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Digital Twin Development: A Step by Step Guideline

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Abstract

Digital Twin (DT) is a virtual representation, which integrates sensor data, physical models, historical data, and etc. to emulate the life of its physical counterpart. Although, existing studies have shown many use cases in health monitoring, decision-making support, and life-cycle management, the development of the DT remains complex. Meanwhile, there is a limited number of studies that investigate a generic and detailed method to develop the DT. Therefore, the aim of this paper is to present a step by step guideline that allows a developer to identify and to populate the requirements for developing the DT as well as to corroborate that the DT fulfil its missions. A case study of a modified mobile asset illustrated how the guideline was applied and how the DT purpose was validated through an empirical test. Further studies will investigate the attributes of the scalability and the flexibility of the proposed framework to pave a way for a common approach for the DT development and evaluation.

Keywords*:* Digital Twin; DT framework, maintenance

1. Introduction

DT is commonly known as a virtual representation of a real object in which data exchange occurs between the digital and physical world [1]. Although, the notion of virtualisation has been around since the 1960s, the concept of DT extends what was used to be known as a separate entity in the realm of a virtual world into a convergent dimension by establishing a connection to the real world. DT acts as a bridge between the digital and physical dimensions as opposed to the traditional concept of isolated systems [2]. The pairing of the virtual and physical worlds enables unprecedented visibility and recognition of the status, behaviour, or condition of a real object. Through data monitoring and analysis, the performance of the physical asset is optimised and potential problems can be detected before they even occur, thus preventing the downtime. Besides, the connection with the virtual world allows the ability to integrate with various software and simulation models, in order to realise new opportunities and plan for the future.

Nomenclature

DT	Digital Twin
PLM	Product Lifecycle Management
AI	Artificial Intelligence

DT, since it was first introduced in the context of lifecycle management in 2003, had not grown much until the first journal article in predicting aircraft structural life using DT was published in 2011, followed by the publication of the first white paper in 2014 introducing the conceptual idea of the DT [3]. Ever since, research in DT has been gaining more and more interest due to its potential in making significant impacts to industry, which is often in the journey of implementing smart manufacturing and Industry 4.0 [4][5]. The main reason underlying the attractiveness of DT is twofold [6]. First, DT is responsible to emulate the life of its physical counterpart, giving transparency to the current state and behaviours of its twin in the real environment [7][8][9]. Second, DT extends the simulation paradigm to every phase of the lifecycle, enabling it as the basis for decision making, control, validation, and test not only for components but also for complete systems and processes [10]. These features have encouraged the implementation of DT to boost fundamental improvements to industrial processes in many areas including manufacturing, engineering, material usage, supply chain, and lifecycle management [11].

Despite showing potential benefits in process monitoring and optimisation throughout the lifecycle for improved decision making, analysis, and control, building an impactful DT is a complex and iterative task. In the literature, there is a limited number of studies that looks at the implementation path that informs the detailed development of the DT. Due to high cohesion of technologies underlying the DT, one is likely to get lost in the implementation of technologies for the DT rather than leveraging the benefits of the DT [12]. This paper provides a generic development framework to develop the DT, which consists of a step by step guideline and templates to populate. In order to validate the proposed framework, a case study was applied to show the process of developing a DT.

2. Literature review

2.1. DT conceptual model

DT is conceptually understood as having three main parts [1]: a) physical products in real space, b) virtual products in virtual space, and c) the connection of data and information that ties the virtual and the real products. However, when the product lifecycle is considered, the products in the real space may include equipment, production line, process, and people. These entities are also reconstructed in the virtual space in the form of computational models to mimic the existence of their physical counterpart. Fig. 1 shows the modified figure based on conceptual model of the DT [1]. The connection of data and information bridges the interaction between physical and virtual objects in two ways: 1) live sensing from physical to virtual and 2) live optimisation from virtual to physical. The first interaction involves a gradually increased comprehensive data collection from the real object and a progressively improved fidelity of models, so that DT can accurately represent and provide full visibility of its physical twin. The second interaction deals with feedback and control, which are based on the analysis of the combination of the physical and virtual data across the lifecycle (e.g. simulation data, prediction data, decision data, etc.) to optimise the operation and the performance of its physical systems.

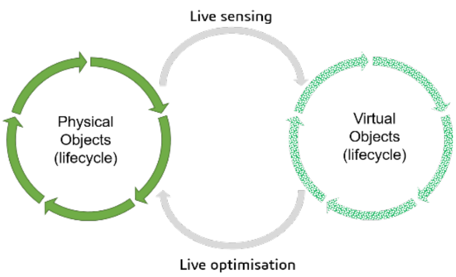


Fig. 1. Modified conceptual model of DT

2.2. DT Development Framework

The full potential of DT lies in its implementation when the whole organizational system from production to enterprise management system is digitally twinned to exchange the data. Nevertheless, even a small scale of DT can already provide the benefit and deliver tangible outcomes if it is properly implemented. In fact, one of the main motivating factors for industries to deploy DT is the presence of an approach to start small and scale-up fast. Therefore, there is a necessity for a DT development framework to be designed and tested to further serve as an implementation guideline to build a DT for any use case.

In the literature, a three entities application framework of DT was developed, consisting of physical space, information processing layer, and virtual space [8]. For the implementation, the authors elaborated the components involved in the physical space, which includes total-elements information perception such as: physical layer (e.g. equipment, machine, material, worker, and so on), technology layer (e.g. sensors, actuators, and so on), data layer (e.g. production data, equipment data, material data, user data, service data, environment data, and etc.), and system layer (e.g. database). In the information processing layer, three activities were involved: 1) data storage, which stores data from the physical space and virtual space, 2) data processing, which consists of data acquisition, data preprocessing, data analysis, and mining, as well as data fusion, and 3) data mapping, which supports the synchronous mapping of the physical and virtual space based on the data storage and data processing module. The virtual space consists of two parts. First, the virtual environment platform (VMP) provides various virtual models for DTs, including polyphysical model, workflow model, simulation model, etc. to establish a unified 3D virtual model and to provide an algorithm library for an operating environment. Second, the DT application subsystems (DTs) collect historical and real-time data of the 3D virtual model and physical object for product lifecycle management and to drive the DTs running synchronously with physical entities. Further, the authors demonstrated the steps required to build a DT through a case study of a welding production line. The steps are composed of the background definition of a DT, DT modeling of a welding production line, information perception and data acquisition, process of data real-time mapping, and evaluation of the DT application.

Following the three entities DT framework, the DT reference model for rotating machinery fault diagnosis was proposed [13]. While, the steps required to construct the DT for representing the physical system of interest are more condensed than the previously mentioned DT modeling, this study included a more detailed step in the model by introducing a step for updating the strategy to enhance the DT model adaptability.

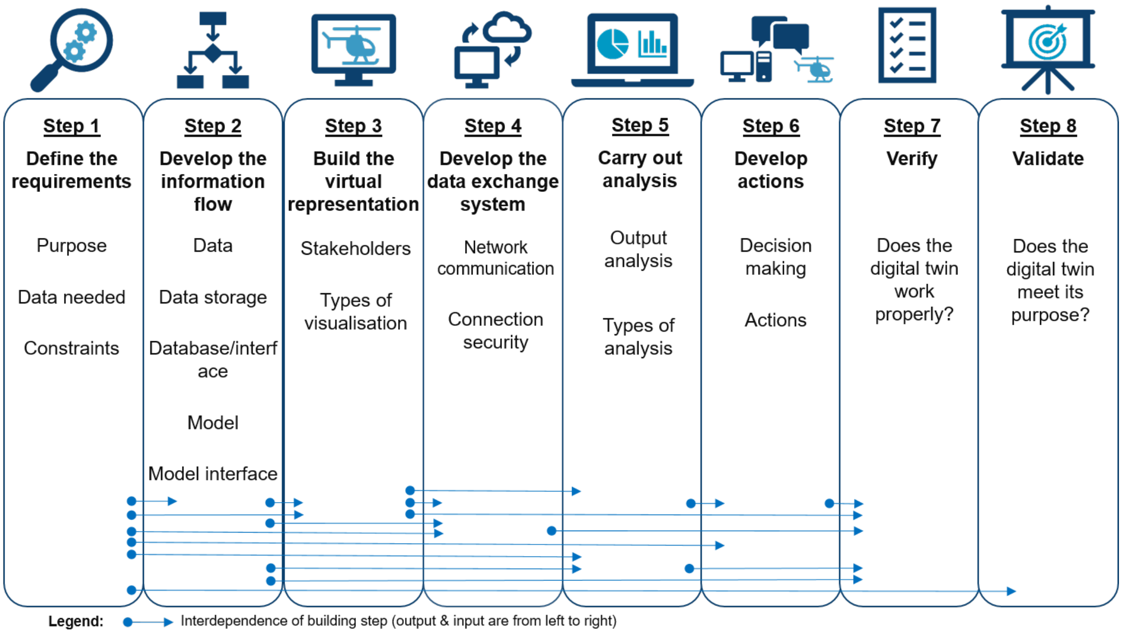


Fig. 2. The proposed building steps for DT development

The three entities DT framework was also used to build a DT-driven product design for iterative redesign of an existing product [14]. It takes six steps to build a functional DT in which the activities involved are similar to the previously mentioned studies, with the difference lying in the sequence of the DT building process.

An extended five-dimension architecture based on the DT model proposed by Grieves [1] was developed by adding DT data and services [15]. In that study, an attempt to increase comprehensiveness and accuracy of information capture, the proposed DT model extends Grieves' architecture from the physical-virtual interaction to data fusion from both physical and virtual space using DT data. The additional element of service helps in encapsulating the functions of DT for unified management and demand usage. A case study of gearbox prognosis was shown to confirm the improved accuracy of prognosis using the DT method as opposed to the traditional method.

Further, DT 8-dimension model was put forward to map the scope of the DT context and the intended behavior of the DT solution to support the individual business context [16]. From this model, six design elements for DT development were derived and presented to inform the linkages between the physical system components, the related software controlled system, and the data-driven analytic design elements.

2.3. Framework validation

The subsequent important step in the framework development is the validation stage, which is aimed at providing accurate evidence to evaluate the fit to a particular purpose. Unlike verification that is done to examine if one has built a system with respect to its specification, validation is used to confirm if the system built serves its application purpose. In the DT literature [8][17][18], the most common approach to confirm the applicability of the developed DT framework is through a case study. This involves the definition of the specific purpose of the DT, followed by the framework implementation and testing to confirm if the predefined objective is achieved.

Meanwhile, several studies [9][13][15] use an empirical test to confirm if the developed DT system brings measurable benefits compared to the non-DT system. This approach becomes necessary when there is a need to quantify the performance growth between the DT and non-DT system. Therefore, it is also meant to consider if the DT development is necessary and worth investment. In general, there are five common steps involved in this type of validation. First, defining the hypothesis which is usually the expected improvement from adopting the DT compared to the non-DT system. Second, identifying the metrics used to measure the performance differences achieved by both systems. Third, apply 'apple to apple' comparison to make the context equal during the testing for both systems. For example, the group of users for DT and non-DT system should come from the same population. Fourth, choose the appropriate statistical method to analyse the results of the empirical data. Fifth, evaluating if the performance improvement observed from using the DT is statistically significant.

3. Proposed DT development framework

DT development can vary widely in terms of its physical twin, the underlying data, models, simulation tools and the lifecycle stage being considered. Nevertheless, every DT application is composed of building blocks (i.e. data and model, virtual representation, communication network, analysis module, etc.) into which different underlying technologies of DT can be categorised. The arrangement of these building blocks makes it possible to produce a framework that systematically guides the development of the DT irrespective of the use cases. Fig 2 outlines a step by step guideline to build the DT. This guideline covers the initial planning of the DT purpose, DT design elements, through the validation to confirm if the DT purpose is achieved. There might be a continual iteration within some of the steps and across steps as the model grows in scope, complexity and sophistication.

Step 1. Define the requirements

The first step of the building process is to define the purpose of the DT and the expected performance gain of the DT. The main aspects of this step are:

- The purpose of the DT:
  1. What is the function of the DT?
  2. What are the improvements expected from the DT?
- Data requirements: Based on the DT purpose and the expected benefit, what are the required types of data.
- Constraints: what are the constraints that have to be taken into consideration for the DT development (e.g. data and model accuracy, lack of infrastructure or data access, etc.)

Step 2. Develop the information flow

DT relies on the data and model to live and co-evolve with its physical counterpart. The data can be generated from different sources:

- Physical sensors: sensors that are set up to collect two types of data: 1) Operational measurements (characteristics of the physical asset e.g. position, displacement and torque) and 2) Environmental or external data (elements that influence the physical asset e.g. barometric pressure, ambient temperature, moisture level etc.).
- Internal software: a computer program that contains models and algorithms to mirror the status and behaviours of the physical asset. Additionally, data can also come from external systems that are not part of the DT but contribute to the operation of the DT.
- Historical data: data history that has been recorded in the past can be integrated to the digital model and used for further analysis.
- User data: data that is collected from human input to keep track of the operation and the action performed on the physical asset including human-machine interaction data (e.g., physiological data)

There are two main ways to store the data: 1) local storage: data is stored on a local server, and 2) Cloud storage: data is stored on an online server. Following this choice, one needs to select the type of database and the data interface.

The model used by DT can vary from a simple schematic that depicts the interaction of multiple parts of the system to a very sophisticated model that uses the computational model to simulate the behaviours of a complex system. The typical models for DT can be categorised in terms of geometrical model, physical model, behaviour model, and rule model [15]. DT can also include data-driven model using AI techniques. Model interfaces are necessary to integrate various models concerning asset lifecycle [19][20].

Step 3. Develop the virtual representation

The virtual representation of the physical system can be done in different ways, depending on the stakeholders and the types of data for a particular task or operation. For example, the remote expert may need a 3D representation of a physical asset in AR/VR environment for checking the spatial relationship among components to help a local operator in troubleshooting whereas an operator may only need a panel/dashboard (2D representation) to view sensor data for monitoring current condition of physical asset and factual information for business-related decisions.

Step 4. Develop the data exchange system

To bring the virtual asset to co-live with its physical twin, a communication link needs to be established, configured with the required speed and latency. The connection can be realised through wires or wireless connections. The network coverage for accessing the DT (e.g., PAN, LAN, or WAN) depends on the physical asset's characteristics, DT purpose, and environmental conditions. Once the connection has been established, data processing (e.g. filtering process) may need to take place to transform the raw data into a usable format for physical to virtual mapping or from virtual to physical optimisation. Multiple measures to ensure cyber security is also needed, so the DT becomes an effective tool

Step 5. Develop the analysis method

Besides providing transparency of the physical system, the real value of the DT is to unfold the meaningful information from a huge volume of data collected from a variety of sources. To realise the impact of DT, one should define the desired insights that contribute to the expected improvements defined in Step 1, considering the type of data, models and tools as well as visualisation requirement.

There are three different ways to carry out analysis, which will be best selected by considering the human and technical system performance consequences [21].

- Manual analysis which involves human user or expert to derive the meaningful information from the DT
- Semi-automatic analysis involves the use of AI techniques to identify the pattern of the data or behaviour of the physical system and have the human expert to extract insight from the DT.
- Automatic analysis involves the use of AI techniques, simulation tool, and data analytics to turn the data into actionable information.

Step 6. Develop actions

Once the insight is obtained, one should determine or implement a decision and/or action that follows. This could be implemented in the form of condition-action rules. The appropriate rules will also determine if the expected improvements of the DT have been optimally captured. The form of the action implemented can be executed by the person following the recommendation from the DT or automatically by using actuators.

Step 7. Verify

The DT needs to be verified to ensure that it accurately mimics the behaviours of its physical counterpart with minor acceptable discrepancy. A list of checks can be performed on the physical system, the network communication, and the virtual system to examine if the data and models are integrated properly and if both assets exchange data with respect to the required specification, including if the DT can deliver the desired insight and execute the action plans.

Step 8. Validation

The validation is the final step. Considering the purpose, one must define a suitable process to carry out the validation. The aim of this validation is to ensure that the DT serves its purpose, achieves the predefined objectives, and if the specification captures the stakeholders' requirements

4. An example case study

A case study representing the aerospace sector was used to demonstrate the implementation of the presented DT framework.

4.1. Description of the case system

The asset was a multicomputer mission system of a complex computer system in operation. The development of the DT would require the asset to be in non-operational mode. Therefore, it was sensible to create a laboratory replica to start building the DT as a support for further research. A replica was created using similar components, structure, and communication protocol. Fig. 3 shows the system architecture representing the asset.

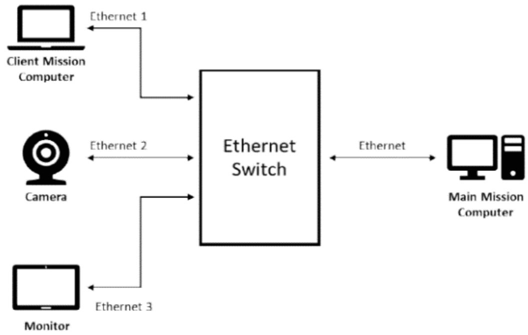


Fig. 3. System architecture of the mission computer system

The Client Mission computer is the device that processes the data and performs control on a client system. The camera and monitor are included in the monitoring system. The Main Mission computer acts as a server to collect the data from other devices. Based on the industrial requirements, the main objectives of the DT are to replicate the current monitoring system for displaying the status (e.g. connectivity) of the component systems and to extend system capabilities for failure analysis and knowledge re-use to improve asset management and maintenance.

4.2. DT development using the proposed framework

To ease the building process of the DT, a template for some steps presented in Fig. 2 was created and populated. It should be noted that the information in the template can vary across DT application.

4.2.1. Define the requirement

Table 1. DT requirement template

Function	Expected improvement	Data to be measured	Constraint
• Replicating existing monitoring system and promoting the re-use of knowledge from historical data	• To maximise the availability of the asset through better asset management and maintenance	• The connection status of the devices, • CPU and RAM usage, • CPU temperature	• The DT was developed based on an on-ground asset

4.2.2. Develop the information flow

Table 2. DT information flow template

Data sources	Type of data storage	Data interface
• Internal software that collects data from the system (e.g. CPU temperature, CPU & RAM usage, and connection status)	• Text files (.txt), • Microsoft Access	• VBA macros on Microsoft Access and Excel

4.2.3. Build the virtual representation

Table 4. DT visualisation template

Type of data	Visualisation of DT	Stakeholders	Components of visualisation
• The connection status of the devices • CPU and RAM usage • CPU temperature	• Dashboard	• Operator	• Schematic of system architecture

4.2.4. Develop the data exchange system

Table 5. DT data exchange template

Type of data	Communication technology and protocol	Bandwidth, latency, coverage	Measures for network security
• The connection status of the devices • CPU and RAM usage • CPU temperature	• Com link: WLAN • Com protocol: TCP/IP	• Bandwidth: 10 Mb/s Latency: 10 ms • Coverage: LAN	• WPA2, • Firewall • MAC authentication

4.2.5. Develop the analysis method

The analysis method used in this case study is manual analysis. Using MS Excel, the data is read, processed and displayed. The different insights are displayed with two tools: a panel and a dashboard. The panel provides data of the current status of the devices. This enables the user to be notified about a device failure and possible cause. For example, if only the Client Mission computer, the monitor or the camera is disconnected, then the failure might come from this specific device. Otherwise, if the panel displays all of them disconnected, the failure might come from the Ethernet switch or from the Main Mission computer. The dashboard provides more information such as the historical data, the frequency of disconnection, and the percentage availability of the devices. This can help to understand the recurring failures, and thus, prevent them in the future.

4.2.6. Develop actions

The action plan of DT operation in this case study is related to a maintenance task with the aim to maximise the availability of the physical asset. For example, if the asset fails during the operation, the panel will show the potential problem underlying the failure. The operator will then be notified and will be able to troubleshoot the right problem immediately.

4.2.7. Verify

The verification process consists of checking that the DT works properly according to the specification. The verification was carried out using a checklist to show the items to be verified.

Table 3. Verification checklist of developed DT

VERIFICATION	
Aim: To verify that the prototype is working properly according to its specification.	
Tests	**Checked or Not?**
Equipment	
✓ Check that all the equipment is properly installed	
✓	
Data and model (C++ program)	
✓ The instructions are sent to the right prompt command device	
✓ The instruction answers are transcribed properly	
✓ ...	
✓ Database automatically updates and saves the new data	
Data exchange	
✓ The communication link is established	
✓ ...	
Virtual representation	
✓ The panel and dashboard display the right data	
✓ The panel and dashboard automatically update the new data	
✓	
Data analysis	
✓ The panel shows the live status of all the component system	
✓ The dashboard shows the chart of system component status	
✓ ...	
Action	
✓ Operator can easily understand the alerts given by the panel and take action	
✓ ...	

4.2.8. Validate

Based on the DT objectives defined in the Step 1, an empirical test was carried out to validate if the DT meet the stakeholder's requirements. To measure to what extent DT brings improvement over non-DT system, two experiments simulating the failures were

	Experiment 1: Ethernet cable disconnection	**Experiment 2: CPU % of usage too high**
Without the digital twin prototype	The testers notice that the devices do not work. Then, they figure out that the failure comes from the ethernet cable. Finally, they try to fix the failure until that the camera, the monitor and the client mission computer work again properly.	The testers notice that the computers are slow. Then, due to the noise generated by the computers, the testers may determine that the failure comes from the CPU utilisation.
With the	The testers have only to look at the panel to identify the	

Table 6. Experimental conditions

carried out. The first experiment involved simulating the disconnection of main computer which represents the common problem of computer mission system. The result of this failure entails that all the devices stop working. The second consisted of forcing the CPU to increase its usage, causing an increment in the processor temperature, the fan speed, and preventing the computer to work properly. The description of the experiments is shown in the Table 6. In this experiment, DT prototype differs from a traditional visualisation tool as it implements a twinning paradigm [22]; the physical-to-virtual connection in which physical process parameters were continuously measured and realised in virtual twin and the realisation of virtual-to-physical connection where information generated in virtual environment was acted on in physical environment by an operator (e.g. A tester notices the failure cause from the DT and apply the change to the physical asset to fix the problem). The results were collected from sixteen people for each experiment where half of the participants took the test with the DT and the other half without the DT. An independent-samples *t-test* was run for the result of both experiments to determine statistically if any difference exists between two settings.

4.3. Overview of the developed DT system

Fig. 4 presents an overview of the system. It includes the physical asset (the mission system replica), the DT (panel) and the connection between two parts.

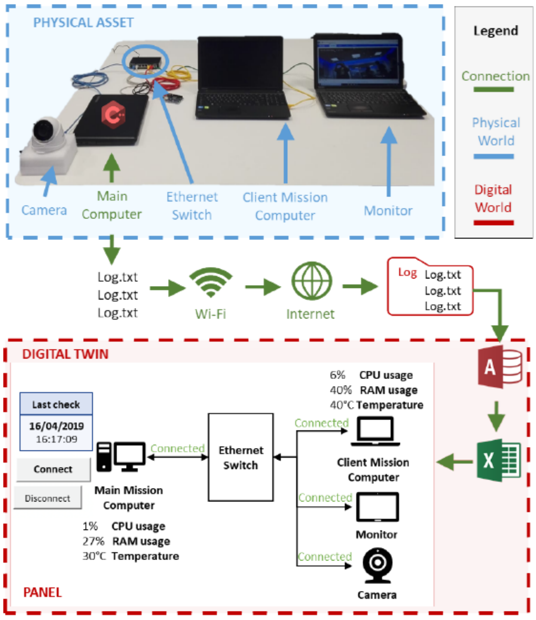
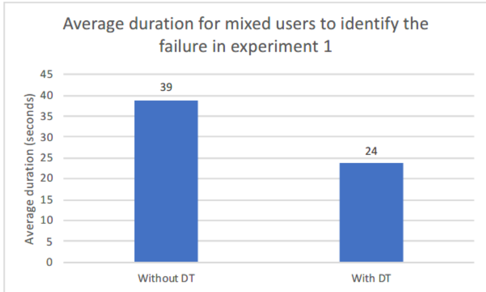


Fig. 4. DT system overview

The main computer contains a C++-based program which gathers data from the devices (e.g. client mission computer, camera, and itself) and saves it in log.txt files. Then, this data is sent through Wi-Fi to an Access database to be stored. Finally, the data is displayed using a panel and a dashboard on MS Excel.

4.4. DT evaluation

The result of the testing was recorded for both



experiments to measure how much improvement was afforded by DT vs. non-DT system. Fig. 5 shows the time differences between two groups for experiment 1. The analysis of *t-test* showed that the DT significantly reduced the time in identifying the failure by 38%. In line with this performance gain, Fig. 6 shows a larger increment in time saving for the experiment 2 by 81% while using the DT as opposed to non-DT system. The statistical *t-test* analysis showed that people were statistically significant faster in finding the problem when they used the DT.

Fig. 5. Average time failure identification (experiment 1)

According to these two cases, the DT can help the user in locating the problem more quickly. With the DT, the user can achieve 39% and 81% of time reduction depending on the type of failure. This result aligns well with the existing monitoring system. The benefit observed was echoed by the industrial sponsors' employees who helped in evaluating the DT panel of the replica. The feedback was that the initial achievement is satisfactory and the developed DT meets the sponsor's requirements. The dashboard was also perceived as helpful to identify a failure. With the DT prototype, a user can consult the dashboard, easily find what caused the problem, and promote knowledge re-use from historical data recording.

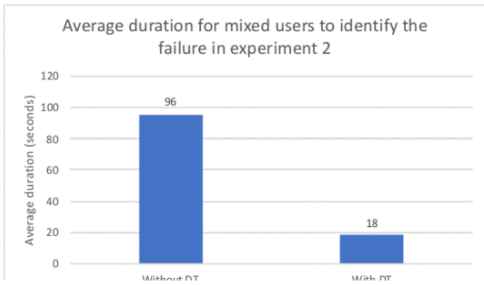


Fig. 6. Average time failure identification (experiment 2)

5. Conclusion and future Work

DT is an enabler for Industry 4.0 to realise a significant operational improvement throughout the asset lifecycle. Nevertheless, industries usually have large and complex systems, and hence, developing the DT may seem inconceivable. In addition, the lack of detailed guideline in the literature often puts users off in undertaking the digital transformation enabled by DT. This paper sought to fill the gap by presenting a framework for the DT development, including a step by step guideline and DT templates for populating the requirement(s) in each step. Although, the applicability of this framework to various assets/systems in different lifecycle phases is left to be tested, this guideline can serve as a starting point for industries and academics to commence the DT development with manageable scopes and measurable benefits. Further study will investigate the DT framework to accommodate a unified DT interface to external systems/modules for enabling a wider integration of DT system.

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