Comparison of Digital Twins in different application domains

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Abstract

Digital Twin is a concept of growing interest due to the advancement in Industry 4.0. It is a relatively new concept and publications on this concept of Digital Twins have increased radically in recent years Hu, W., Zhang, T., Deng, X., Liu, Z., & Tan, J. (2021)[6]. We write this report to better understand and contribute to the concept even more. Digital Twin applications have been built in different domains but in this paper we focused on the applications that have been implemented in Smart City and Manufacturing domains. We chose these domains because we wanted the domains to be as different as possible for better comparison. We will compare each digital twin by using a set of criteria namely hierarchical, dynamic, computability, multiplicity, usage, enablers, technology used, model data and compare the similarities and differences of the applications.

Keywords

Digital Twin, Application, Smart City, Manufacturing, Smart Factory

1. Introduction

Digital Twin is a concept that has gained a lot of attention with the developments of Industry 4.0. There are many definitions of the Digital Twins but the first definition was made by Grieves in a 2003 presentation and later published on paper. However the main milestone for defining it is set by the National Aeronautical Space Administration (NASA) [1, 2, 3]. But NASA's definition is specific for its own application and excludes the other domains so a more inclusive and definitive definition is needed but for this paper we can use the definition of LIU et al. 2018 [4] : "The digital twin is actually a living model of the physical asset or system, which continually adapts to operational changes based on the collected online data and information, and can forecast the future of the corresponding physical counterpart." as it is more inclusive of other domains. The concept of Digital Twin is used in many domains such as Industry, Health, Agriculture, Architecture, etc. In this research we will only look at applications in two domains in this paper and compare the digital twins of those applications according to criteria defined. Manufacturing and Smart City domains are chosen for this research. Those domains chosen because of the number of research papers published about these domains and the differences of these domains paves the way of comparing the Digital Twin applications.The Digital Twin applications will be examined for finding the comparison criterias. Our main goal is to contribute to the research of the concept digital Twin and investigate the effects of digital twin applications in different domains. To achieve these goals we define the following research questions (RQ):

RQ1: What are the Digital Twin applications in the Manufacturing and Smart City domains ?

RQ2: Which criteria can be used to compare Digital Twins ?

RQ3: What are the similarities and differences of the digital twins in these two domains ?

By the end of this research we expect to find the strengths and weaknesses of the Digital Twins in those domains, compare them in terms of the criteria and make a critical analysis of the end results.

2. Related Work

In this section, we go over some of the related work in these application domains. Although the concept of Digital Twin first emerged in the 2000s, most of the articles were published after 2016 Figure1[6]. For the number of written articles about Digital Twins. We divide the related work into the domains that we choose :

For Manufacturing Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018) [7] research draws a general perspective on Digital Twin applications in manufacturing and they listed the applications made in manufacturing domain, In the paper Shao, G., & Helu, M. (2020)[8] they described the scope and the requirements of a digital twin in the manufacturing domain.

For The Smart City domain the digital twin concept is increasingly used as the development in modeling improves, it enables the digital twins in that domain to be used constantly. This paper Ruohomäki, T., Airaksinen, E., Huuska, P., Kesäniemi, O., Martikka, M., & Suomisto, J. (2018, September)[9] talks about how Smart Cities enables the digital twin to be used and here is a feasibility study of a Digital Twin application made for smart livestock farming Jo, S. K., Park, D. H., Park, H., & Kim, S. H. (2018, October)[5]. This paper is important for us as it studies the feasibility of the digital twin in that domain for us to make comparisons for this domain.

Most of the research on Digital Twin applications is made for analyzing the application so it is necessary for us to set criteria and compare each domain application with the other.

3. Methodology

This section will explain the details on how to answer each research question. For this research following steps are defined: 1- Selection of the candidate application in the set domains

2- Defining the comparison criterias

3- Study of specific digital twin applications

4- Comparison of the applications

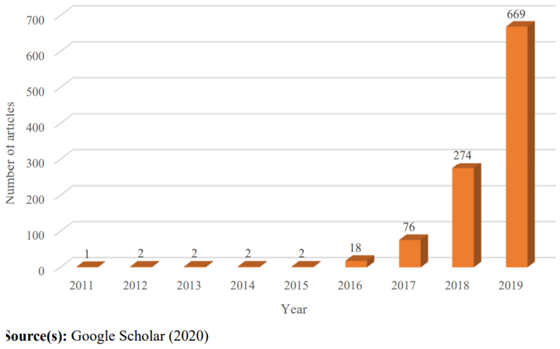
5- Analyzing the end results.

Furthermore a literature review from Google Scholar, IEEE and Scopus will be made for finding the candidate applications and comparison of the candidate applications.

3.1 On Answering Research Questions

The studies on article Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018) [7] focuses on the digital twin applications in manufacturing and article Jo, S. K., Park, D. H., Park, H., & Kim, S. H. (2018, October) [5] also analyzes and explains the applications on the Agricultural domain. We can use them to identify the candidate applications for our research for answering the first RQ. Finding a good candidate application is important as the criterias for the research will be determined as a result of this question's findings. For criteria we will use the defined characteristics of DT to determine the criterias for our research. We will use the Oakes et al.(2020) and the book Wang(2018)[6] for answering the second research question. Finally for the Research Question 3 the paper Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., & Calinescu, A. (2020) [13] is used as the paper defines questions about similarities and differences arising in different domains of DT applications.

Figure 1. Number of Published Articles about DT [6]



4.What is a Digital Twin ?

Digital Twin is a concept that has many definitions specific to their domains and few of them that are general. The concept is described as a model of the specific project in most of the definitions, however in 2015 with the work of Rios it gained a more inclusive meaning and was described as a "product". All the definitions can be found in Table 1[12].

For this research we will use the definition of LIU et al. 2018 [4] because we find it more suitable for our chosen applications. This diversity among the definitions of the Digital Twins makes it interesting to define and understand more about the concept. But first we need to mention a few things to understand more about Digital Twins.

According to the paper Singh, M., Fuenmayor, E.,Hinchy,E., P., Qia, Y. ,Murray N., &Devine, D., (2021)[13] the Digital Twins categorized according to five categories:

Digital Twin creation time

-Digital Twin Prototype(DTP): It is a virtual copy that contains information of the physical product.

-Digital Twin Instance(DTI): It is the DT that is connected to the system once the system is built. It helps to predict the behavior of the system through the information that is gathered from the real world.

Level of Integration

-Digital Model(DM): In this kind of DT the data is flowed manually between the physical object and the digital object.

-Digital Shadow(DS): In this DT the data flow is made manually from the Digital Object to the Physical Object and automatically from the Physical Object to Digital Object.

-Digital Twin(DT) : In this DT the data flow is made automatically between the Physical Object and the Digital Object in both ways.

Application

-Product Digital Twin: It is mostly used for prototyping as it is the type of a DT that analyzes the product in the digital environment to plan the behavior of the product.

-Production Digital Twin: It is used before producing the physical product by stimulating and analyzing the production phase of the product.

-Performance Digital Twin: It is used for analyzing and decision making of the product by the data that is gathered from the product. Since it contains data from both production and the product it helps us to optimize the operations from both states of the product in terms of efficiency, which also helps us to receive feedback for the Performance and The Product DTs.

Hierarchy

-Unit Level DTs: It is based on the DT of the physical units of the product like material,component and equipment.

-System Level DTs: It is the combination of the Unit Level DTs such as the complex product and shop floor. It examines the interoperability of the units of the product.

-System of Systems (SOS) DTs: It is the connection of the System Level DTs throughout the product's life cycle. It integrates different phases of the product.

Level of Maturity/Sophistication

-Partial DT: It has the small data points to help us determine the functionality of the DT. Such as humidity and temperature.

-Clone DT: It has all the important data that help us to prototype the actual product or system .

-Augmented DT: It contains all the previous,present and useful data to analyze the product/system with functions and algorithms.

Applications In Manufacturing and Smart City Domain

Most of the digital twin applications that have been built so far are from the manufacturing domain. One of the reasons for that is the requirement of the predictability of the manufactured products and that is why most of the applications are made for tracking and monitoring, for saving money and time. Applications vary from an assembly line to a wind turbine but if we generalize, The broad areas are usually in the mass production and energy areas. For this paper we choose the Smart Factory to study. The reason for choosing the smart factory is that different technologies are used for creating the Digital Twin like Simulation, Cloud, CPS, Industry 4.0, AI and more.

Smart City domain is specifically chosen for this paper because it has an increasing use and potential for Digital Twin due to the recent developments in using Internet of Things. Internet of Things increases the amount of data that can be usable for the Digital Twin which is essential for the efficiency of the DT. Just like the manufacturing domain some applications focus on the energy area but the other applications are more diverse Hu, W., Zhang, T., Deng, X., Liu, Z., & Tan, J. (2021)[6] than the manufacturing domain from livestock farms through infrastructure analysis. For this domain we choose the Smart Livestock application to further study and compare it with the Smart Factory application because of the large variety of the technology used for the Digital Twin.

5.Digital Twin Comparison Criteria

For better understanding and better comparison we selected some criterias for the DT's in the applications. The first one is Hierarchy. If a twin is hierarchical then it consists of many parts that make the final digital twin then it is hierarchical. Second one is being dynamic. A digital twin is dynamic if it can improve itself through constant interaction. Third one is computability. If a twin is using calculating algorithms to stimulate the product or system. The other ones are: Multiplicity is the number of DTs that are interacting with the system. Usage is the purpose of the DTs that are in the system.Enablers are the DT components that are using the data and models. Technology used is the list of technologies that DT is used for models and data gathering. Models and Data are the models and datas that are being used by the DT.First three criteria are determined by the book of Wang(2018) and the rest is from Oaks et al(2020).

Manufacturing in Smart Factory Application

Let's look at the Bilberg,Malik(2019)[15]'s Digital Twin Driven Human-Robot Collaborative (HRC)in an assembly line, "the DT advantages for HRC are focussed at skill based tasks distribution between human and robot, generating an optimized robot trajectory, balancing the workload during production, and generating robot program. This dynamic control of human–robot collaboration is evaluated especially for variant oriented production environments" Bilberg, A., & Malik, A. A. (2019)[15]. So the DT is supporting the assembly line worker by distributing the work accordingly by optimizing the robot. You can see the DTs in HRC in Figure 2. Lets analyze the DT according to our criteria.

Hierarchy: The HRC consists of four different modules that are separate twins working together that comply with the criteria of hierarchy.

Dynamic: The HRC collects real time data from the sensors or actuators.

Computability: The system generates operation plans calculating estimated cycle times after the event trigger system's signal is received. It is not stated what kind of calculation techniques are used in the paper but we can understand that it uses mathematical calculations to decide the operation since the system uses real time data. It is also very clear that a simulation is used to stimulate the operation so it is certain that the HRC also complies with this criteria.

Multiplicities: Four DT instances per each assembly

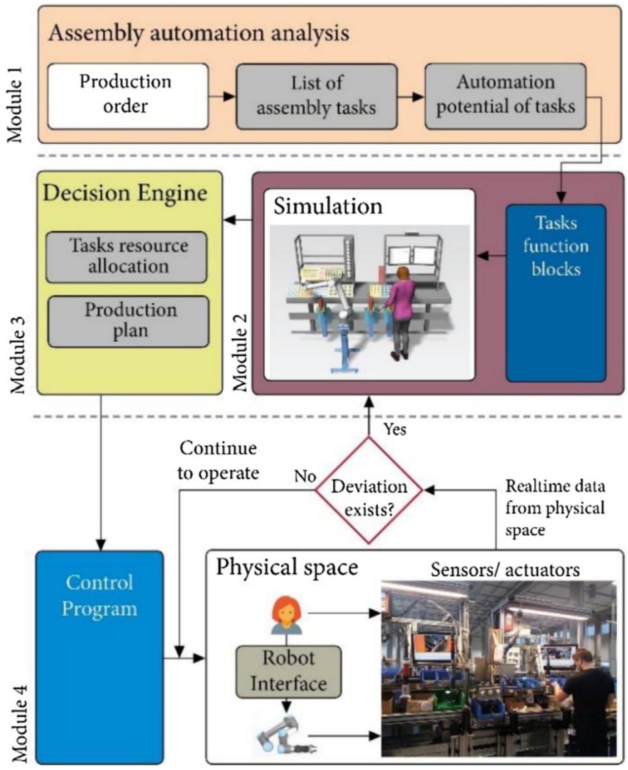
Usage: optimizing the robots trajectory, balancing the workload between humans and robots

Enablers: An engine to decompose and evaluate tasks, Function block,decision engine,simulator, control program for the robot.

Technologies Used: Simulation

Models and Data: Real Time data from the actuators, Model is not mentioned.

Figure 2. Digital Twins in HRC assembly



Smart Livestock Farm Application

For the Smart City domain we choose the Jo (2018)[5]'s Smart Livestock Farm application. We will evaluate the application with the given criteria. Smart Livestock Farm application's goal is to optimize the farm conditions to increase the efficiency of the production of the farm. This DT application has two layers: Digital Engine Layer is used for analyzing the giving conditions and Digital Farm Framework Layer gathers data through sensors. You can see the framework in Figure 3.

Hierarchy: The application consist of four components (Modeling&Analysis,Simulation,BigData, Visualization)

Dynamic: The system has constant real time gathering functions through sensors so the system is dynamic.

Computability: The data gathered from the sensors are monitored and the data stimulated from the stimulator is used for decision making.

Multiplicities: Two DT instances per smart farm

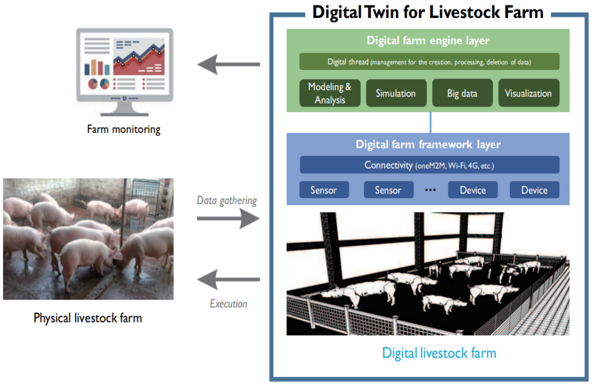
Usage: Analyzing and monitoring the data to create an optimal environment for the farm.

Enablers: Digital Farm Engine Layer and Digital Farm Framework Layer

Technologies Used: Industry 4.0,Simulation

Models and Data: Real Time and Historical Data, Model is not mentioned.

Figure 3. Framework of the Smart Livestock Farm[5]



Comparing the Digital Twin Applications In Different Domains

From these two applications we can see that the Human Robot Collaborative(HRC) Application's Digital Twin was created with the intention of building a fully functional Digital Twin. However the application ended up being a Digital Shadow. The Smart Livestock Farm(SLF) application on the other end was created with the intention of building a Digital Twin and reached its goal. This is due to the high complexity of the HRC application compared to the SLF. Even though it is beneficial to use the Digital Twin for the expensive and hard to test products such as a robot-human assembly line, because of the insufficient synchronization between the physical and digital space the data flow from the DT to the system is not made sufficiently. Also because of the lack of high fidelity models, as stated in the paper, the accuracy of the processed data is significantly low which results in controlled manual data flow even though both of the applications gather real time data, the lack of insufficient models significantly lowers the efficiency of the DT. Same could be said for the criteria of being dynamic and computability since the efficiency of the data gathered is crucial for these two criteria and lack of good models significantly affects the quality of the data and therefore lowers the quality of the dynamism of the DT.

For the enablers the HRC is more multidisciplinary than SLF which makes the system more complicated and hard to manage but it also uses more DTs to manage that complex system. SLF however works with less complex machinery in a mechanical sense which increases the success of the DT. Similar technologies are used in both DTs however the HRC is using real time data which requires a good model to process the data fast and efficiently which it is not and SLF is working with data that is easy to gather which is mostly environmental data. Also SLF is using its historic data to determine the action that gives it an advantage to succeed in being a DT.

6. Conclusion

There is no universal definition of digital twin that exists till now but more and more publications are made and the definition of it will get more clear. In this paper we compared the Human Robot Collaborative Assembly application in the Manufacturing Domain and the Smart Livestock Farm application in Smart City domain with set criteria for the purpose of classifying the DTs in different domains. In both applications similar technologies were used however we get different results from them. We investigated the reasons why this is happening and concluded that efficiently using such technologies is needed to succeed.

Table 1. Digital Twin Definitions

No.	Ref	Year	Definition of Digital Twin
1	[16–18]	2010 and 2012	An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. The digital twin is ultra-realistic and may consider one or more important and interdependent vehicle systems.
2	[19]	2012	A cradle-to-grave model of an aircraft structure's ability to meet mission requirements, including submodels of the electronics, the flight controls, the propulsion system, and other subsystems
3	[20]	2012	Ultra-realistic, cradle-to-grave computer model of an aircraft structure that is used to assess the aircraft's ability to meet mission requirements
4	[23]	2013	Coupled model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge
5	[21]	2013	Ultra-high fidelity physical models of the materials and structures that control the life of a vehicle
6	[24]	2013	Structural model which will include quantitative data of material level characteristics with high sensitivity
7	[25]	2015	Very realistic models of the process current state and its behavior in interaction with the environment in the real world
8	[22]	2015	Product digital counterpart of a physical product
9	[26]	2015	Ultra-realistic multi-physical computational models associated with each unique aircraft and combined with known flight histories
10	[27]	2015	High- fidelity structural model that incorporates fatigue damage and presents a fairly complete digital counterpart of the actual structural system of interest
11	[28]	2016	Virtual substitutes of real world objects consisting of virtual representations and communication capabilities making up smart objects acting as intelligent nodes inside the internet of things and services
12	[29]	2016	Digital representation of a real world object with focus on the object itself
13	[30]	2016	The simulation of the physical object itself to predict future states of the system
14	[31]	2016	Virtual representation of a real product in the context of Cyber-Physical Systems
15	[32]	2016	An integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin
16	[33]	2016	A unified system model that can coordinate architecture, mechanical, electrical, software, verification, and other discipline-specific models across the system lifecycle, federating models in multiple vendor tools and configuration-controlled repositories

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