is presented. As the major objective is to analyze the benefits of DT applications in PDPs, a quick introduction to the concept of a DT is provided in Section 2.2. Following is the literature review of DT applications in PDPs in Section 2.3, and the introduction of PMBOK knowledge domains as the classification method of the literature review is offered in Section 2.4.

2.1 Product development processes

PDPs are a sequence of activities to create, design, and market a product. The six phases are planning, concept development, system-level design, detailed design, testing and refinement, and production ramp-up. We analyze the use of a DT model where the benefits can be from the PDP lifecycle or a single phase.

2.2 DT concept

A physical product, a virtual product, and their connections make up the three primary components of the DT concept [5]. It was introduced by Grieves as a "Conceptual Ideal for Product Lifecycle Management (PLM)" demonstrating the connection between real and virtual spaces [6]. Liu et al. described DT as a digital entity that replicates a physical entity's behavior rules and is updated during a real entity's lifecycle [3]. The application of DTs, especially in manufacturing, has grown significantly. DT has various applications such as assisting decision-making as well as simulating, monitoring, and elevating design performance [6].

2.3 Review of DT applications based on different classification methods

DT applications in product design and development processes have experienced significant growth in recent years [6]. Several authors have written review articles. The current paper presents an analysis according to the classification methods.

Lo et al. presented a general classification and stage-based categorization by research area including manufacturing, automotive, computing, energy, aerospace, etc. [6]. Stages of the product lifecycle (product design, manufacturing, logistics, use, and end of life) as well as stages of new product development (idea generation, market analysis, product design, testing, and commercialization) were introduced as two main approaches to investigate DT applications. Liu et al. classified DTs by product lifecycle stages, the content of literature including concepts, key technologies, paradigms and frameworks, and applications [3]. Kritzinger et al. carried out a categorical literature review by research type (definition, review, concept, and case study) [7]. Moreover, focus area (layout planning, product lifecycle, process design, manufacturing, and maintenance) as well as key technologies were also applied as categorization criteria. Phanden et al. analyzed simulation-based DT and DT-based models in aerospace, manufacturing, and robotics fields [8]. Fuller et al. presented smart cities, manufacturing, and healthcare applications [4]. They classified papers based on enabling technologies, such as the internet of things, augmented reality, artificial intelligence, etc. Zhang et al. reviewed integrated methods associated with DTs such as TRIZ, lean and green design to create a DT-driven, smart product design framework [9]. Hoiler et al. presented classifications based on industry (aerospace, automotive, manufacturing, …), literature domain (product development, manufacturing, lifecycle management, modeling and simulation, ...), and geographic distribution [10].

As shown in Table 1, the majority of review papers classified articles based on application domain or industry. Furthermore, categorizing papers based on PLM stages as well as enabling technologies were the most common criteria. However, an important factor has been neglected: identifying the benefits obtained from DT application in manufacturing and mapping the benefits to different knowledge areas that exist in each PDP. The current paper does this.

The PMBOK knowledge areas cover all stages of a PDP, all required tools, techniques, and outcomes; therefore, it is a more comprehensive manner to classify benefits. Moreover, classification based on knowledge areas provides a clearer way for decision-makers to find the proper solution for challenges they are facing when shifting to smart manufacturing.

Table 1. Literature review paper classification criteria

Authors	Year	Classification criteria								
		Application domain	Product life cycle stages	NPD stages	Enabling technologies	Frameworks	Article content type	Simulation modeling	Geographic distribution	Integrated methods
Lo et al. [6]	2021	●	●	●						
Liu et al. [3]	2021	●			●	●				
Kritzinger et al. [7]	2018	●	●		●		●			
Phanden et al. [8]	2021	●						●		
Fuller et al. [4]	2020	●			●					
Zhang et al. [9]	2020									●
Hoiler et al. [10]	2016	●	●					●	●	

2.4 PMBOK project management knowledge areas

The Project Management Institute (PMI), the premier management organization in the world, uses 10 major knowledge areas of project management in their most influential guideline, PMBOK Guide. Each PMBOK knowledge area involves several project management processes and covers different parts of each process: requirements, tools, techniques, and outcomes. The 10 PMBOK project management knowledge areas are: integration, project scope, time, cost, quality, human resources, communications, risk, procurement, and stakeholder, which the authors used to map DT benefits [11].

3 Methodology in Research Selection

A systematic search was conducted to identify articles. The search was carried out in the Scopus, Google Scholar, and Science Direct databases. A comprehensive search was also conducted by our team in China's national knowledge internet and Engineering Village databases to obtain papers in the Chinese language. Collected articles were screened and refined through a three-step approach.

First, articles were selected via keywords and titles from 2017 to 2022. The search was focused on quality publications in journals, conference papers, and book chapters. Since our paper is centered on DT applications in manufacturing, different combinations of keywords that relate DT to PDPs were examined. In addition to DT, terms such as "virtual twin" and "cyber twin" were used. Selected papers were re-examined to ascertain that they included DT applications in PDPs. For the second step, a secondary source for articles used cited references from the articles selected in step 1. In step 3, from the papers collected in steps 1 and 2, articles were selected that specifically focused on DT applications and gave benefits for PDPs. Finally, 26 papers in English and 19 papers in Chinese were included in the classification.

4 Research Findings

4.1 Mapping DT application benefits to PMBOK knowledge areas

Given the methodology described in Section 3 articles are reviewed for the benefits of DT applications in product design and development. Benefits are mapped to knowledge areas based on the PMBOK definitions as shown in Table 2.

Table 2. DT application benefits as related to knowledge areas.

PMBOK Knowledge area	DT application benefit	Articles
Integration	Multidisciplinary collaborative design	[12-14]
	Analyzing the composition and integration of mechanical, electrical, and other subsystems	[15]
	Description of a DT's technical architecture	[16,17]
	Increasing product understanding	[18]
	Mechanisms and integration of assembly processes	[19]
	Physical and virtual cutting tool lab test platform	[20]
	DTs with integrated production knowledge	[21]
	Engineering product family design and optimization	[22]
Scope	DT applications in all stages of PLM	[17,20,23,24]
	Reducing the number of manufacturing operations	[25]
	DT applications for metalized film capacitors	[16]
	DT driven data flow for the cutting tool lifecycle	[20]
	DT applications for product design	[9]
Time (Schedule)	Minimizing debugging time	[12]

	Shortening the development lifecycle	[14,18,26,27,28-30]
	Reducing blade machining time by 26%	[31]
	Reducing design and operation time	[15]
	Optimizing design schedule	[16,24,32,33,34]
	Shortening assembly time to 46%	[19]
	Improving combat command efficiency	[35]
	Shortening personnel training time	[36,37]
Cost	Minimizing total cost	[12,16,18,38]
	Reducing physical validation cost	[27]
	Reducing maintenance cost	[33]
	Developing a cost estimation model	[39]
	Cost effectiveness validation	[40]
	Cost effective solutions using DT technology	[38]
	Logistics precise distribution	[24]
Quality	Improving product quality	[26,38,41]
	Increasing machining precision by 23%	[31]
	Improving inspection	[25]
	Decreasing the defective rate of products	[25]
	Monitoring equipment online	[24]
	Intelligent maintenance	[29]
	Optimizing the quality of an entire system	[42]
	Improving model accuracy	[35]
	Tracking vibration and surface quality of a fixture	[12]
	Solving quality specific problems	[43]
	Improving DT accuracy	[44]
	Reference model for factory construction quality	[30]
Human Resource	Involving process personnel in developing a real DT	[31]
	Describing human resources role in DT development	[31]
	Reducing the number of workers	[25]
	Effect of human resource knowledge	[28]
	Effect of personnel position	[36]
	Effect of macro-supervision and precise supervision	[45]
Communications	Communication connection	[19]
	Intelligent decision-making through real-time output	[35]
	Communications for interaction between physical	[46]
	Communication operating modes	[47]
Risk	Finding types of component failures	[48]
	Identifying high failure rate subsystems	[49]
	Reducing the risks for new conceptual products	[50]
	Condition monitoring and providing early warnings	[16]
	Addressing future challenges of DT applications	[21]
	Improving reliability	[33,51]
	Decreasing maintenance frequency	[33]
	Predictive maintenance	[40]
	Improving maintenance and repair processes	[38]
	Future predictions	[38]
	Improving the success rate of innovative design	[34]
	Predicting stability	[43]

	Identifying problems in the design to make process	[37]
Stakeholder	Logistics precise distribution	[24]
	Increasing customer satisfaction	[32]

4.2 In-depth analysis

A framework based on DT for smart development processes was created using 45 articles of which 20 articles built an actual DT model and 9 presented simulation results of a real-world DT implementation and compared results to statistically support benefits. Furthermore, articles that built an actual DT model provided more benefits in multiple knowledge areas. Benefits are categorized qualitatively, e.g., increased product understanding, and quantitatively, e.g., machining reduced by 26%. Fig 1 gives the number of articles that cover each knowledge area using data from Table 2. Fig. 2 gives the number of benefits for each knowledge area based on Table 2, where an article can have more than one benefit and benefits can be in more than one knowledge area.

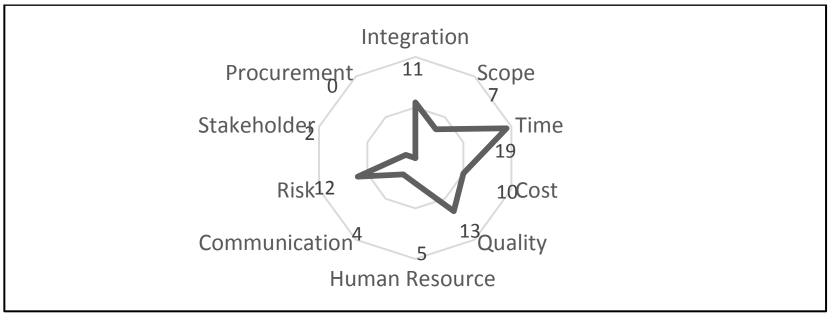

Fig. 1. Number of articles in each PMBOK knowledge area

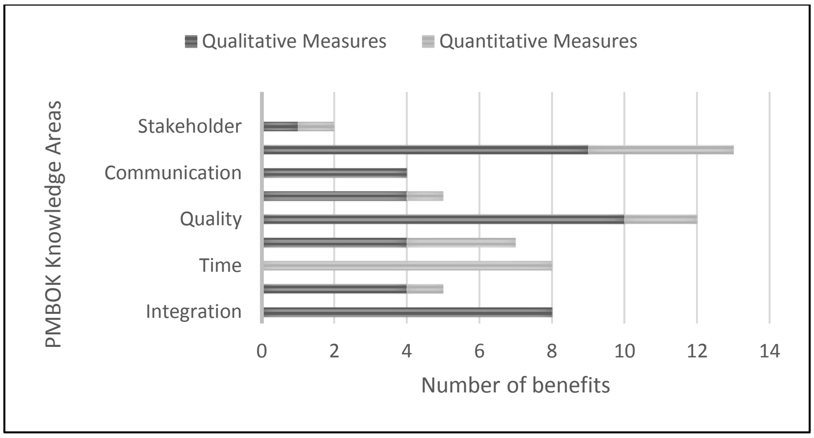

Fig. 2. Qualitative and quantitative measures of DT application benefits

From our point of view, time, quality, and risk are not only the most used knowledge areas, but also the most important. Time has the most articles (19) with proven benefits (Table 2) and all such articles are quantitative. Conversely, procurement, communication, and stakeholders areas seem to be neglected by researchers. Nevertheless, these areas seem useful for a decision-making team to decide whether DT could assist them in their challenges.

5 Conclusion and Future Directions

The main goal of the current paper is to facilitate the process of shifting to smart manufacturing by decision-makers. To facilitate this goal, first, this paper made an endeavor to find the articles with benefits for the application of DT to PDPs. Second, the paper mapped the obtained benefits to PMBOK knowledge areas. The PMBOK knowledge areas cover all aspects of a PDP; therefore, decision-makers that deal with challenges in the transition to smart manufacturing can find examples in their area of interest and understand how the benefits were achieved. This should help decision-makers to know the likelihood of being successful in shifting to smart manufacturing based on the knowledge area in which the company faces challenges. The knowledge areas with the most research were time, quality, and risk. There were few DT studies in the procurement and stakeholder knowledge areas, which highlights areas where more research could be done. Moreover, one of limitations of the study is that the frameworks, techniques, and tools used to achieve benefits are not discussed in detail.

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