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A Proposal to Elucidate the Net Benefits of Digital Twins in Electrical Generation Facilities: An IS Success Perspective

Short Paper

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Abstract

The rapid integration of industrial Internet of things (IoT) technology has enabled widespread adoption of digital twin (DT) technologies. The work herein proposes to understand the net benefits of the DT technologies using the IS Success model. We propose to conduct interviews and surveys of DT users at industrial gas turbine electrical generation facilities to gain a better understanding of the costs and benefits of DTs in electricity generation. In doing so we will revise and the IS success model with the latest research on technology use and extend it to DT technologies.

Introduction

The concept of digital twinning is currently undergoing a period of widespread adoption in a variety of industries. The estimated global sales from this technology was 8 billion USD in 2022 with a projected growth rate of 25% from 2022 through 2032 (Global Market Insight, 2023). These billions of dollars represent only some of the costs associated with DTs, while others remain unknown. Similarly, not all the potential benefits of DTs are known. This research seeks to understand these net benefits by investigating the net benefits of DT technologies.

DTs represent a fundamentally new approach to physical systems management. They consist of a "a physical entity, a virtual counterpart, and the data connections in between" the two (Jones et al., 2020, p. 36). This physical entity is often a physical piece of equipment, such as an electric motor, that is part of a larger physical system, such as a cooling system. In some instances, the DT may represent the entire system itself, where the system is comprised of all the discrete components. The DT is a virtual representation of the physical entity and is kept up to date on the state of the physical entity by continually monitoring the state of the physical entity and sending that information to the virtual environment that contains the DT. The information on the state of the physical entity may contain performance, maintenance, and health status data (Madni et al., 2019).

The central difference between a DT and earlier concepts of component modeling is mainly the real-time updating of the DT through IoT technology. The DT is a virtual representation of a physical reality, in both a time and spatial sense. By modeling many different physical entities at the same time, a whole system may be modeled. For example, a crane's position, wind loadings, motors, cable tension, and other components may be measured in real time to create a DT of the crane and model an attempt to lift an object.

While the benefits of DTs are clear, they have many costs associated with them that are less clear. For example, software is not a static asset. Continual maintenance is needed to ensure fidelity and usability is maintained. This can be accomplished through service contracts or in-house teams, but these costs must be factored into net benefits. Thus The following research questions are proposed for investigation into this concept: (1) What are the net benefits from digital twinning? (2) Are the net benefits of digital twinning significant enough to be economically viable? This proposed research will be the first known attempt to determine and document the net benefits of DTs in an organization.

To understand the net benefits of DTs we employ the IS success model (Delone and McLean, 2003). The IS success model is ideal for understanding the net benefits of DTs as it has been used in the past to understand innovative and now commonplace technologies such as ecommerce (Wang, 2008) and cloud computing (Flack and Dembla, 2021; Lian, 2017). The IS success model is well accepted in IS research, with hundreds of papers having employed it to understand the net benefits of many different technologies under a variety of circumstances. DTs offer a unique test for the IS success model. The study proposed here will be at an industry association of energy producers based in the United States. More specifically, we will be reviewing the efficacy of DTs applied to industrial gas turbine electrical generation facilities. DTs both take in and produce data that is consumed in heavy industry by machines. We can find no examples of IS success being used in such industrial environments.

The rest of this paper proceeds as follows. First, we review the literature on DTs and IS success. In this, we analyze components of the IS success model to understand what the drivers are of DTs. Next, we propose qualitative and quantitative methods to gather data on DTs at the target organization. Then, we give possible contributions to theory and practice of this research.

Literature Review

Digital Twin Benefits

Much research has been done into the benefits of DTs. Some of the proposed/evaluated benefits include design time reduction, predictive maintenance capabilities, and immersive training. The throughline for all these benefits is that once a DT is implemented, mistakes can be made in digital space rather than in physical space. Understanding the net benefits of these systems is a foundational question, as many companies are deciding whether to roll out DTs systems. Note, the benefits discussed here represent a subset of the total benefits provided by DTs; these were chosen to be discussed due to significant research efforts in these areas.

The first benefit, predictive maintenance**,** of DTs is likely the best understood and most heavily studied. This maintenance methodology uses real-time data feeds, historical data, and advanced analytics to drive maintenance according to real physical needs rather than using a generic time-based strategy such as standard maintenance schedules or monthly/quarterly/annual downtimes. A well-functioning predictive maintenance system has the potential to have positive benefits, detectable on the balance sheet in many industries. To put this into perspective, Coleman et al. (2017) found that unplanned downtime costs industrial manufacturers an estimated $50 billion annually. This unplanned downtime would be heavily mitigated through a predictive maintenance system.

For instance, if fidelity to the physical component or system is maintained, then predictive maintenance is heavily simplified. In a critical process, a company would be unlikely to allow a component to run to failure, thereby necessitating maintenance prior to the end of life of a component. With a digital model, simulating run to failure is not an issue, thereby allowing an informed decision to be made with regard to maintenance on the physical component (Cattaneo and Macchi, 2019). Aivaliotis et al. (2019) investigated this item in the context of robotics manufacturing using a case study. In this instance, the authors were able to make predictions regarding remaining useful life of a robotic arm through the fusion of digital and physical data. Some researchers went a step further to provide a statistically meaningful evaluation of the benefits of using a DT for predicting remaining useful life in the context of a computer numerical control (CNC) machine (Luo et al., 2020). The use of a DT in this process was shown to greatly improve the prediction results.

The second benefit of DTs is immersive training. Individuals can be trained in an augmented/virtual environment, allowing them to work out nuances in repairs in a virtual environment and reduce possible mistakes on the actual repair. The DT is versatile in that a well-designed digital asset can be extremely multi-purpose. For instance, once the twin is built for design lifecycle or predictive maintenance, it can be modified for enhanced training applications. When paired with AR/VR, it can be a powerful tool for training applications. Strielkowski et al. (2022) present how this type of operator and maintenance training can be used in the energy utility sector.

The third benefit of DTs is design time reduction. DTs allow rapid prototyping in design space. While developing physical iterations can be costly and time consuming to build, a digital model can be created much quicker and easier (Lo et al., 2021). After design is complete, the information associated with the twin is available throughout the entire lifecycle of the asset. “The vision of the digital twin itself refers to a comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in all – the current and subsequent – lifecycle phases” (Boschert and Rosen, 2016, p. 59). All relevant information needed in design space is already present and adjustable in the DT prior to the manufacture of the physical twin. This allows rapid prototype of the system and provides the ability for cheaper optimization of design constraints.

Using DTs in design allows improved scalability, interoperability, expansibility, and fidelity (Schleich et al., 2017). These ideas are at the conceptual core of their proposed “reference model” for use in the design space. Guo et al. (2019) performed a case study about factory design using a modular DT approach. In this study, hidden design flaws were discovered and solutions proposed through use of the DT.

Digital Twin Costs

West and Blackburn (2017) provided cost estimates for Department of Defense’s Next Generation Air dominance aircraft DT development. These estimates were greater than 1 trillion USD. Although the estimates provided in this research are based on a fidelity that is impractical to implement, they do demonstrate the potentially massive upfront cost associated with this technology. Bowman et al. (2022) provide a nuclear industry use case that at least provides perceived cost benefit, even though a detailed cost/benefit analysis was not undertaken.

One of the most thorough cost analysis available on DTs is found in Portela et al. (2021) . This work investigated the cost benefit of utilizing a DT in the pharmaceutical industry across the lifecycle of a given drug. Here a twin implementation cost of $4 million per project is used as a baseline with the acknowledgement that this is representative rather than exact. Irrespective of these high implementation costs, the cumulative cost savings within a ten-year window were projected to be between $6.67 million to $13.34 million. This shows that although upfront investment may be high, the cost savings are so significant in some instances that it is well justified. The key savings were driven by a reduction in product development timeline, enhanced automation, enhanced quality, and regulatory benefits. Given the lack of peer reviewed literature and some contradictory results, it is not currently possible to come to a final decision on the net benefits of DTs in many industries.

IS Success

The update IS success model (Delone and McLean, 2003) remains a good way to determine the net benefits of a system (Petter and McLean, 2009). The model proposes that the net benefits of an IS may be predicted by the system quality, information quality, and service quality of the system. According to the model, the relationship between these constructs and net benefits are fully mediated by use of the system and user satisfaction with the system. The theoretical model is shown in Figure 1. Each component of the theoretical model will be discussed and adapted to the DT context.

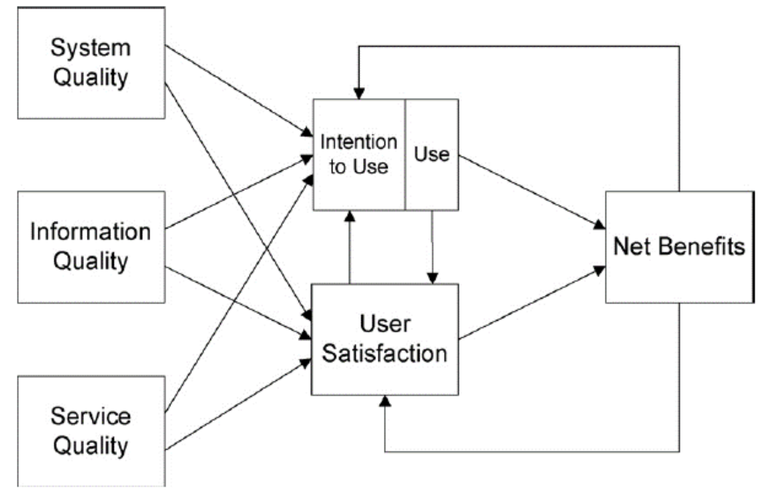

Figure 1. IS Success Model (from Delone and McLean, 2003)

Net Benefits

While significant interest has been generated around DT technology, we could not find any that have been completed on the real-world benefits of DTs. We define the benefits of a DT system as the positive effect the system has on the organization (Petter and McLean, 2009). These benefits are netted together with the costs of the system. Costs include platform implementation and maintenance costs, training costs, and costs to upgrade physical twins so they can report information to the DTs. Thus, net benefits are the positive benefits of the system minus the negative costs.

Use

The efficacy of the use construct in the IS success model have been questioned by some researchers (Gorla et al., 2010). This questioning was brought about from a lack of clarity on what is meant by "use." Recent work in IS use, particularly post-adoptive use, has clarified this construct greatly (Williams and Gupta, 2018, 2023). The benefits of a technology are brought about by the post-adoptive use of the technology (Jasperson et al., 2005). Thus, we will focus our examination of the use of DTs on post-adoptive use. Recent work on post-adoptive use shown that it has two natures: static use and innovative use (Williams and Gupta, 2018, 2023). Static use occurs when a user uses a technology in a previously known way to achieve a work goal as efficiently as possible. Innovative use occurs when a user uses a technology in a novel or experimental way. These two use types are likely tied to different benefits, with static use bringing benefits from efficiency in existing applications of DTs and innovative use bringing benefits from flexibility and new applications of DTs. Both will be explored. However the, "intention to use," part of the IS success model, will not be studied since intention to use is an adoption construct and adoption has already occurred in the post-adoption setting and first-time use intentions have passed. Behavioral intention to use a technology is also conceptually different than the actual use of the technology (Venkatesh et al., 2008).

User Satisfaction

Seddon and Kiew (1996) define user satisfaction as, "The net feeling of pleasure or displeasure that results from aggregating all the benefits that a person hopes to receive from interaction with the information system." (p. 95). This construct has face validity as being an important precursor to net benefits. User satisfaction has sometimes been used as a proxy for IS success itself (DeLone and McLean, 1992). However, the user satisfaction construct has had is efficacy called in to question (Gorla et al., 2010). It was originally measured by a single-item (DeLone and McLean, 1992). Some studies that have used it have found it to be insignificant (Shim and Jo, 2020). Because of its instability, user satisfaction will not be used in the present research.

Information Quality

The data flow from the real world to the DT and the information from the DT system is a truly unique feature of DTs. No other system take in real-world data, virtualizes it for analysis and then re-sends it back to the real world in the form of parameters for real world machines to follow. Thus information quality is of central importance to DTs. Such data flows are is typically achieved by IoT technologies. Sensors on equipment report its status. This data is picked up by the DT environment and shared with the appropriate DTs to update them. This information can be data mined and used to build machine learning models that can control the equipment automatically and respond to faults and other events.

Information quality was originally studied by Wang and Strong (1996) and then expanded on by Lee et al. (2002). Recent work on the construct has shown how it can be malleable and customized to fit new technologies (Bhagat et al., 2022). Petter and McLean (2009) suggest accuracy, timeliness, and completeness as important dimensions of information quality. To these we propose to add the dimensions listed under the categories “usefulness” and “usability” in Lee et al. (2002). These dimensions include “appropriate amount,” “relevancy,” “understandability,” “interpretability,” “objectivity,” believability,” “accessibility,” “ease of operation,” and “reputation.”

System Quality

When considering the system quality of DTs, one must consider two distinct systems. The first system is the platform that houses the DTs themselves. This is the system that users will interact with to use the DTs. The other system is the physical system in which the physical twins reside. This is the real-world system that produces net benefits for the organization. This means that system quality must consider both the real world and virtual systems and should be separated as such. Prior research on system quality has found that important components of the system are its reliability, convenience, ease of use, and functionality (Petter and McLean, 2009).

Service Quality

The service quality of the virtual and physical systems should be considered when determining the net benefits of a system. Service quality is defined as “support of users by the IS department, often measured by the responsiveness, reliability, and empathy of the support organization” (Petter and McLean, 2009) p.161. Because we are considering both the virtual and physical systems’ quality, we must also consider the service quality of both systems. The definition of service quality above only applies to the virtual system. To parallel the virtual system, the physical system’s service quality is defined as “support of equipment by the engineering and/or maintenance department.” The measures of physical system service quality will be the same as the virtual system measures.

Given the above definitions and constructs, Figure 2 shows the proposed research model. In accordance with the IS success mode, all relationships shown in Figure 2 are proposed to be positive.

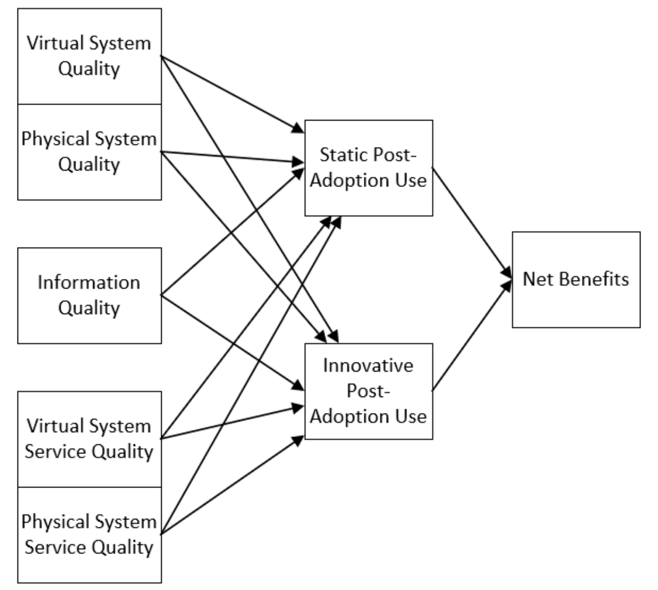

Figure 2 Research Model

Proposed Methods

Research Setting

The proposed setting for this work is in the context of an industrial gas turbine electrical generation facility (i.e., power plants that burn natural gas). Gas turbine generation facilities are a ubiquitous power generation source in many countries, leading to a large set of practitioners that can apply the findings of the proposed research. With many utilities investing in Maintenance and Diagnostics Centers utilizing Digital Twin technology, this context represents an area with significant data availability.

The company operating the gas turbine generation facilities we will study is located in the United States, with a yearly revenue greater than $15 billion USD and a staff of more than 14,000 employees. This setting was chosen for a variety of reasons including the scale of facilities, long-term asset management strategies, the researchers' access to the facilities and users, and the level of DT adoption. One of the authors is currently employed in the energy generation industry and is heavily connected with companies and research groups in the area, leading to significant data access. Documentation of asset costs is available for the organization, enabling accurate cost-benefit analysis.

The research data collection will be targeted at individuals working at one or more gas turbine generation facilities, with stakeholders including maintenance & diagnostic support staff, traditional engineering support, operations staff, and management. This group encompasses more than thirty individuals per site.

With power plant lifetimes in decades and the relative newness of DTs, these facilities are often retroactively fitted with DTs, meaning that we will not be engaging with the rapid prototyping use case of DTs. At these sites, DTs are primarily used to forecast future generation and predict equipment downtime/needed maintenance. Thus, we will focus on these benefits in our study. Several recent whitepapers on DTs have been dedicated to research related to implementation on gas turbines (Krishnababu et al.; Panov and Cruz-Manzo; Trinkle et al., 2021). While these papers have examined the affordances of various DT platforms DTs, they have not reported on the costs of the DT implementations.

Proposed Research Methods

We will use an exploratory sequential mixed methods approach (Creswell, 2014) to understand the net benefits of DTs. This mixed methods approach first uses qualitative methods, such as interviews, to develop quantitative survey items. Such a mixed methods approach allows us to first gather rich data and do deep analysis of it and then to use the knowledge gained from the rich data to develop an informed survey, the results of which can be used to draw statistical inferences on the data (Venkatesh et al., 2016). This research design is appropriate when a new area is under investigation and valid, reliable survey items have not yet been published in the literature. This mixed-methods approach can utilize the strengths of both qualitative and quantitative research methods and provide a stronger understanding of the net benefits of DTs than just using one method.

First, we will conduct semi-structured interviews with representatives from all stakeholder groups: system users, system support staff, and organizational leaders. We will seek to understand their perspectives on the DT implementation, and their perceptions of its costs and benefits. Interview recordings will be reviewed by the researchers to identify quotes, codes, and themes and reveal previously unknown cost and benefit areas. These benefit areas will need to be studied alongside the standard IS success constructs discussed above. New learnings from the interview data will be incorporated into the survey as items for new constructs.

Second, we will develop and distribute a survey about the perceptions of the net benefits to members of the organization. This survey will allow us to understand if the stakeholders of the DT initiative see it as worthwhile. The data from this survey will be analyzed quantitatively to gain insights and test relationships of the research model.

Third, we will conduct a financial cost/benefit analysis of the DT initiative to understand its monetary costs and benefits. This analysis will be conducted at the same time as the survey. To conduct the cost/benefit analysis we will use secondary organizational data such as purchase orders, travel receipts, salary reports, and maintenance schedules. Such data collection, while normally difficult, will be aided by the level of access the researchers will have to the target industry association. Much of this data may be relatively easily collected from the organization’s enterprise resource and planning (ERP) system.

Proposed Contributions

Theoretical Contributions

The IS success model has a long history of providing a theoretical foundation for studying the net benefits of a technology. This proposed research will allow the IS success model to be employed with a new technology- DTs. DT implementations bridge the gap between the physical world and the digital world and thus allow an interesting edge case for the IS success model that has thus far been applied to the digital world. This is done by identifying and defining system constructs for the physical and DTs. We also extend the IS success model by using interviews to identify new DT-specific constructs for inclusion in the model. We further expand on the IS success model by breaking down the monolithic “use” construct into two types of post-adoption use. The two types of use will be studied independently for their contributions to net benefits. This will help tie the post-adoption IT use literature more closely to the IS success literature.

Practical Contributions

This proposed research can help practitioners understand the nature of DT benefits, where they come from, and how to achieve them. We do this by selecting a ubiquitous context for the deployment of DTs: gas turbine electrical generation facilities. Our proposed survey of perceived benefits will help DT users set benchmarks for use and understand how the physical and digital systems work together to create benefits.

Conclusion

Through this proposed research, we hope to gain a better understanding of the costs and benefits of DTs in electricity generation. By using the IS success model, we can ensure all important drives to the benefits of DTs are captured.

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