CRANFIELD UNIVERSITY

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Digital Twin Representation of a Modified Mobile Asset in Aerospace Maintenance

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ABSTRACT

A new technology, called *digital twin*, is currently investigated by many companies to get the best advantage out of it. In short words, a digital twin is a virtual representation of a physical asset with which it exchanges data. Babcock put technology at the core of their activities continually looking for innovations. Thus, they are focusing on developing digital twin technology to extend their competencies in system design, integration and support.

Available papers have been digested to better understand the digital twin technology. Then a scalable framework describing how a digital twin works and how it is built is suggested. This framework is followed to realise a prototype of a digital twin. This latter is tested and analysed to demonstrate its impacts and benefits in aerospace maintenance.

The digital twin technology has several advantages. It allows the company to reduce the time needed to identify a failure on their assets. It also enables the employees to be more autonomous in the decision-making process. Analyses from validation have demonstrated that digital twin technology enables to increase the asset's availability. In fact, the time needed to identify a failure is reduced by 38% or 81% with the use of digital twin depending on the experiments done during the validation of the prototype. Finally, based on the testers' feedbacks, the users find the digital twin prototype user-friendly and would be pleased to use it again in the future.

Keywords:

Internet of Things, Smart manufacturing, Industry 4.0, Industry of future, Digitalisation, Data.

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AI	Artificial Intelligence
ANOVA	Analysis of variance
AR	Augmented Reality
CAD	Computed Aided Designing
CAE	Computer Aided Engineering
DTI	Digital Twin Instance
DTP	Digital Twin Prototype
FEM	Finite Element Method
GE	General Electric
IoT	Internet of Things
IT	Information Technology
NASA	National Aeronautics and Space Administration
VR	Virtual Reality

1 Introduction

With the technological advances of the last decades, the manufacturing industry has changed. It is now taking a new turn known as "Industry 4.0". As part of the Industry 4.0, a new technology, called *digital twin*, is currently investigated by many companies to get the best advantage out of it. In short words, a digital twin is a virtual representation of a real asset with which it exchanges data.

This project aims to develop a framework to build a digital twin prototype and demonstrate the potential impacts and benefits on a complex asset.

To do so, the project focuses the following objectives:

- Carry out literature review about digital twin technology.
- Develop a scalable and flexible framework for the creation of a digital twin.
- Build a functional digital twin prototype for an asset.
- Carry out experiments with the prototype to demonstrate the benefits of the digital twin prototype and discuss the results.

The motivation of this research project comes from Babcock International Group. Babcock International Group is a British company that provides services to its customers to allow them to improve their performance while allowing significant cost savings. They provide their clients with better capability, reliability and availability of their assets. They put technology at the core of their activities, continually looking for innovations. In that perspective, they are focusing on developing their knowledge about digital twin technology to extend their competencies.

This project uses literature review to find an existing methodology that can be adapted in the development of the framework for the creation of a digital twin. This framework is then tested and validated with the creation of a digital twin prototype for a defined asset.

To cover this project, this paper starts with a brief explanation of the project approach and the methodology used. It explains first the purpose of this project and then the high-level end-to-end process used to realise this project. Then, the report presents the state of the art of the digital twin. In other words, it highlights the definitions of a digital twin, the different existing methodology of development, the current practices, the potential benefits a digital can have and the future trends and the research gaps of this new technology. Moreover, a framework to develop a digital twin is proposed. This framework is then used to create a prototype of a digital twin. Then, the prototype is developed, verified and validated. The results from the validation lead to a discussion. Finally, this paper concludes with some areas for improvement on the prototype and on the research on this technology.

2 Project methodology

2.1 Scope of the project

The scope and restrictions of the project are as follow:

- The framework needs to be flexible and scalable to set up a digital twin.
- The digital twin prototype is created using the framework.
- The digital twin prototype is developed using a replica of the mission system integrated on a helicopter from Babcock. The prototype might work on the real asset.
- This prototype focuses on the components of the mission system connected through ethernet wires and having an Internet connection.
- The communication between the replica and the prototype is realised using the Internet and Wi-Fi.
- The prototype mainly enables the identification of failures. It does not fix them.
- The experiments are only done using the mission system replica and not the real asset.
- The results are based on people from Cranfield who tested the prototype.

2.2 Research Methodology

This section describes the methodology used throughout all the project to achieve the above objectives.

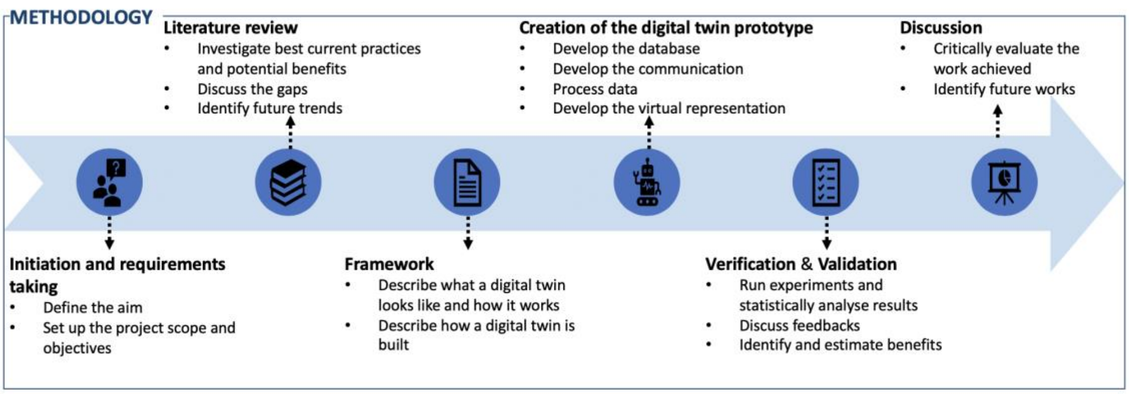

Figure 2-1 Project Methodology

2.2.1 Literature review and framework

The literature review is conducted using online databases such as Science Direct, Scopus and Knovel and Publications from companies that have already developed digital twins. Moreover, the literature review is carried out using specific keywords and combinations such as *Digital Twin*, *IoT*, *Framework*, *Collecting Data*, *Manufacturing*, *Maintenance*, etc. (list of keywords in Table A-1). The results are sorted out using filters such as *Language* and *Document Type* (i.e. *Conference Paper*, *Article*) and *Year* (from *2012*).

This methodology helps to identify relevant papers in order to acquire basic knowledge about digital twin technology. Approximately 30 different papers are used. They help to determine the existing practices in this research area. Finally, these papers are compared to identify potential gaps that can be discussed.

A framework is a document describing how to build a digital twin. Different frameworks that have already been published were consulted, discussed and analysed to develop a new scalable and flexible framework. Therefore, the framework is created based on a combination of several frameworks found in the papers.

2.2.2 Development of the digital twin prototype

Once the framework is created, a prototype is built to validate the framework. The creation of the prototype follows the steps established by the framework. Several meetings (a call or a visit every other week) with Babcock are scheduled in order to collect customer requirements (*0*

Questions to Babcock). The gathered answers processed and analysed to define the final aim of the project in order to meet their requirements.

Given that the physical asset is not always available during the project a replica of the physical asset is created on the Cranfield University campus to ease the development the digital twin prototype.

The research gathers several potential ways to develop a digital twin. An analysis comparing the advantages and disadvantages of the different possibilities is carried out in order to enable the stakeholders to agree on a solution. This choice is based on the user friendliness and sufficient performance of the software, more explanations are detailed in *5. Conceptual design.* A conceptual design is developed aiming to describe all the hardware and software used to build the digital twin prototype.

2.2.3 Verification, validation and discussion

The prototype is verified during different stages of the project with a checklist which summarises the different points of interest. This leads to verify that all the features work, and that the information provided by the digital twin is correct.

The aim of the validation is to identify the potential benefits of the digital twin prototype for Babcock's maintenance activities. To do so, a quantitative and qualitative validation is conducted with external testers. Around 30 students from Cranfield University were asked to identify a failure and its cause in the physical asset without the digital twin, and then with the digital twin. The tests are timed in order to have quantitative data. The tests are timed in order to have quantitative data. Statistical analyses (f-test, t-test and ANOVA) were carried out to highlight the impacts of the digital twin prototype. These same testers are also asked to answer a survey at the end to get their feedback about the digital twin, which constitutes the qualitative validation.

Moreover, a validation is conducted with Babcock's employees (engineers and management) who have also answered the survey.

All the data collected is analysed and the results give an insight of the potential benefits of a digital twin in maintenance and recommendations about future works to accomplish.

3 State of the art of digital twin technology

3.1 Definitions of a digital twin

There are several definitions for a digital twin (Table B-1). All the definitions agree that the digital twin is a virtual representation of a real asset with which it exchanges data. However, they do not focus on the same aspect of a digital twin. Some definitions emphasise that a digital twin is a virtual model that detects all the defects of a physical asset and that would be continually updated to cover the evolution of the physical asset during its use. Other definitions emphasise that a digital twin is a virtual model of a physical object equipped with sensors used to collect data (Parrott and Warshaw, 2017).

The definition which suits the most this project is the one exposed by NASA in 2012 (Glaessgen and Stargel, 2012):

"A digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin."

According to this definition, a digital twin can be defined as a virtual replica of a physical asset that can be a product, a process, a building etc. The digital twin can be used at all scales, even for complex assets. It is connected to the physical asset through several devices to exchange real-time data in both ways.

3.2 Development of a digital twin

Many papers highlight the main steps to create a digital twin. Almost all of them describe the same steps but not in the same order (comparison in Table B-3). Deloitte suggest six main steps to set up a digital twin (Parrott and Warshaw, 2017):

- **Create:** Sensors are set up on the physical asset to measure inputs from the physical asset and its surroundings. This information is represented using a virtual model of the physical asset (CAD, 2D modelling, ERP, etc.).
- **Communicate:** A real-time and bidirectional connection between the physical and virtual asset is established during this step. This connection

is realised using technologies such as network communication and cloud computing.

- **Aggregate:** A database is created to store data collected from different sources. The data is prepared for analysis.
- **Analyse:** Data collected is analysed and visualised.
- **Insight:** Analysis is carried on. Based on this analysis, some areas which potentially need investigation and change, are identified. Therefore, the user can use advanced technologies to generate recommendations and guide decision making.
- **Act:** It is during this step that recommendations from the previous steps can be realised. The user orders the physical asset to perform behaviours, based on the insights obtained from the previous analysis. This interaction between the two assets is the loop connection between the physical world and the digital world.

These steps are summarised in Figure 3-1.

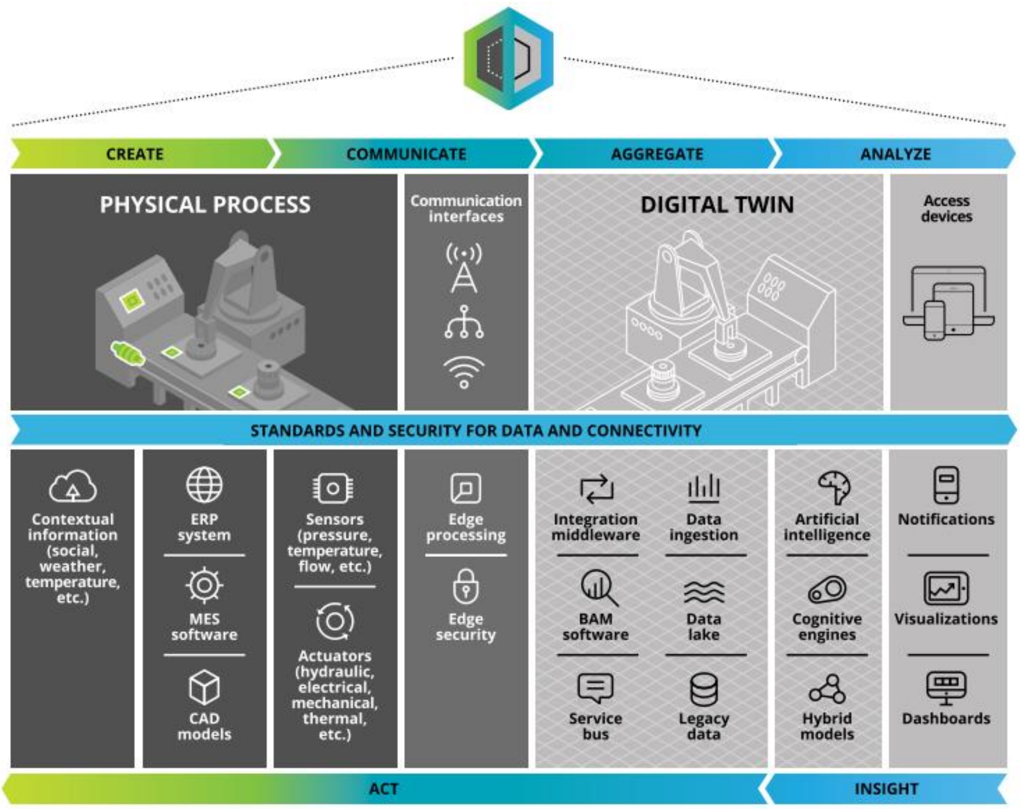

Figure 3-1 Digital Twin conceptual architecture (Parrot and Warshaw, 2017)

3.3 Current practices to implement a digital twin

Some of the technology leader companies have taken one step further by introducing the digital twin technology into their activities. Some examples of companies which have implemented this technology.

Rolls Royce and General Electric created their own digital twins of their engines to improve their maintenance activities. For instance, GE can monitor accurately the maintenance of an engine blade with the help of this technology. As a result, workers can make faster and appropriate decisions when a failure occurs, saving time (Mussomeli et al., 2018).

Digital twins have been also implemented in other sectors. The tractor manufacturer Stara used this technology to modernise agriculture. Their tractors are equipped with IoT sensors which enable to improve their efficiency. By collecting real-time data from them, the company can prevent equipment failures and extend their lifecycle. Based on the advantages that the digital twin gave them, the company decided to change their strategy. This strategy consisted in introducing a new cost-effective service that informed the farmers in real time about the optimal conditions for sowing, allowing them to increase their farm's productivity (Ohnemus, 2018).

3.4 Benefits of a digital twin

Parrott and Warshaw explain in 2017 that, in the past, due to the limitation of computer capabilities and cost, companies were not willing to invest in digital twin technology. Nowadays, with the increase of storage capacity and computer performance, companies invest more and more in this technology.

Ulbert highlights one of the main benefits of the digital twin (Ulbert, 2017): a better understanding of their physical assets. Many companies used expensive prototypes to run experiments on their products before launching them for production. Today, digital twins can replace these expensive prototypes and enable companies to carry out cheaper experiments.

Moreover, Ulbert points out another benefit: a digital twin can collect data in real-time by using devices, such as sensors, equipped on the physical asset. Thus, the digital twin can analyse the data and use it to detect defects. Therefore, a digital twin can be helpful to support fault diagnosis and understand wear and degradation better. As a result, it can lead to a better planning of maintenance activities.

In addition to these two examples, Table B-2 presents other benefits. The digital twin technology can have different benefits depending on the purpose of its implementation.

3.5 Future trends

Digital twin technology is in its early stage. However, in 2023 the market for digital twins is expected to reach $16 billion (Parrott and Warshaw, 2017). In the future, GE Digital (2017) highlights that the goal is to apply digital twins from the smallest component to a complete chain of production. The digital twin will change the way that industry works. This technology will involve organisational changes within the industry to enable an effective production.

Beyond the industrial sectors, other sectors are also interested in twin digital, such as:

- Healthcare: in the future, digital twins will be used to test drugs or prosthesis before they are used on humans. These digital twins will be based on the patients' data. This technology will lead not only to an increase of the security for the patients but also to a significant decrease in research costs (Marchal, 2018).
- Smart cities: digital twins will enable municipal administrations to simulate any project before implementing it physically, for example checking for potential problems before they become reality (Aaron, 2018).

3.6 Research gaps

Although there are several documents concerning the digital twins, some research gaps can be identified. As the digital twin technology is at its beginnings, further steps need to be taken:

- The implementation of a digital twin remains complex. It demands effort, time and money from the companies. Companies need to have all the required technology infrastructure (software, database, etc.) in order to be able to implement this technology. Some of these technologies may be also at their beginnings (IoT platforms, for instance). For this reason, the digital twin technology is not yet widespread.
- The communication establishment between the virtual model and the physical asset is not very clear. The speed of data transmission is not mentioned. Several documents suggest ‘real-time’ data without being precise. Every data exchange requires time to be realised, thereby the ‘real-time’ expression is not really appropriate.
- The issues that a digital twin might generate (data-sharing, security, and accessibility concerns) are not deeply discussed.
- There is a lack of consistent approaches to develop digital twins, which makes difficult to find a common methodology.

4 Framework to develop a digital twin

This part describes the framework which answers the questions ‘What does a digital twin look like? How does it work?’ and ‘How to build a digital twin?’. It is composed of two main parts:

- Architecture: it gives an overview of what the digital twin looks like and how a digital twin works. It describes the components required to build a digital twin, and how they interact together to make the digital twin work.
- Building a digital twin: it is the main part of this chapter. It describes the steps that need to be followed in order to build a digital twin.

4.1 What does a digital twin look like and how does it work?

- **Data collection from the physical asset**

The digital twin collects information from the physical asset. This information is essential for the digital twin given that it is used to mimic the behaviour of the physical asset in the most accurate way. The information comes mainly from sensors integrated in the physical asset, but it can also come from other sources, such as historical records, user interaction.

- **Communication between the physical asset and the digital twin database**

The physical asset and digital twin are configured with a real-time, bidirectional and secured connection. The information that is collected from the physical asset is sent in order to be processed and stored in the digital twin database. This can be done through wires or wireless connections, depending on the physical asset’s characteristics, digital twin purpose, and environment conditions.

- **Process the information**

The data collected needs to be processed and transformed in order to reduce the size of the data that is stored, keeping only the key information.

The key information is selected and then translated in a more understandable way in order to be used for the virtual representation of the digital twin and for analysis purposes. For example, the temperature measured with a sensor might be obtained in terms of voltage, which needs to be translated into degrees Celsius.

- **Storage of the information in a database**

All the data processed is stored in a database for future use (virtual representation and analysis). This database is automatically being updated with the new information that comes from the physical asset. The database can be stored on local servers or on cloud.

- **Actions performed based on the analysis**

This last part of the architecture achieves the purpose of the digital twin itself. The digital twin analyses the data collected from the physical asset and recommends some actions in response. It can even perform those actions in the physical asset using actuators or software.

Figure 4-1 below presents the architecture of the digital twin and how the physical and virtual worlds interact with each other.

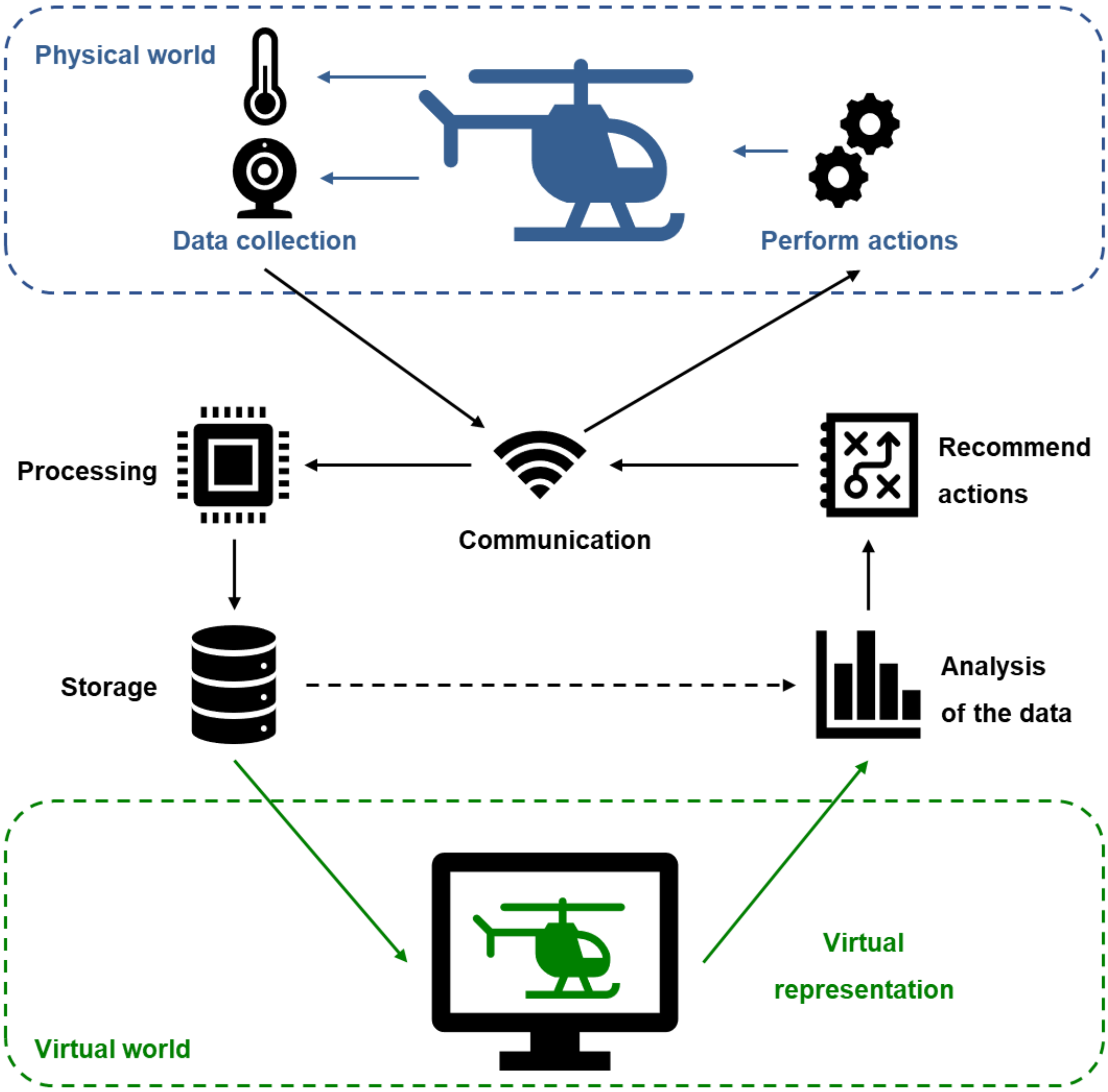

Figure 4-1 Architecture of the digital twin

4.2 How to build a digital twin?

The actions that need to be undertaken in order to build a digital twin can vary in many ways, depending on the physical asset characteristics and the purpose of the digital twin. Although, there are a set of common steps that need to be followed in order to successfully build a digital twin.

4.2.1 Define the requirements

The first step of the building process is to define the requirements of the digital twin to be built properly. The main aspects of this step are:

1. *Aim of the digital twin:* A digital twin can have several purposes. To define the aim of the digital twin, the user needs to answer these two questions:
    - What are the outcomes and improvements that the user expects from the digital twin?
    - What kind of analysis does the user expect to carry out with the digital twin?
2. *Data to be measured:* Based on the digital twin purpose, the type of data that needs to be collected has to be defined. It is essential to define what data needs to be measured.
3. Constraints: In most cases, there are constraints that have to be taken into consideration for the development of the digital twin.

4.2.2 Develop the information flow

One of the main functions of the digital twin is to collect real-time data that is going to be used later for analysis. Then, this data is stored in a database.

The data can come from different sources:

- *Physical sensors:* sensors are set up on the physical asset in order to collect data from the physical asset itself and its surroundings. Sensors mainly collect two types of data:
    - operational measurements (characteristics of the physical asset; such as position, displacement and torque)

    - environmental or external data (elements that influence the physical asset; such as barometric pressure, ambient temperature, moisture level etc.).
- *Internal software:* a computer program can be installed on the physical asset in order to collect internal data from the system. These programs can be generic or developed specially for the digital twin, depending on its requirements (such as security, safety, integration, element to be measured, etc.).
- *Historical data:* historical data that has been recorded in the past and stored can be integrated to the digital model and used for further analysis.
- *Data entered manually by the user:* one source of data could be user input. For instance, the bill of materials of a new product, subjective data, visual inspection, etc.

Regarding data storage, and considering the requirements of the digital twin, such as accessibility, size, security, etc.; there are two main ways to store data:

- Local storage: data is stored on a local server.
- Cloud storage: data is stored on an online server. The data can be easily accessed by all the users from anywhere with an Internet access.

4.2.3 Develop the virtual representation

This step involves building the virtual representation of the physical asset. The virtual representation can be done in different ways, depending on the following possible analysis of a digital twin:

- Geometrical / Geospatial analysis: A 3D representation of the physical asset is created using a CAD software.
- Mathematical / Physical analysis: The physical asset is displayed as a 3D representation using a CAE software in order to carry out the simulation (for example, a FEM analysis).
- Business intelligence analysis: A can panel/dashboard is developed in order to display the main information. Even if it is not essential for this

purpose, a 3D or 2D representation can be realised to have a better representation of the physical asset.

4.2.4 Develop the data exchange system

At this stage, the communication between the physical asset and the digital twin database needs to be established. This must be a real-time, bidirectional interaction/connection.

Many different technologies can be used depending on the characteristics of the physical asset and where the digital twin database is stored. Some examples of these technologies are Bluetooth, Wi-Fi, 3G/4G, ethernet, optical fibre, etc.

Network security needs to be considered at this point. The data exchanged between the twins through network technologies can be sensitive. Therefore, the network communication needs to be secured. For example, data can be encrypted when using Wi-Fi or 3G/4G connection.

4.2.5 Verify

The digital twin needs to be verified in order to ensure that it accurately mimics the physical asset's behaviour in the most accurate way. The verification consists of checking if the digital twin works properly and if both assets exchange data. For example, checking that the digital twin is updated after the physical asset performs some actions.

4.2.6 Develop the analysis methods

Once the digital twin is verified, the data collected needs to be analysed. This step is crucial to ensure that the purpose of the digital twin is achieved.

There are different ways to carry out analysis. Some examples are:

- Compare data taken at different times
- Check if some criteria are met
- Do statistical calculations
- Identify patterns

This analysis can be displayed in tables, pie charts or graphs.

Finally, based on this analysis, the digital twin can recommend the physical asset to perform some actions/behaviours.

4.2.7 Develop actions

Once the data is analysed, the user has to implement condition-action rules to be automatically performed over the physical asset depending on the analysis obtained from data, and thus fixing errors over the physical asset.

4.2.8 Validate

The validation is the final step. Considering the purpose, the user must define a suitable process to carry out the validation. The point of this validation is ensuring that the digital twin achieves the objectives defined by the user at the beginning of the creation.

5 Conceptual design of the digital twin prototype

The purpose of this part is to present the conceptual design of the digital twin prototype.

The asset used for the creation of this prototype is a complex multicomputer mission system representing one of Babcock's assets. Given that it is not possible to work on the real asset, a replica of this asset is created, and the digital twin prototype is developed for this replica. The whole system includes:

- The replica of the original asset from Babcock
- The digital twin prototype

The methods, processes and strategies used to build the prototype are described in the following paragraphs.

5.1 Description of the system

5.1.1 The real asset and the replica

Considering the confidentiality agreement, the original mission system used in Babcock's helicopters is not developed in this document.

The replica consists of a part of the mission system. This replica is created using similar components, structure and communication protocol as the real asset. Thus, this replica is a relevant representation of the asset.

The components used are:

- A main mission computer
- A client mission computer
- A monitor
- A camera
- An ethernet switch
- Four ethernet cables

Figure 5-1 shows how these components are connected.

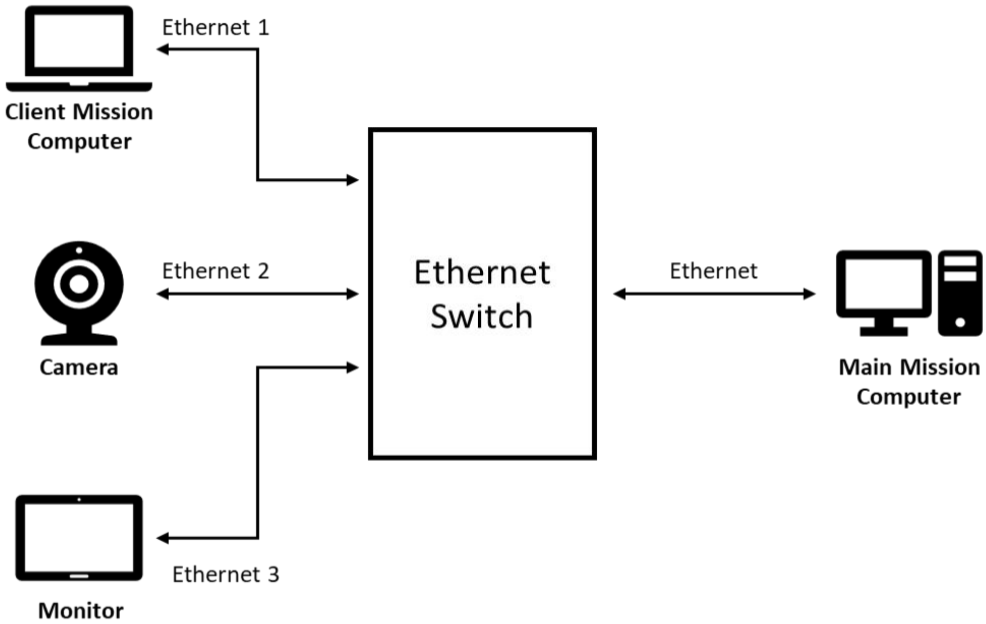

Figure 5-1 Replica of part of the mission system

5.1.2 Main objectives of the prototype

Based on Babcock's requirements, the main objectives of this prototype are:

- The creation of a real-time and historical database: this can help Babcock to ease decision-making by collecting useful data.
- The identification of failures: Babcock could have an overview of the status of all the components (connection/disconnection).
- The identification of the potential causes of the failures detected: Babcock could do forecasts and better plan their maintenance activities.

5.2 Conception of a solution for the digital twin prototype

5.2.1 Potential solutions

Regarding the requirements collected from Babcock and the aim of the project, three solutions are considered. These solutions aim to meet the objectives described above. Table 5-1 gives an overview of the different solutions considered and their main pros and cons, Table C-1 gives more information concerning these solutions.

Table 5-1 Solutions considered

	Solution 1: C++ code/Microsoft Access and Excel	Solution 2: Java/Open Source/Dashboard	Solution 3: Microsoft Azure
	C++ A X	Java ThingsBoard ditto MQTT	Microsoft Azure
Pros	• Easy to procure • Using C++ and VBA	• Open source, thereby it is possible to change the program	• Easy to use with minimal IoT experience (templates are available) • Package contains everything to create the digital twin (e.g. database, dashboard, functionalities to set up a bidirectional communications)
Cons	• Might require more time given that everything is built from scratch	• Might require to combine several software/languages to build the digital twin • New knowledge to acquire and then might require more time	• Not free • Not very widespread, it is at its beginnings • Source code not accessible • Confidentiality concerns: Microsoft store the data
Price	• Free, everything already available	• Standard version is free • Further functionalities require fees	• Depends on the amount of devices, messages sent : £1.5/device/month + £3.7/1M messages/device

5.2.2 Solution selected

After a workshop with Babcock's engineers, it has been decided to pursue the project with the first solution given that the short duration of the project and the project scope.

This solution enables the prototype to be built from scratch and be adapted to Babcock's requirements. Finally, this solution allows the project to highlight the limitations encountered in creating a framework.

5.3 Creation of the prototype

5.3.1 Use of the framework

The framework is applied to build the digital twin prototype. This highlights the scalability and feasibility of the framework.

5.3.1.1 Define the requirements

Aim of the digital twin: The main aim of the digital twin prototype is to identify the failures and suggest some potential causes responsible for the failure. This leads to the improvement of maintenance operations by increasing asset availability while saving time in identifying failures. The user could visualise and compare data in real-time thus easing decision-making on how to fix the failure.

Data to be measured: The digital twin prototype displays the connection of the devices. This is done by sending pings to the devices and analysing their responses. Moreover, it measures the CPU, RAM usage, and the CPU temperature.

Constraints: The digital twin is developed based on an on-ground asset.

5.3.1.2 Develop the information flow

Physical sensors: No physical sensors are used.

Internal software: A C++ code installed in the replica collects internal data from the system (CPU temperature, CPU usage, and RAM usage) and data about the connection between devices (Figure C-2 shows the high-level diagram of this code).

Historical data: Historical data of the asset is not available.

Data entered manually by the user: No data needs to be entered manually.

The C++ code is installed on the Main Mission System (shown on Figure 5-1). Moreover, all the devices communicate with each other through ethernet cables. Each device has its own fixe IP address. The C++ code communicates with the command prompt of the Main Mission Computer and sends instruction requests to the devices using their IP address.

Depending on the device, there are different instructions sent by the C++ code to collect data:

- ***Ping****:* A ping is a software command which allows the Main Mission computer to check the connectivity of the other devices to which it is connected. This command sends a fixed number of packages to the IP address of the device concerned. This command enables the Main Mission computer to identify how many packages come back. If all of them come back, it is considered as a success. Otherwise, there is a failure in the connection.
- ***CPU and RAM usage, CPU temperature****:* The C++ code runs an instruction to get the CPU and RAM usage, and the CPU temperature at

a specific time. Therefore, the Main Mission computer and the Client Mission computer use this command to collect this data.

The answers of these instructions are saved in text files (.txt), called “log files”. These files are stored online in an external server. Thus, the data is easily accessible, and it allows different users to access the same data from different locations at the same time. Moreover, using an external server ensures data integrity in case the physical asset or computer on which the digital twin is installed breaks down.

The next step involves Microsoft Access, which is used as a database. It contains the data that comes from the “log files” saved in the external sever. Microsoft Access enables relevant results in terms of data management and compatibility with other software.

Microsoft Excel is used to create a panel and a dashboard composed of different graphs displaying the asset’s status. Excel imports the data from the Microsoft Access database.

Figure C-1 shows the high-level diagram of the VBA code in the Access and Excel, as well as their interactions.

Finally, several VBA macros are created on the Excel and Access software to enable an instant update of the database, panel and dashboard.

An overview of the information flow between the mission system replica and the digital twin prototype is shown on Figure 5-2.

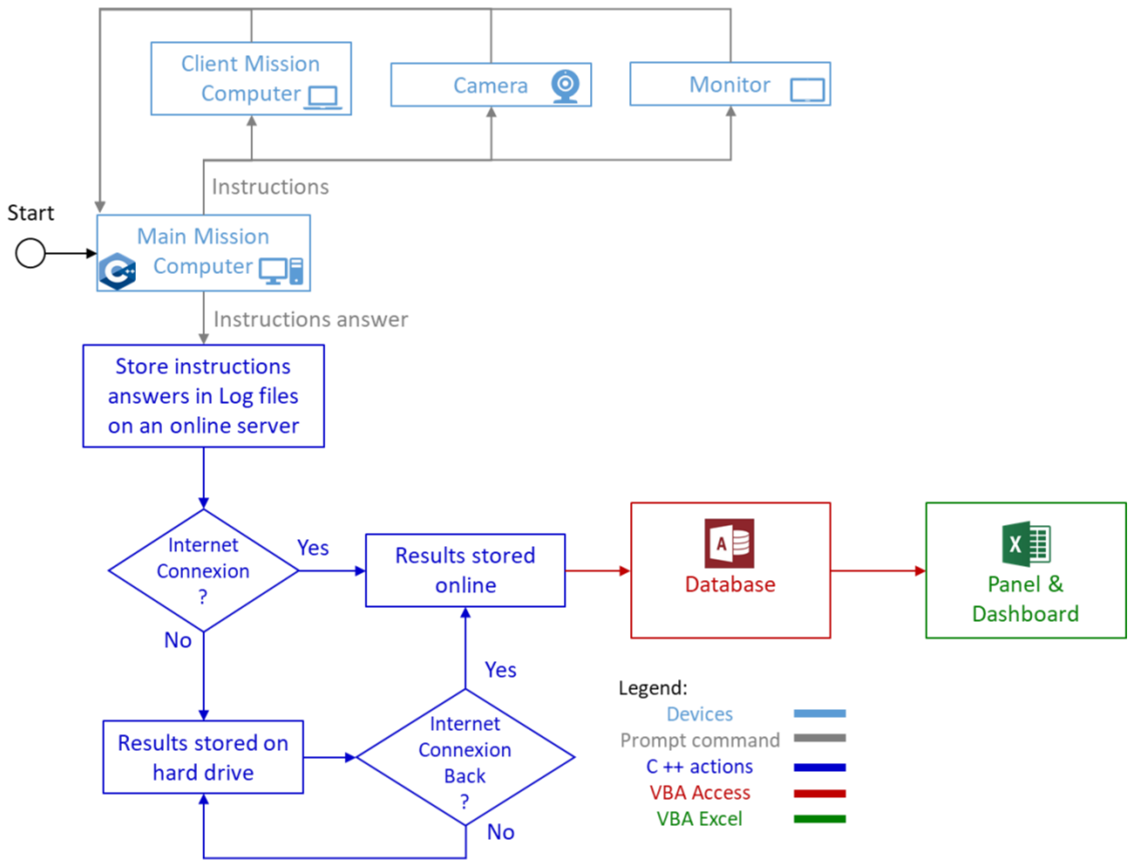

Figure 5-2 Information flow between the digital twin and the replica

5.3.1.3 Develop the virtual representation

The panel on Excel (Figure 5-3) displays performance information about the replica. The parameters shown are the device connectivity status, CPU and RAM usage and temperature. The panel can be connected and disconnected at any time according to the user preference with simple buttons to display data (connect/disconnect buttons).

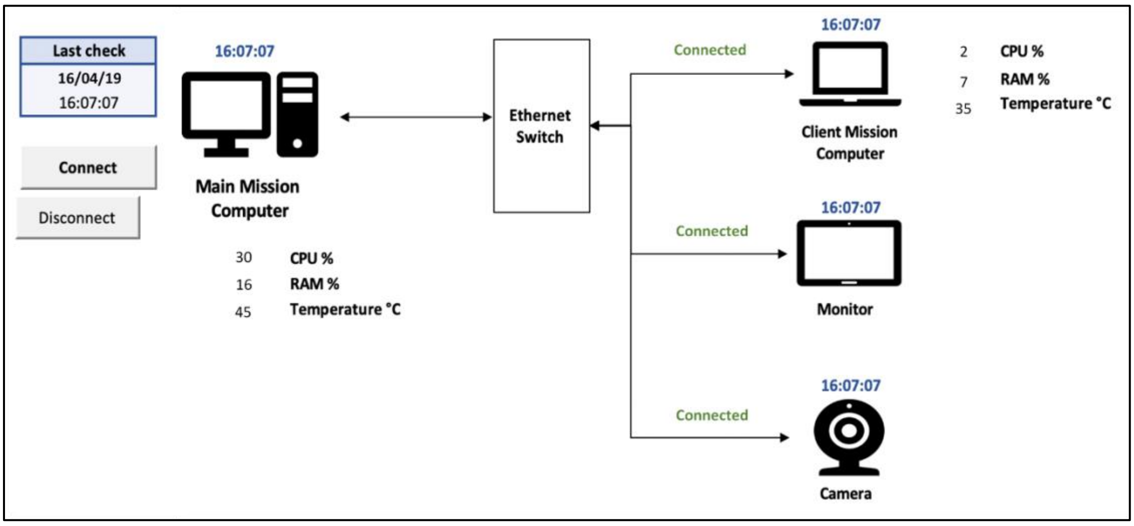

Figure 5-3 Digital twin panel

The dashboard (Figure 5-4) shows time-series graphs of the data recorded from the replica and stored in the database to do further analysis. The user is able to select the timeframe of the data to be displayed.

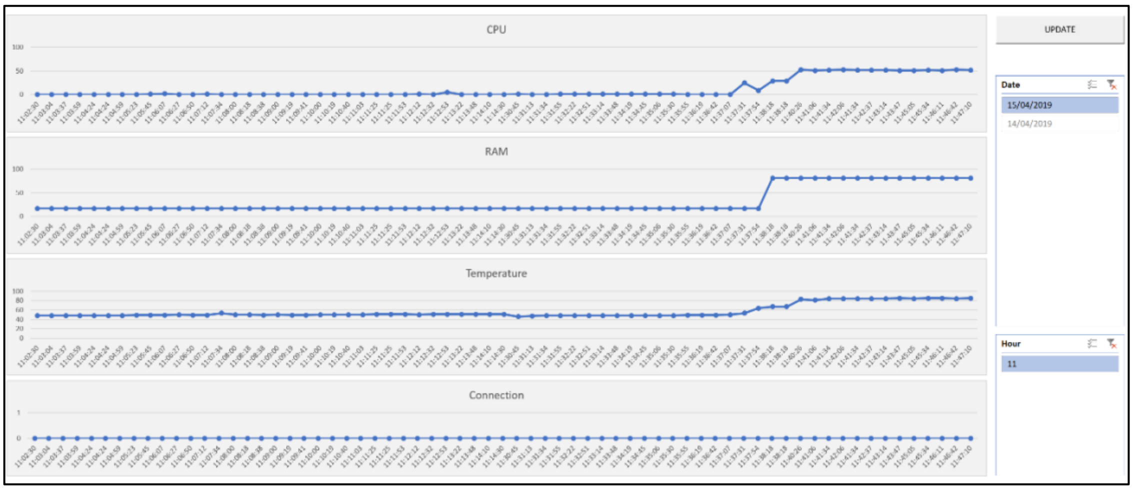

Figure 5-4 Dashboard

5.3.1.4 Develop the data exchange system

As previously mentioned, data is exchanged between the digital twin and physical asset. The digital twin collects data from the external server. This data stored on the external server comes from the outputs of the C++ code. Therefore, the communication is established through the Internet using Wi-Fi.

5.3.1.5 Verify

The verification process consists of checking that the digital twin works properly. This step ensures that the digital twin does not display the wrong information. Concerning Access and Excel files, a checklist is used to mention the items which need to be verified. This part is discussed in detail in *6. Verification and validation*.

5.3.1.6 Develop the analysis methods

Using Excel, the data is read, analysed and displayed. The analysis consists of comparing the different data collected through graphs. These highlight the abnormal behaviours of the components. The different analysis can be achieved 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 to analyse the data to identify the 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 (Figure 5-4) provides more information. It is used to visualise historical data in order to find relationships, understand the potential causes of the failures and, therefore, prevent them in the future. This data is also processed to display the frequency of disconnections, and the percentages of availability of the devices. Therefore, it highlights the devices to which the user must pay attention to avoid potential failures.

5.3.1.7 Validate

The validation consists of demonstrating the benefits of using a digital twin in maintenance. The validation is carried out by realising several experiments run by external people. These experiments consist of simulating failures and analysing how people identify the failure with and without the digital twin.

A quantitative validation through a stopwatch study and a qualitative validation through a survey are conducted to evaluate digital twin benefits. This estimates the reduction of time by using the digital twin prototype and collecting feedback and comments from users. The validation is detailed in *6.2 Validation*.

5.3.2 Overview of the system

Figure 5-5 presents an overview of the system. It includes the physical asset (the mission system replica), the digital twin (more precisely the panel) and the communication between two parts. As agreed, the prototype is developed with the solution 1. Therefore, the main computer contains a C++ code which gathers the data from the devices and save it in log.txt files. Then, this data is sent to the Access database to be stored. Finally, the data is displayed using a panel and a dashboard on Excel.

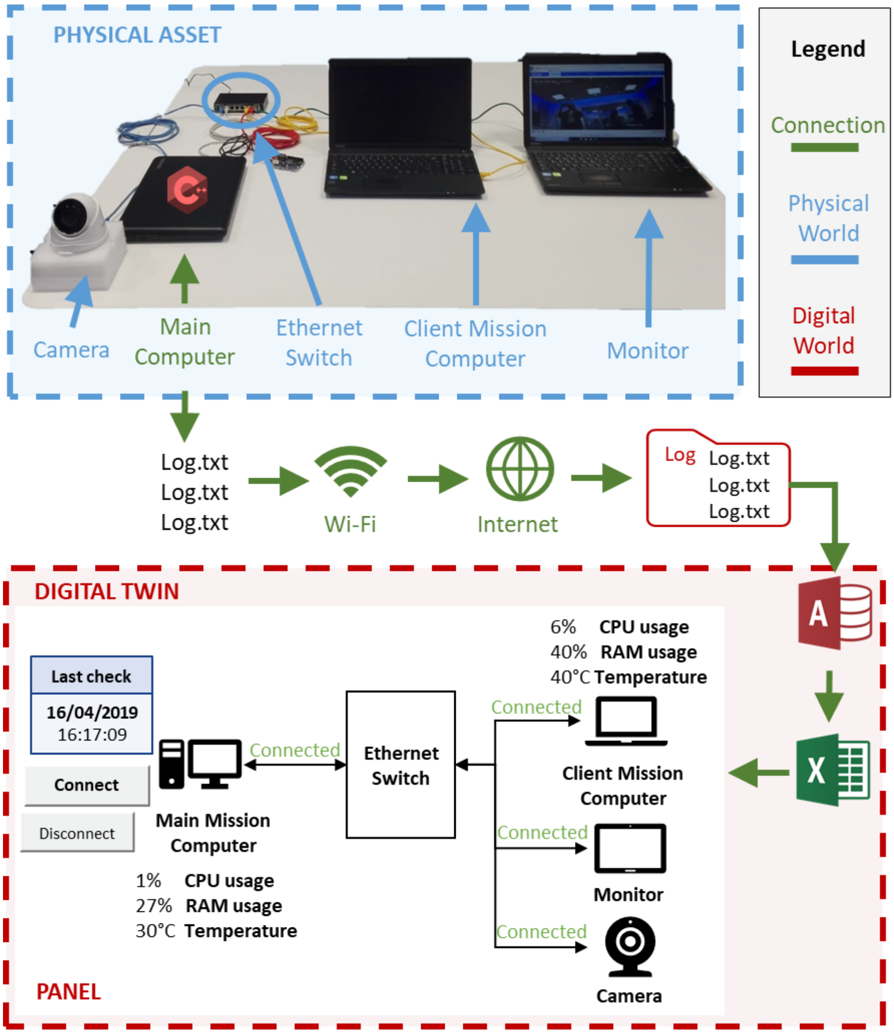

Figure 5-5 Overview of the system

6 Verification and validation

6.1 Verification

Once the prototype is developed, the verification is done before starting the validation part of the prototype, in order to ensure the correct performance of the prototype. The verification is carried out using a checklist showing the different points that need to be checked.

Table 6-1 Verification checklist

VERIFICATION	
Aim: To verify that the prototype is working properly.	
Tests	**Checked or Not?**
Equipment	
✓ Check that all the equipment is properly installed.	
C++	
✓ Check that the instructions are sent to the right prompt command device.	
✓ Check that the devices answer properly to the instructions.	
✓ Check that the instruction answers are transcribed properly on the 'log.txt' files.	
Access	
✓ Check that the path where the 'log.txt' files are saved is correct.	
✓ Check that the VBA Access collects the right data from the 'log.txt' files.	
✓ Check that the database automatically updates and saves the new data collecting from the 'log.txt' files.	
Excel	
✓ Check that the path where the database is correct.	
✓ Check that the data on Excel equivalent the data from Access.	
✓ Check the formulas in Excel are correct.	
✓ Check that the panel and dashboard display properly the right data.	
✓ Check that the panel and dashboard automatically update the new data collecting from the database.	

As shown in Table 6-1, the verification concerns the hardware and the software. It starts by checking that all the equipment is properly installed. Then, the verification consists of checking that the software (C++, Access and Excel) does what it has been programmed to do. It mainly involves checking that the data is correct, displayed and updated.

Once the prototype is verified, the below behaviours confirm that it is working properly:

1. Connections: The cable connections and disconnections in the physical asset match the information displayed in the panel, within the updating period.
2. Computer parameters (CPU, RAM and temperature): The parameters displayed in the digital twin panel and in the activity monitor of each of the computers match within the update period.

Therefore, the verification ensures that everything works properly, allowing the validation phase to be started.

6.2 Validation

The validation of the prototype aims to confirm that the digital twin can significantly improve the maintenance activities and that the data collected can be useful to predict potential failures.

The validation process is composed of two experiments, each of them is carried out twice: one time without the digital twin and one time with. Then, some analyses are carried out to highlight the benefits of using a digital twin. These experiments attest if developing a digital twin is worth it.

6.2.1 Description of the experiments and the tester sample

6.2.1.1 Description of the experiments

The experiments consist of simulating a failure. These experiments are based on common failures that usually affect the main mission system.

The experiment 1 consists of unplugging the wire between the ethernet switch and the main computer, as shown in Figure 6-1. This causes the disconnection of the Client Mission Computer, the camera and the monitor. Therefore, all the devices stop working.

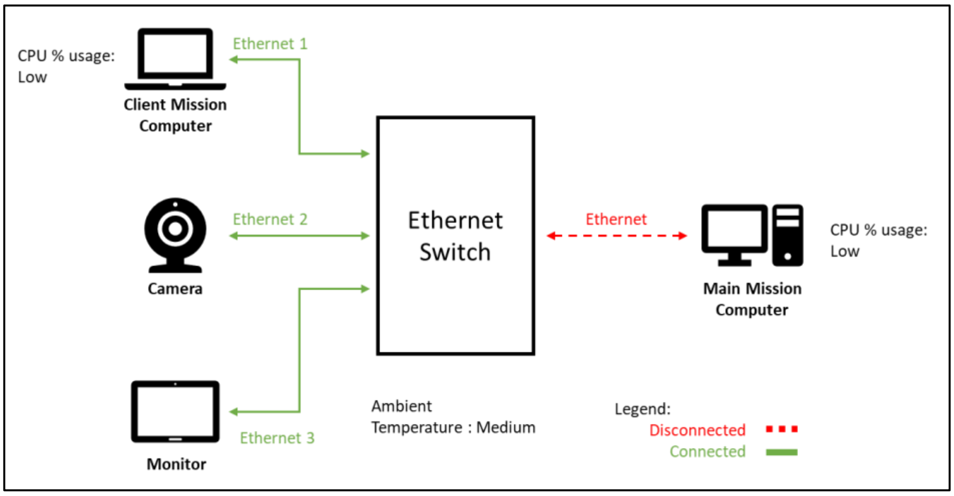

Figure 6-1 Visual description of the experiment 1

The experiment 2 consist of forcing the CPU to increase its usage, causing an increment in the processor temperature and, therefore, increasing the fan speed, as shown in Figure 6-2. Therefore, this prevents computers from working properly.

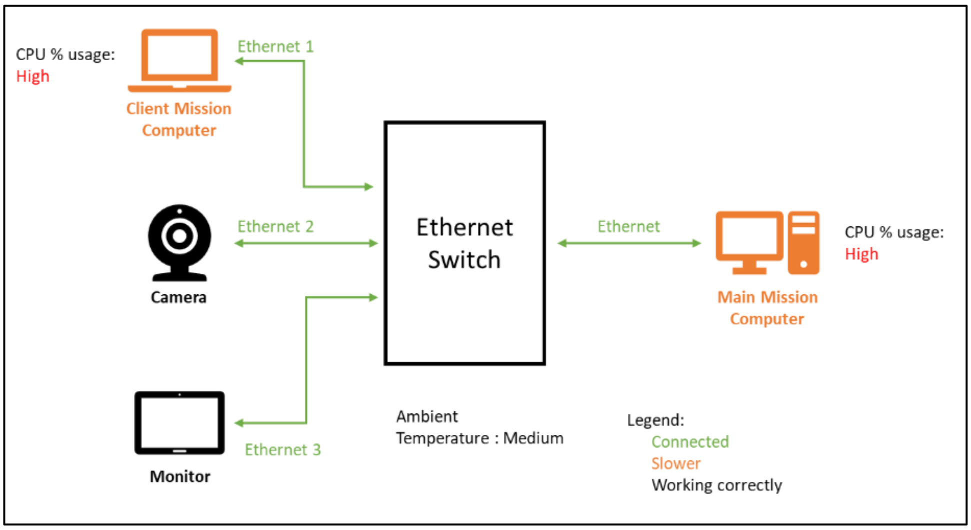

Figure 6-2 Visual description of the experiment 2

The testers have to identify these failures with and without the digital twin prototype, as described in Table 6-2.

Table 6-2 Description of experiments 1 and 2

	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 digital twin prototype	The testers have only to look at the panel to identify the failure.	

The experiments are performed by several testers to have representative results. Although some Babcock employees carried out these experiments, the results presented in this document focus on the experiments performed by testers from Cranfield. The feedback from Babcock is discussed further in this chapter (*6.2.5 Babcock's expertise and feedback*).

6.2.1.2 Validation Indicators

To validate these experiments, time is chosen as the validation indicator. For each tester, the time that they take to identify the failure is measured.

6.2.1.3 Description of the tester sample

To validate the digital twin prototype, 32 people from Cranfield University participated in these experiments:

- 16 people were part of the experiment 1:
    - people without the digital twin prototype and among them 4 are IT-users and 4 are not.
    - people with the digital twin prototype and among them 4 are IT-users and 4 are not.

- 16 people were part of the experiment 2:
    - people without the digital twin prototype and among them 4 are IT-users and 4 are not.
    - people with the digital twin prototype and among them 4 are IT-users and 4 are not.

6.2.2 Quantitative analysis

The quantitative analysis focuses on how the digital twin prototype and the background of the users impact the time required to detect the failure.

6.2.2.1 Hypothesis used for validation

This section describes the different hypotheses that the experiments aim to answer, and the analyses carried out to answer each of them.

Hypothesis 1: A digital twin significantly reduces the time required to identify a failure. For both experiments 1 and 2, the following comparisons are realised:

- *For IT users:* 'without digital twin prototype' vs. 'with digital twin prototype'
- *For non-IT users:* 'without digital twin prototype' vs. 'with digital twin prototype'
- *For all testers:* 'without digital twin prototype' vs. 'with digital twin prototype'

Hypothesis 2: The background of the user (IT or non-IT) has an impact on the identification of the failure when **not using the digital twin prototype.** For both experiments 1 and 2, the following comparison is realised:

- Without Digital Twin prototype: 'non-IT' vs. 'IT users'

Hypothesis 3: The background of the user (IT or non-IT) has an impact on the identification of the failure when **using the digital twin prototype.** For both experiments 1 and 2, the following comparison is realised:

- With Digital Twin prototype: 'non-IT' vs. 'IT users'

6.2.2.2 Statistical methods and results

Regarding the analysis, three different statistical methods are used: f-test, t-test, and ANOVA test. All these methods are used to compare the impact of factors between several samples, more detailed in *D.1 Descriptions of statistical methods*.

For this project, all the methods are always carried out between two samples, considering a unique factor and its impact on the time result.

To begin with, an f-test is realised to determine whether the variances of the two samples are equal. If the variances are equal, then an equal variance t-test is realised, otherwise an unequal variance t-test is applied. Finally, to check the t-test results, the ANOVA method is also realised. The following Table 6-3 presents the overall conclusions drawn from the statistical methods, which are further developed in the *D.1 Descriptions of statistical methods.*

Table 6-3 Statistical results

	Experiment 1: *Ethernet cables failure*	**Experiment 2:** *CPU utilisation too high*
Case 1: Without the digital twin prototype. *Samples:* 'IT users' vs 'no-IT users' *Factor:* IT Background	Being an IT-user or not is ***not significant*** for this experiment.	Being an IT-user or not is ***significant*** for this experiment.
Case 2: With the digital twin prototype. *Samples:* 'IT users vs 'no-IT users'. *Factor:* IT Background	Being an IT-user or not is ***not significant*** for this experiment.	Being an IT-user or not is ***not significant*** for this experiment.
Case 3: IT users. *Samples:* 'with digital twin prototype' vs 'without digital twin prototype'. *Factor:* Use of the digital twin	Using or not the digital twin prototype is ***significant*** for this experiment.	Being or not an IT-user is ***not significant*** for this experiment.
Case 4: no-IT users. *Samples:* 'with digital twin prototype' vs 'without digital twin prototype'. *Factor:* Use of the digital twin	Using or not the digital twin prototype is ***not significant*** for this experiment.	Using or not the digital twin prototype is ***significant*** for this experiment.

	<u>Experiment 1:</u> *Ethernet cables failure*	**<u>Experiment 2:</u>** *CPU utilisation too high*
<u>Case 5:</u> all the testers. <u>*Samples:*</u> 'with digital twin prototype' & 'without digital twin prototype'. <u>*Factor:*</u> Use of the digital twin	Using or not the digital twin prototype is ***significant*** for this experiment.	Using or not the digital twin prototype ***might be significant*** for this experiment according only to the ANOVA test.

6.2.2.3 Experiment 1 analysis

6.2.2.3.1 Case 1: Without the digital twin prototype. Samples: 'IT users' vs 'no-IT users'

For this case, the testers did not have access to the digital twin prototype.

According to the statistical methods (the calculations are detailed in D.2.1), being an IT-user or not does not have a significant impact on identifying the cause of the failure. Indeed, to identify that an ethernet cable is unplugged the subject does not need to have a specific background.

However, the small observable difference between non-IT and IT users is due to the fact that the non-IT users tended to first look at the cables to check the connectivity to identify the failure while IT users tended to look at the camera and the monitor the be sure the components are responding well. Therefore, due to their background, the IT users were biased, thus increasing the mean time to identify the failure compared to non-IT users.

6.2.2.3.2 Case 2: With the digital twin prototype. Samples: 'IT users vs 'non-IT users'.

For this case, the testers had access to the digital twin prototype.

According to the statistical methods (the calculations are detailed in 0), being an IT-user or not does not have a significant impact on identifying the failure. The identification of the failure is facilitated by the panel of the digital twin prototype that displays data. The identification is mainly based on the interpretation of the panel by the user. It does not require a specific background to interpret the panel.

However, the small observable difference between non-IT and IT users is due to their ability to interpret data quickly.

6.2.2.3.3 Case 3: IT users - Samples: 'with digital twin prototype' vs 'without digital twin prototype

Based on the statistical analyses (the calculations are detailed in 0), for the IT users, using the digital twin prototype or not is significant for this experiment, as shown in Figure 6-3.

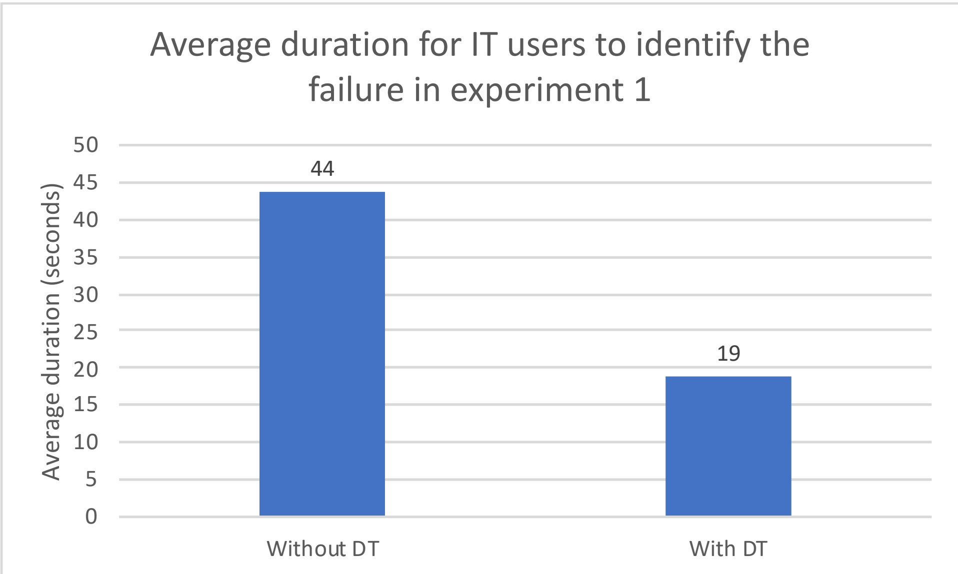

Figure 6-3 Experiment 1 - Case 3 - Benefits of the digital twin prototype for IT users

Calculations are as follows:

$$\%\ Time\ saved = \frac{(t_{Without\ DT} - t_{With\ DT})}{t_{Without\ DT}}$$

$$\%\ Time\ saved = \frac{(44 - 19)}{44} = 57\%$$

Therefore, for the IT-users, using the digital twin prototype has a significant impact on the time required to identify the failure. It reduces the time identification by 57%. With the digital twin prototype, the IT-user saves time by consulting the panel to identify the failure.

6.2.2.3.4 Case 4: Non-IT users - Samples: 'with digital twin prototype' vs 'without digital twin prototype'.

According to the statistical methods (the calculations are detailed in 0), for the non-IT users, using a digital twin prototype or not does not have a significant impact on identifying the failure. The non-IT users take about the same time to identify the failure with or without the digital twin prototype.

Indeed, contrary to the IT-users who think of more complex failures, the non-IT users first think of checking the cables. For this reason, non-IT users identify the failure faster. Moreover, this experiment focuses on a low complexity failure, identifying an unplugged ethernet cable does not require a long time.

6.2.2.3.5 Case 5: All the testers - Samples: 'with digital twin prototype' & 'without digital twin prototype'.

Based on the statistical analyses (the calculations are detailed in 0), for all the testers, using the digital twin prototype or not is significant for this experiment, as shown in Figure 6-4 below.

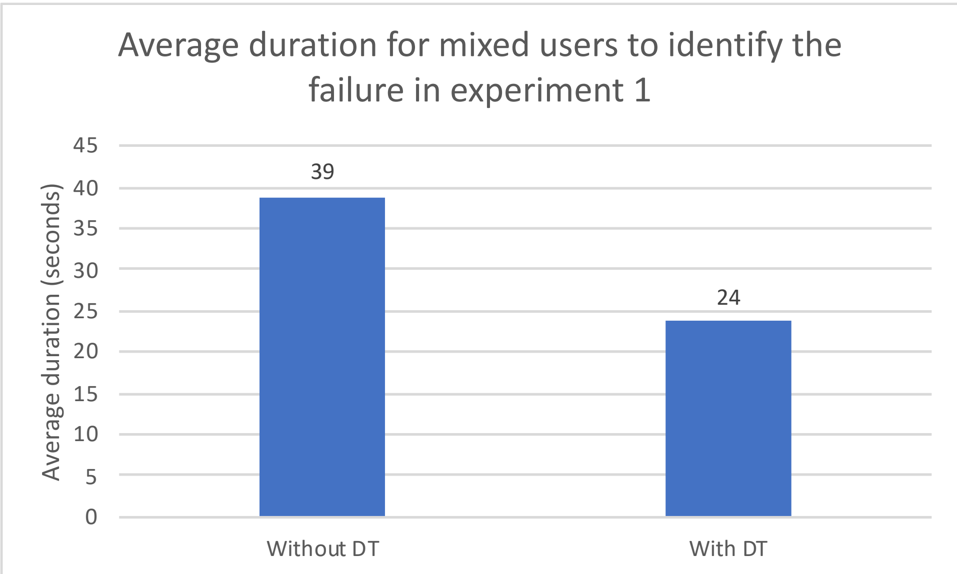

Figure 6-4 Experiment 1 - Case 5 - Benefits of the digital twin prototype for mixed users

Therefore, for all the testers, using the digital twin prototype has a significant impact on the time required to identify the failure. It reduces the time identification by 38%.

6.2.2.4 Experiment 2 analysis

6.2.2.4.1 Case 1: Without the digital twin prototype - Samples: ‘IT users’ vs ‘no-IT users’

For this case, the testers did not have access to the digital twin prototype.

Based on the statistical analysis (the calculations are detailed in D.3.1), having an IT background or not is significant for this experiment, as shown in Figure 6-5.

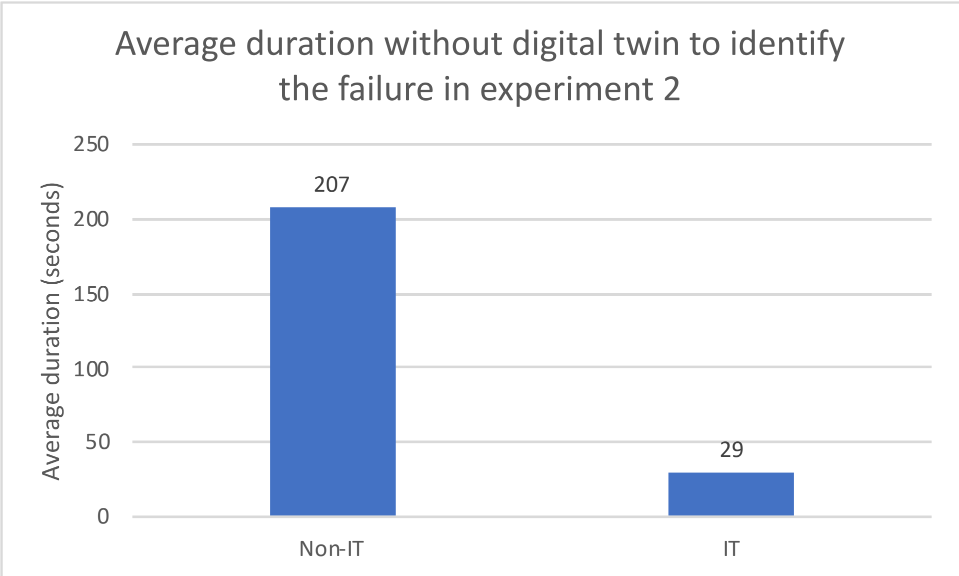

Figure 6-5 Experiment 2 - Case 1 - Benefits of the digital twin prototype for mixed users

Although for this case, the testers did not have access to the digital twin prototype, having an IT background enables the testers to take 86% less time to detect the failure.

Therefore, given the high complexity of the failure in this experiment, having an IT background helps to identify the failure faster even without having access to the digital twin prototype.

6.2.2.4.2 Case 2: With the digital twin prototype. Samples: ‘IT users’ vs ‘no-IT users’.

For this case, the testers had access to the digital twin prototype.

According to the statistical methods (the calculations are detailed in 0), being an IT-user or not does not have a significant impact on identifying the failure.

The identification of the failure is facilitated by the panel of the digital twin prototype that displays data. The identification is mainly based on the interpretation of the panel by the user. It does not require to have a specific background to interpret the panel.

The small observable difference between non-IT and IT users is due to their ability to interpret data quickly.

6.2.2.4.3 Case 3: IT users - Samples: 'with digital twin prototype' vs 'without digital twin prototype'

According to the statistical methods (the calculations are detailed in 0), for the IT users, using a digital twin prototype or not does not have a significant impact on identifying the failure.

Contrary to the non-IT users who need more time to identify the failure, the IT users first think of checking the computer parameters (CPU, RAM, CPU temperature).

Therefore, the IT users take about the same time to identify the failure with or without the digital twin prototype.

6.2.2.4.4 Case 4: Non-IT users - Samples: 'with digital twin prototype' vs 'without digital twin prototype'

Based on the statistical analyses (the calculations are detailed in D.3.4), for the non-IT users, using the digital twin prototype or not is significant for this experiment, as shown in Figure 6-6.

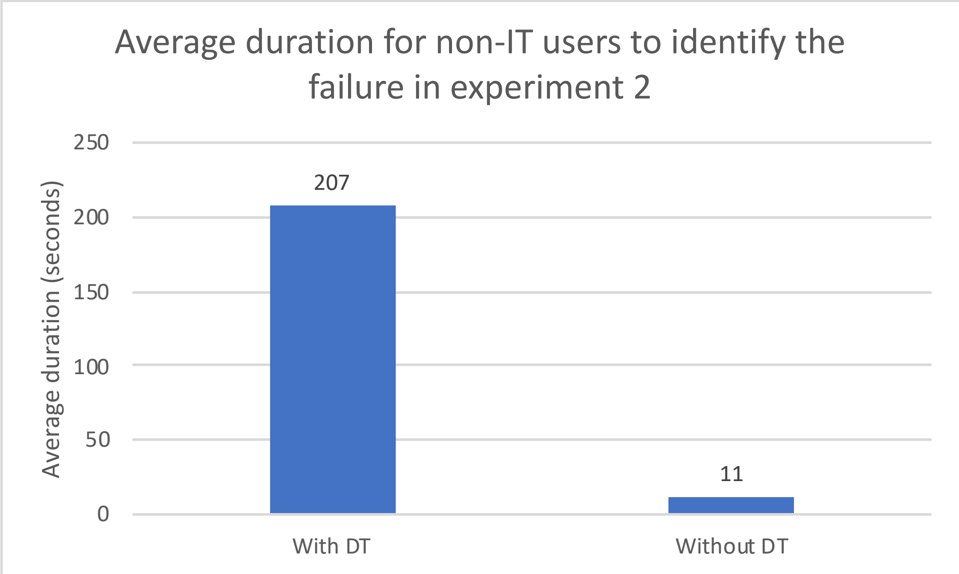

Figure 6-6 Experiment 2 - Case 4 - Benefits of the digital twin prototype for mixed users

Therefore, for the non-IT users, using the digital twin prototype has a significant impact on the time required to identify the failure. It enables to reduce the time identification by 95%.

6.2.2.4.5 Case 5: all the testers - The samples: 'with digital twin prototype' & 'without digital twin prototype'

As the results given by the t-test are close to the critical values (the calculations are detailed in D.3.5), the results might not be significant enough to be interpreted without error. For this reason, the results of the ANOVA are used.

Thus, in this case, for all the testers, using the digital twin prototype might have a significant impact on the time required to identify the failure, as shown in Figure 6-7. Using the digital twin prototype would reduce the time identification by 81%.

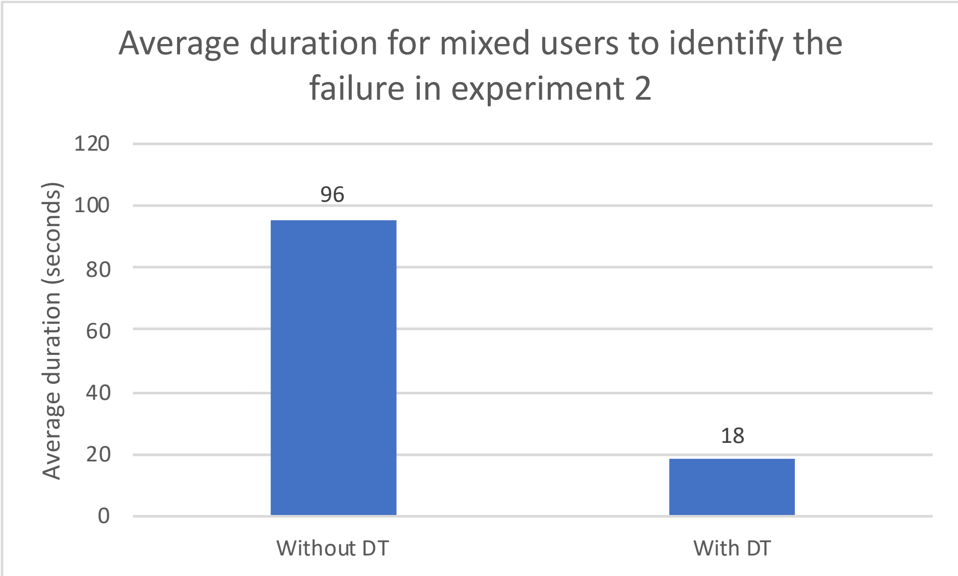

Figure 6-7 Experiment 2 - Case 5 - Benefits of the digital twin prototype for mixed users

6.2.3 Qualitative analysis

6.2.3.1 Description of the survey and presentation of the results

At the end of the experiments, all the testers who used the digital twin panel completed a survey to get feedbacks.

The survey consists of 8 questions which focus on two main aspects: the user-friendliness and the data relevancy/usefulness of the digital twin prototype. These questions are ranked 1 to 5:

1. not at all
2. needs to be improved
3. acceptable
4. good
5. very good

The answers are related to the questions below:

1. **User-friendliness**

Question 1.1: Do you find the digital twin easy to use?

Question 1.2: Do you think that the use of the digital twin made the identification of the failure easier?

Question 1.3: Do you think that it was useful?

Question 1.4: Were you happy to have a tool like this?

Question 1.5: Will you be happy to continue to use it?

2. **Collection of data**

Question 2.1: Do you think the data collected are useful?

Question 2.2: Do you see some information that can be useful to have and that you hadn't?

Question 2.3: Do you see some information that are not useful and that you had?

The answers collected from the survey are detailed in the appendix D.4, while a brief summary is shown in Figure 6-8 below.

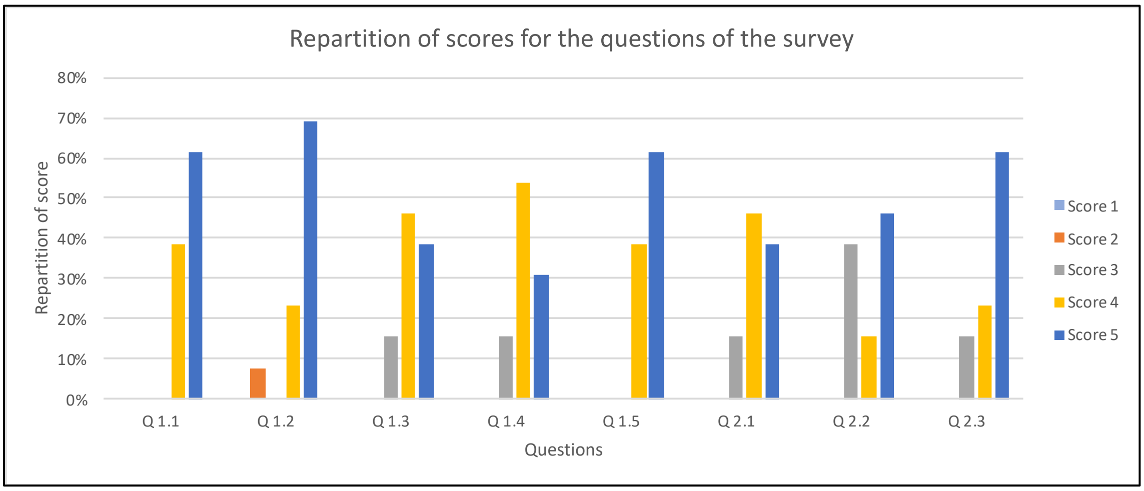

Figure 6-8 Answers collected from the survey

The results show that most of the questions are marked from 3 to 5.

6.2.3.2 Criteria validation

The answers were used to evaluate the user-friendliness of the digital twin panel and usefulness of the data collected from the asset by the digital twin. Figure 6-9 shows these results.

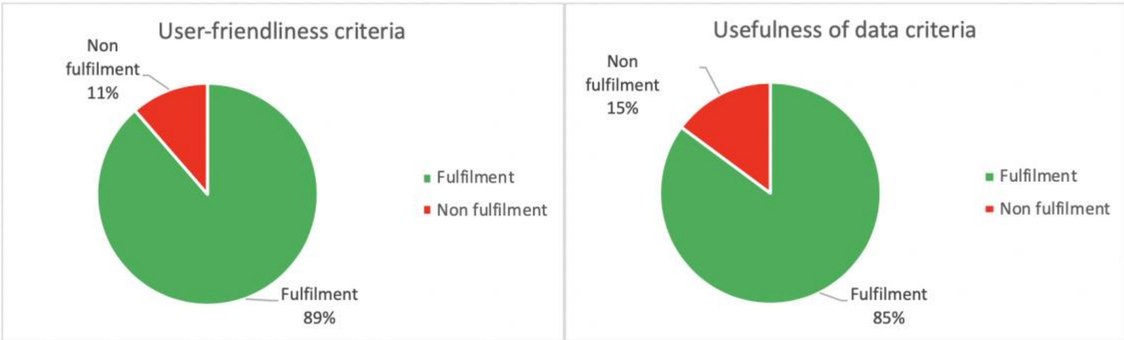

Figure 6-9 Criteria validation.

6.2.3.3 Feedbacks and comments from testers

At the end of the experiments, some feedbacks and comments from the testers are collected concerning the digital twin prototype:

- **The data transmission speed**: the speed of the data transmission between the physical asset and the digital twin is not optimised. Therefore, some testers suggested adding some information about the speed of the data transmission to inform the user of the progress of data transmission.
- **The panel does not explicitly indicate the cause of the failure**: some testers (mainly those who realised the CPU experiment) suggested adding a feature on the digital twin prototype that clearly indicates the cause of the failure.
- **The data relevancy**: The panel and dashboard always display the same type of data whatever the failure. Therefore, some testers suggested displaying only the data needed to identify a failure. For instance, in the experiment 2, it would be better to display only the CPU and not the RAM.

6.2.4 Overview of the outcomes

Concerning the quantitative validation, the results from the validation conform with the hypothesis previously defined:

Hypothesis 1: A digital twin significantly reduces the time required to identify a failure.

⇒ According to the cases previously analysed, the digital twin enables between 39% and 81% of time reduction depending on the type of failure.

Hypothesis 2: The background of the user (IT or non-IT) has an impact on the identification of the failure when **not using the digital twin prototype.**

⇒ The background of the user might have an impact, evaluated at 86% of time reduction for the experiment 2 when the digital twin is not used.

Hypothesis 3: The background of the user (IT or non-IT) has an impact on the identification of the failure when **using the digital twin prototype.**

⇒ The difference observed is not significant enough to be taken into account. However, doing more measurements in order to increase the size of the samples might help to improve the accuracy of the analysis.

Concerning the qualitative validation, the main outcomes are:

- 89% of the testers think that the digital twin prototype is user-friendly.
- 85% of the testers think that the data given by the prototype is useful.

6.2.5 Babcock's expertise and feedback

The following Babcock employees, with more than 10 years of experience, also took part in the validation experiments:

- Head of Research and Partnerships
- Technical Support Manager
- Head of Data Analytics

They carried out the experiments with and without the digital twin. Plus, as the testers from Cranfield University, Babcock's employees answered the survey. In addition to this survey, they were given additional questions about the features of the digital twin. These questions are listed below:

- To what extent is the replica representative of the asset?
- To what extent do all the technical features reach your expectations?

Most of the testers from Babcock think that this achievement is a really great beginning and that it would perfectly fit their expectations when it is fully developed.

One of these features is the dashboard. As previously explained the dashboard helps to do further analysis and some historical data analysis. As a result, Babcock testers were given questions about the dashboard:

- Do you think the currently proposed analysis are useful and meaningful?
- Do you see some analysis that can be interesting to have and that you haven't?

With the development of such a prototype, Babcock identified new capabilities for some devices with great potential. For example, with this prototype, Babcock think that they can use it to record the connectivity status of these devices. Thus, it would enable them to collect more data and increase their knowledge of the physical asset.

Moreover, according to Babcock engineers, the development of this digital twin prototype highlights some of the challenges Babcock faces such as the collection of data.

In addition, according to Babcock's engineers, being able to know the disconnections and their causes is very useful. In that way, this prototype makes the decision-making easier for the employees. Babcock's engineers point out that the purpose of the digital twin is to guide the employees to identify the failure. By displaying data and notifying the user when data values are abnormal, this prototype reached Babcock's requirements.

Finally, some Babcock engineers highlight that the dashboard of the digital twin is very user friendly. They explained that it can sometimes take them hours to identify a failure. Now, with the digital twin prototype, and especially the dashboard, they no longer have this problem. They can consult the dashboard to detect models and avoid future failures related to the maintenance.

7 Discussion

Throughout the project, several decisions were taken. These decisions were mainly related to the methodology adopted, the created framework and the digital twin prototype. Some of these decisions need to be discussed.

7.1 Discussion of the development and conception of the framework

To create the framework, some papers from the literature review were analysed. However, the digital twin technology is relatively new, therefore there is not a lot of existing framework describing how to build a digital twin. The developed framework is based on the different already existing frameworks. It is difficult to assess its scalability, as it has been applied only for one asset during this project.

7.2 Discussion of the creation of the digital twin prototype

The digital twin prototype is created using the developed framework. Moreover, as agreed, the prototype is developed using C++, Access and Excel. This choice led to some limitations which are mainly linked to the literature review gaps.

- The data is not actually real-time because of the huge amount of data. The different software used requires time to collect and update the data. Plus, the data has to flow from one software to another, which takes time. A limitation of the design investigated is that the updating time cannot be reduce.
- When the C++ code is copying a file into the online server and Access wants to get the information from this log file at the same time it's creating an empty log file. This limitation is linked to the chosen software. In fact, Access opens and tries to read the file before the C++ code finishes writing all the data in it, corrupting the file and leaving it empty.
- The Internet connection is used to do the communication between the replica and the digital twin prototype. Sometimes, this connection is unstable, causing delays in the exchange of data between the virtual word and the real word. The data has to wait for the connection to return to be collected by the digital twin prototype and to be updated on the database.

- The Main Mission Computer contains the C++ code which enables the collection of data from the other computers and from itself. To get data from other computers, the C++ code has to send instructions to the command prompt of the other computers. However, the C ++ code has to bypass the firewall of the other computers. To do so, another C++ code is created on Client Mission Computer enabling data to be saved and collected through a Local Area Network (LAN).
- The exchanged data is saved in the Access database, which is stored on an online server. When the digital twin prototype uses this database from a computer, it actually uses an image of this database which is temporarily saved locally on the digital twin computer. However, if an error causes a loss of communication between the online server and the image; the file will be deleted, leading to a loss of all the information. This happens rarely.

7.3 Discuss of the results

Despite the issues encountered during the development of the prototype, the prototype validates and highlights the benefits of a digital twin in aerospace maintenance. The main benefits displayed by the prototype are:

- **Time saved:** With the digital twin prototype, the user takes less time to identify the failure.
- **User-friendliness:** the digital twin prototype is easy to manipulate and therefore the users are glad to use this kind of tool.
- **Usefulness of the data:** the digital twin prototype provides relevant data for further analyses.

Saving time and facilitating the users' work are benefits that all the companies are looking for.

However, these results have to be discussed. The results might not be significant for the company for the following reasons:

- The experiments were not done with the real asset but with the mission system replica. The conditions of the experiments were different to Babcock's environment.

- All the results are based on a sample of 32 students and academic people from Cranfield University. Therefore, these people are different from Babcock's employees. Contrary to the testers, Babcock's employees know the asset and sometimes by experience they can quickly guess where the failure is and where it comes from.
- Moreover, although the size of the sample is fine to carry out analyses, it is not big enough to completely rely on the results. There were 32 people in total, 16 people did the experiment 1 and 16 did the experiment 2. Among these 16 people for the experiment 1, 8 people did the experiment with the digital twin and 8 without. Plus, within these 8 people, 4 of them have an IT background and 4 have not. There is a similar distribution for the experiment 2. These distributions lead to do analyses with small size of samples, which causes more errors in the statistical analysis. The smaller the sample size, the less significant the results of the statistical analysis. Therefore, because of the size of the sample, the results from f-test, t-test, and ANOVA test might contain errors.
- All the results are based on the timing of the experiments given that time is the validation indicator. However, errors might be present due to a poor timing precision of the experiments.
- The analysis of the validation relied on the impact of the digital twin prototype on the time criteria. However, in maintenance, the objective is to maximise the asset's availability. Thus, it would have been interesting to convert the time saved with the digital twin into a percentage of increase in asset's availability. Unfortunately, it could not be done due to a lack of historical data.

7.4 Is developing a digital twin worthwhile?

The development of the prototype revealed potential challenges in developing a digital twin that were not considered so far. Moreover, GE also developed a digital twin for their engines which has shown great potential with satisfying results and benefits. Indeed, GE managed to reduce the reactive maintenance activities and saved $11M by detecting and preventing defects (GE Digital, 2019). These outcomes from GE support the results of this project and give a clearer idea of the potential of digital twin at the industrial scale. Therefore, this project demonstrates that having a digital twin is worthwhile to improve maintenance activities.

8 Conclusion and future works

Babcock put technology at the core of their activities, continually looking for innovations. Thus, they are focusing on developing digital twin technology to extend their competencies in system design, integration and support. This project focuses on the digital twin potential to improve the ability to plan maintenance for an asset.

In that order, a scalable framework describing how a digital twin works and how it is built is suggested. This framework is then used to develop a functional digital twin prototype. This prototype collects data from the replica built in Cranfield University based on Babcock's physical asset and processes this data for monitoring and failure detection purposes. Moreover, it creates a historical database for further relevant analysis to allow predictive maintenance.

The creation of the prototype proves that the framework is scalable. Moreover, analyses from validation have demonstrated that the digital twin technology has several advantages. The digital twin allows the company to reduce the time needed to identify a failure on their assets. It also enables the employees to be more autonomous in the decision-making process. Therefore, the digital twin technology increases the asset's availability. In fact, the digital twin prototype reduces by 39% or 95% the identification time depending on the type of failure. Based on the testers' feedbacks, the users find the digital twin prototype user-friendly and would be pleased to use it again in the future.

Despite satisfactory results, this project showed some challenges. The solution selected (C++, Access and Excel) to develop the prototype seemed appropriate at the beginning of the project. However, moving forward to the project and adding additional features to the prototype, the selected solution revealed the limitations of the solution. Moreover, during the validation of the prototype, the analyses revealed that, for some cases, the size of the samples was very small, thus making it difficult to interpret the results.

Although the digital twin prototype leads to relevant results, it still needs to be improved. The following are some potential future works on the prototype in order to improve its efficiency and enlarge its application:

- Make the data collection system more robust and consider the impact of the amount of data collected on the overall digital twin system.
- Reduce time needed to update data. Indeed, Babcock are interested in a 5 to 10 seconds updating time while the prototype is achieving it around 15 to 20 seconds.
- Realise deeper analyses with the data for patterns identification to provide better forecasts in terms of failures that can be prevented. For example, relate the CPU and RAM percentage usages to the processes that are running on the computer, in order to identify patterns on software and processes that may cause failures.
- Improve the digital twin prototype so that it can suggest actions to perform on the real asset.
- Validate the prototype with Babcock’s employees to get more suitable results and try to estimate its impact on the asset’s availability.
- Improve the adaptation of the prototype to Babcock’s asset. For example, some failures encountered by Babcock (GPS, temperature) are not represented on the prototype.

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APPENDICES

Appendix A Project Methodology

A.1 Research

Table A-1 Keywords used to carry out the literature review

Keywords
("digital twin") AND ("maintenance" OR "manufacturing")
("digital twin" AND "digital transformation") OR ("virtualisation")
("digital twin" OR "virtual replica") AND ("framework" OR "methods" OR "architecture" OR "development" OR "conception" OR "design")
("digital twin" OR “virtual replica") AND ("benefits" OR "advantages" OR "outcomes")
("digital twin" OR "virtual replica") AND ("application")
("digital twin" AND "IoT") OR ("Internet of Things" OR "Industry 4.0" OR "innovation") AND ("industrial maintenance" OR "predictive maintenance" OR "failure detection")
("digital twin" AND "case study") OR ("business case")
("digital twin" AND "future works") OR ("future" OR "potential" OR "risks")
("digital twin" AND "asset management")

A.2 Questions to Babcock

Some questions asked to Babcock during the meetings.

At the beginning of the project:

1. Why is Babcock interested in Digital Twins? What are Babcock's motivations?
2. What background does Babcock have on Digital Twin?
3. What assets would Babcock like to develop a digital twin for?
4. What outcomes do you expect from this project?

At the middle of the project:

1. What kind of data do you want to get from the physical asset?
2. Do you have any restrictions regarding the security of the information?
3. Do you have historical data?

At the end of the project:

1. How do your employees do the maintenance activities? How do they identify the failures?
2. How long do your maintenance activities last?
3. What are the causes of the failures (for example damage of the cable, heating of the devices)?

Appendix B State of the art of the digital twin technology

B.1 Digital twin definitions

Table B-1 Definitions of the digital twin

Definition	Remarks
Deloitte (Parrott and Warshaw, 2017)	
A digital twin can be defined, fundamentally, as an evolving digital profile of the historical and current behaviour of a physical object or process that helps optimise business performance. The digital twin is based on massive, cumulative, real-time, real-world data measurements across an array of dimensions.	This definition focuses on updating instantly data according to the evolution of the physical asset. This updating is the consequence of a connexion between the virtual world and the real world. According to this definition, one of the main goals of a digital twin is to improve the performance.
Microsoft (Services, 2017)	
A digital twin is a virtual model of a process, product, production asset or service. Sensor-enabled and IoT-connected machines and devices combined with machine learning and advanced analytics can be used to view the device's state in real time.	The definition focuses on the devices used to make the connection between the digital and virtual assets. These methods enable the virtual asset to exist simultaneously with the physical asset.
GE (GE Power Digital Solutions, 2016)	
Digital Twin is an organized collection of physics-based methods and advanced analytics that is used to model the present state of every asset in a Digital Power Plant.	The definition focuses on the methods used to create the digital asset.
NASA (Glaessgen and Stargel, 2012)	
A digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin.	The digital twin can be used at all scales, even for complex assets. The digital twin must be a perfect copy of the physical asset.

Definition	Remarks
Conceptualisation of Digital Twins in the Through-life Engineering Services Environment (Erkoyuncu and Birkin, 2018)	
A digital twin is a digital representation of a physical item or assembly using integrated simulations and service data. The digital representation holds information from multiple sources across the product lifecycle. This information is continuously updated and is visualised in a variety of ways to predict current and future conditions, in both design and operational environments, to enhance decision making.	Contrary to other definitions, this one mentions the environment of the physical asset. The environment plays an important role for the digital twin.

B.2 Digital twin benefits

Table B-2 Digital twin benefits (Parrott and Warshaw, 2017).

Category of business value	Potential specific business values
Quality	• Improve overall quality. • Predict and detect quality trend defects sooner. • Control quality escapes and be able to determine when quality issue started.
Warranty cost and services	• Understand current configuration of equipment in the field to be able to service more efficiently. • Proactively and more accurately determine warranty and claims issues to reduce overall warranty cost and improve customer experiences.
Operations cost	• Improve product design and engineering change execution. • Improve performance of manufacturing equipment. • Reduce operations and process variability.
Record retention and serialization	• Create a digital record of serialized parts and raw materials to better manage recalls and warranty claims and meet mandated tracking requirements.

Category of business value	Potential specific business values
New product introduction cost and lead time	• Reduce the time to market for a new product. • Reduce overall cost to produce new product. • Better recognize long-lead-time components and impact to supply chain.
Revenue growth opportunities	• Identify products in the field that are ready for upgrade. • Improve efficiency and cost to service product.

B.3 Existing frameworks

Table B-3 Comparison frameworks

Deloitte (Parrott and Warshaw, 2017)	**International Journal of Production Research** (Tao et al., 2018)
1. **Create:** sensor set up and virtual representation of the physical asset. 2. **Communicate:** real-time and bidirectional connection between the physical and virtual asset. 3. **Aggregate:** data ingestion into a data repository, processed and prepared for analytics. 4. **Analyse:** data is analysed and visualized. 5. **Insight:** insights from the analytics are presented through dashboards. 6. **Act:** actionable insights from the previous steps can be fed back to the physical asset.	1. **Build** the virtual representation of the physical product. 2. **Process data** to facilitate design decision-making. 3. **Simulate** product behaviours in the virtual environment. 4. **Establish** real-time, two-way, and secure **connections** between physical and virtual product. 5. **Collect** all kinds of product-related **data** from different sources.

Appendix C Conceptual design

C.1 Solutions do develop the digital twin prototype

Table C-1 Suggested solutions to develop the digital twin prototype

Solution 1: C++ programme, Microsoft Office Access & Excel The first solution consists of using a C++ code installed in the replica in order to collect data. This solution can be quickly developed because the software is easily accessible. However, this requires more time as every feature needs to be created from scratch. This solution is entirely free as software is already accessible for the researchers.
Solution 2: Java, Open Source and Dashboard This solution consists of using open source IoT platforms such as ThingsBoard and Eclipse Ditto. These platforms have some functionalities already developed for example the data collection, visualisation with dashboards and data management. Other functionalities are accessible, but they are chargeable. However, one of their main advantages is that the source code is available to the public and therefore can be changed to specific needs.
Solution 3: Microsoft Azure The third solution uses Microsoft's IoT platform called "Microsoft Azure". Microsoft Azure combines different software such as: • "Azure IoT": which allows to connect assets with IoT to gain real-time insights. • "Azure Digital Twins": which helps to create a digital model from the physical world and run repeatable experiences that correlate data from the physical world. This solution is convenient as many features are already developed, but it has a considerable cost. Moreover, it raises the question of confidentiality of the data collected.

C.2 Code logic diagrams

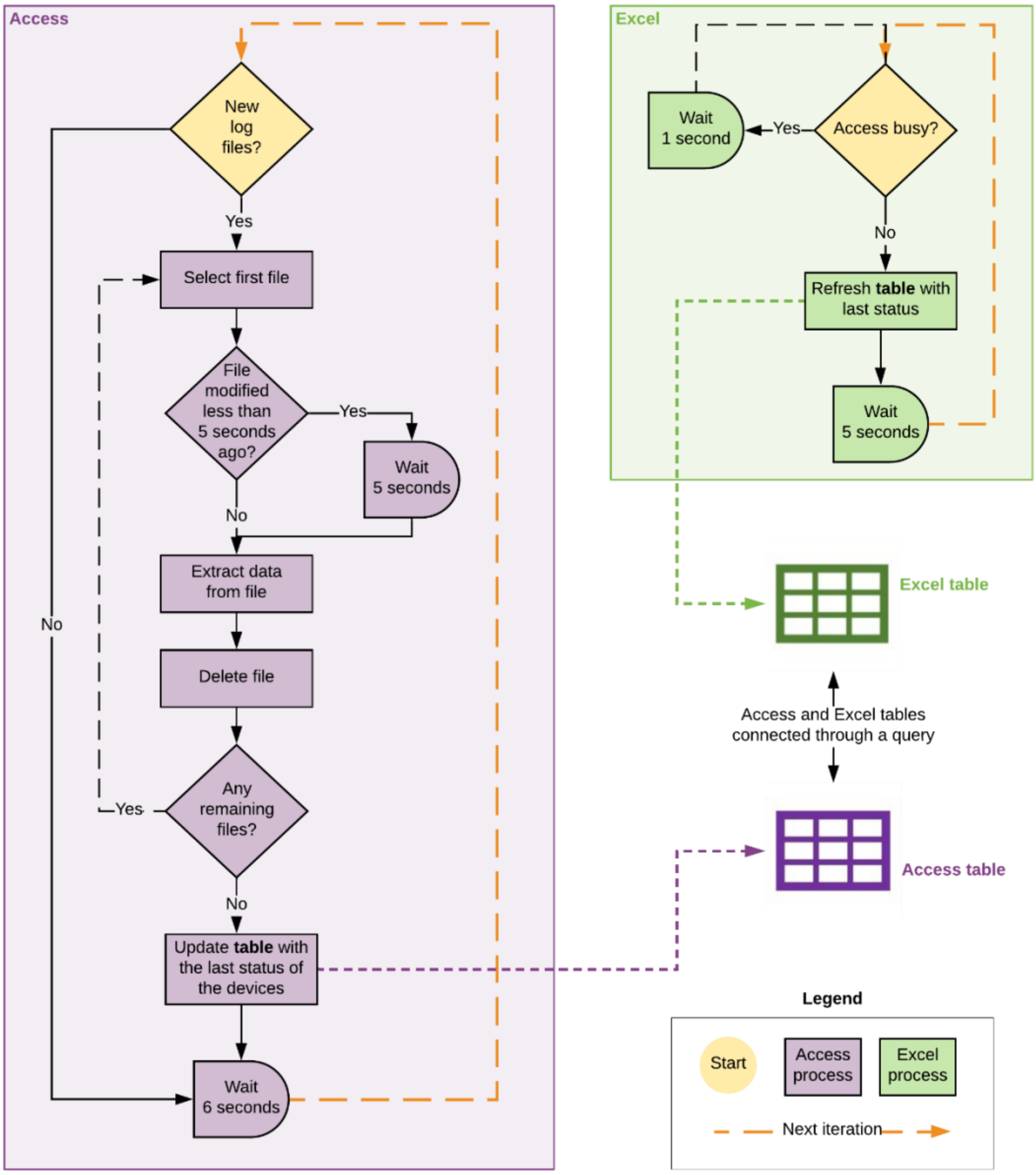

Figure C-1 Access and Excel diagram

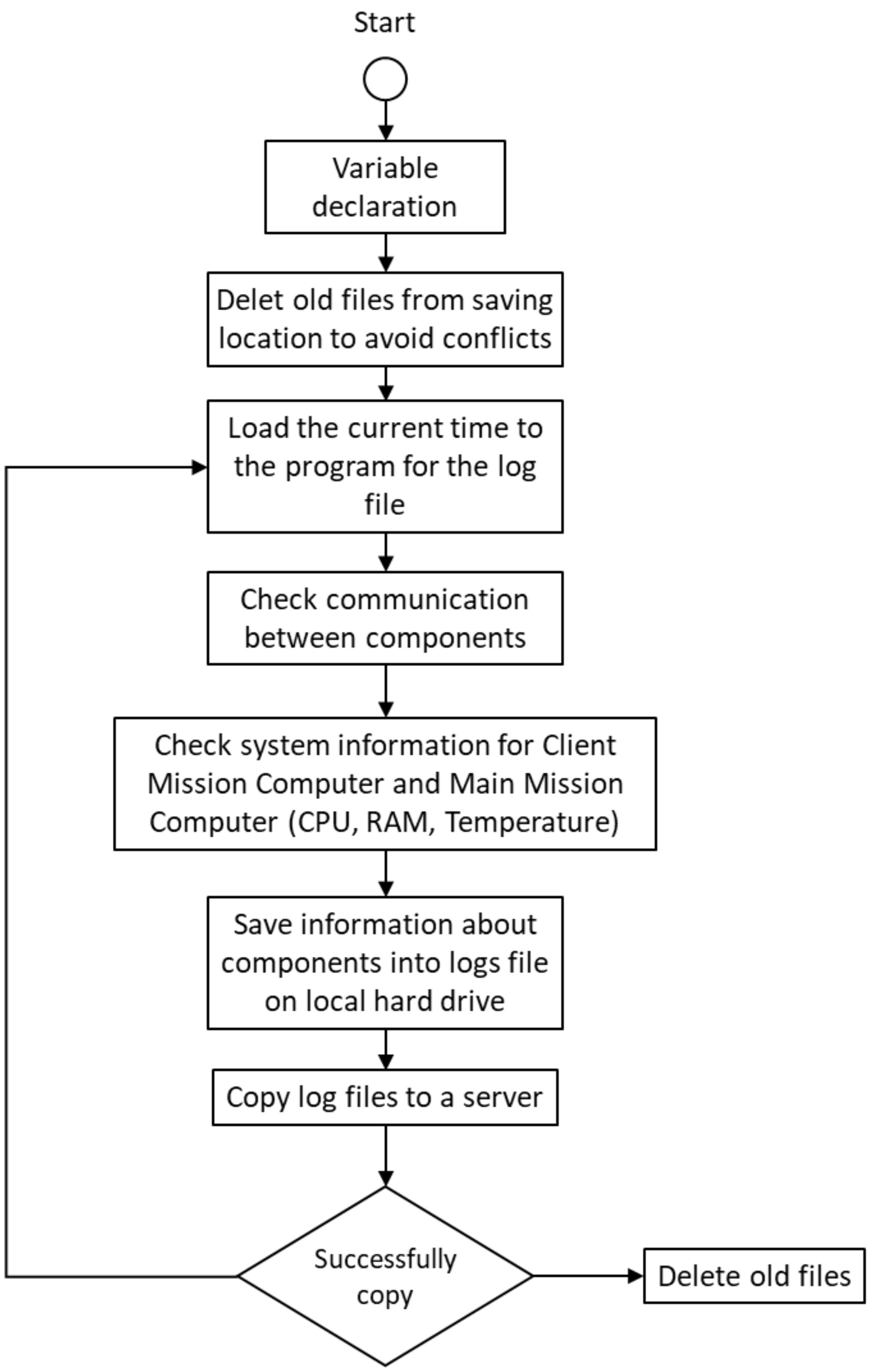

Figure C-2 C++ code diagram

Appendix D Validation

D.1 Descriptions of statistical methods

A common approach to do that is to use hypotheses called H_0 (called "null hypothesis") and H_a (called "alternative hypothesis"). According to the method, the hypotheses are different.

- f-test: it tests whether the variance of a sample is different from another.
  - H_0: $\sigma_1^2 = \sigma_2^2 = \cdots = \sigma_k^2$ with k the number of samples
  - H_a: at least one pair of variances is different.
- t-test: A t-test focuses on small size samples and enables to determine whether the mean of a sample is different from another. There are two different t-tests depending on whether the sample variances are equal or not: unequal variance t-test and equal variance t-test. Both are based on the same hypotheses.
  - H_0: $\mu_1 = \mu_2 = \cdots = \mu_k$ with k the number of samples
  - H_a: at least one pair of means is different.
- ANOVA test: the one-way ANOVA (involving just one factor) test evaluates whether the mean of a sample is different from another.
  - H_0: $\mu_1 = \mu_2 = \cdots = \mu_k$ with k the number of samples
  - H_a: at least one pair of means is different.

For all these statistical methods, if H_0 is true, there is not a lot of variation between the samples. If H_0 is not true, there is a significant variation between the samples and then the factor has a significant impact on the results.

D.2 Experiment 1

D.2.1 Experiment 1 - Case 1 "Without Digital Twin prototype" - Samples "Non-IT" vs. "IT"

Here, the background of the testers is analysed in Experiment 1 without digital twin in order to evaluate its impact.

Table D-1 below shows the time spent by the testers to compare IT and non-IT results.

Table D-1 Experiment 1 - Case 1 - Groups values

Experiment 1 - Without DT - Duration (seconds)	
IT	**Non-IT**
30	30
45	30
45	45
55	30

An F-test is run to analyse the variances of the groups. The following hypothesis are tested:

- H_0: $\sigma_1^2 = \sigma_2^2$
- H_a: $\sigma_1^2 \neq \sigma_2^2$

Table D-2 below shows the results of the F-test.

Table D-2 Experiment 1 - Case 1 - F-test results

F-TEST	*IT*	*Non-IT*
Mean	**43.75**	**33.75**
Variance	**106.25**	**56.25**
Observations	4	4
Degree of freedom (dF)	3	3
F	**1.889**	
P(F<=f) one-tail	0.307	
F Critical one-tail	**9.277**	

The F-test shows that $F < F_{critical\ one-tail}$. This means that the null hypothesis H_0 cannot be rejected and thus variances are equal.

As a result, a t-test two-sample assuming equal variances is run with the following hypothesis:

- H0: $\mu_1 = \mu_2$
- Ha: $\mu_1 \neq \mu_2$

Table D-3 below shows the results of the t-test assuming equal variances.

Table D-3 Experiment 1 - Case 1 - t-test results

T-TEST	*IT*	*Non-IT*
Mean	**43.75**	**33.75**
Variance	**106.25**	**56.25**
Observations	4	4
Pooled Variance	81.25	
Hypothesized Mean Difference	0	
Degree of freedom (dF)	6	
t Stat	**1.569**	
P(T<=t) one-tail	0,084	
t Critical one-tail	1.943	
P(T<=t) two-tail	0.168	
t Critical two-tail	**2.447**	

The **t-test** shows that $|t_{Stat}| < |t_{Critical\ two-tail}|$. This means that the null hypothesis H0 cannot be rejected and the means are equal. In other words, it means **there is no significant difference** between the two groups.

A one-way ANOVA test is run to verify these results with the following hypothesis:

- H0: $\mu_1 = \mu_2$

Ha: $\mu_1 \neq \mu_2$Table D-4 below shows the results of the ANOVA test.

Table D-4 Experiment 1 - Case 1 - One-Way ANOVA test results

SUMMARY				
Groups	*Count*	*Sum*	***Average***	*Variance*
Without DT	4	175	**43.75**	106.25
With DT	4	135	**33.75**	56.25

ANOVA TEST						
Source of Variation	*SS*	*ddl*	*MS*	***F***	***P-value***	***F crit***
Between Groups	200	1	200	**2.462**	**0.168**	**5.987**
Within Groups	487.5	6	81.25			
Total	687.5	7				

The **ANOVA test** shows that $F < F_{critical}$ which means the null hypothesis H_0 cannot be rejected. Moreover, $p - value > 0.05$ which means that **the difference in the means is not significant enough**. This verifies the results from the t-test.

Table D-5 Experiment 1 - Case 1 - Conclusion

	Case 1 - Without DT - Non-IT vs. IT
F-test	H_0: $\sigma_1^2 = \sigma_2^2$
t-test	H_0: $\mu_1 = \mu_2$
One-way ANOVA test	H_0: $\mu_1 = \mu_2$
Conclusion	The difference between the non-IT and the IT is not significant enough when not using the digital twin in the experiment 1.

D.2.2 Experiment 1 - Case 2 “With Digital Twin prototype” - Samples “Non-IT” vs. “IT”

Now, the same study is realised when using the digital twin prototype.

The values analysed are shown in

Table D-6 below.

Table D-6 Experiment 1 - Case 2 - Groups values

Experiment 1 - With DT - Duration (seconds)	
IT	**Non-IT**
40	20
15	20
30	20
30	15

Table D-7 below shows the results of the F-test.

Table D-7 Experiment 1 - Case 2 - F-test results

F-TEST	*IT*	*Non-IT*
Mean	**28.75**	**18.75**
Variance	**106.25**	**6.25**
Observations	4	4
Degree of freedom (dF)	3	3
F	**17**	
P(F<=f) one-tail	0.022	
F Critical one-tail	**9.277**	

The F-test shows that $F > F_{critical\ one-tail}$, meaning that the null hypothesis H_0 can be rejected and variances are unequal.Table D-8 below shows the results of the t-test assuming unequal variances.

Table D-8 Experiment 1 - Case 2 - t-test results

T-TEST	*IT*	*Non-IT*
Mean	**28.75**	**18.75**
Variance	**106.25**	**6.25**
Observations	4	4
Hypothesized Mean Difference	0	
Degree of freedom (dF)	3	
t Stat	**1.886**	
P(T<=t) one-tail	0,078	
t Critical one-tail	2,353	
P(T<=t) two-tail	0,156	
t Critical two-tail	**3,182**	

The **t-test** shows that $|t_{Stat}| < |t_{Critical\ two-tail}|$, meaning that the null hypothesis H_0 cannot be rejected and the means are equal. In other words, **there is no significant difference between the two groups**.

Table D-9 below shows the results of the ANOVA test.

Table D-9 Experiment 1 - Case 2 - One-Way ANOVA test results

SUMMARY

Groups	*Count*	*Sum*	***Average***	*Variance*
Without DT	4	115	**28.75**	106.25
With DT	4	75	**18.75**	6.25

ANOVA TEST

Source of Variation	*SS*	*ddl*	*MS*	***F***	***P-value***	***F crit***
Between Groups	200	1	200	**3.556**	**0,108**	**5,987**
Within Groups	337.5	6	56.25			
Total	537.5	7				

According to the **ANOVA test**, $F < F_{critical}$ which means that the null hypothesis H_0 cannot be rejected. Moreover, $p - value > 0.05$, meaning that **the difference in the means is not significant enough.** This verifies the results from the t-test.

Table D-10 Experiment 1 - Case 2 - Conclusion

	Case 2 – With DT - Non-IT vs. IT
F-test	H_0: $\sigma_1^2 \neq \sigma_2^2$
t-test	H_0: $\mu_1 = \mu_2$
One-way ANOVA test	H_0: $\mu_1 = \mu_2$
Conclusion	The difference between the non-IT and the IT is not significant enough when using the digital twin in experiment 1.

D.2.3 Experiment 1 - Case 3 “IT profile” - Samples “Without DT vs. With DT”

Now, the impact of the digital twin prototype is analysed in Experiment 1 for IT users only.

The values analysed are shown in Table D-11 below.

Table D-11 Experiment 1 - Case 3 - Groups values

Experiment 1 - IT users - Duration (seconds)	
Without DT	**With DT**
30	20
45	20
45	20
55	15

Table D-12 below shows the results of the F-test.

Table D-12 Experiment 1 - Case 3 - F-test results

F-TEST	*Without DT*	*With DT*
Mean	**43.75**	**18.75**
Variance	**106.25**	**6.25**
Observations	4	4
Degree of freedom (dF)	3	3
F	**17**	
P(F<=f) one-tail	0.022	
F Critical one-tail	**9.277**	

According to **the F-test**, $F > F_{critical\ one-tail}$. This means that the null hypothesis H_0 can be rejected and variances are unequal.Table D-13 below shows the results of the t-test assuming unequal variances.

Table D-13 Experiment 1 - Case 3 - t-test results

T-TEST	*Without DT*	*With DT*
Mean	**43.75**	**18.75**
Variance	**106.25**	**6.25**
Observations	4	4
Hypothesized Mean Difference	0	
Degree of freedom (dF)	3	
t Stat	**4.714**	
P(T<=t) one-tail	0,009	
t Critical one-tail	2,353	
P(T<=t) two-tail	0,018	
t Critical two-tail	**3.182**	

As $|t_{Stat}| > |t_{Critical\ two-tail}|$, the null hypothesis H_0 can be rejected and the means are unequal. In other words, **there is a significant difference between the two groups**.

Table D-14 below shows the results of the ANOVA test.

Table D-14 Experiment 1 - Case 3 - One-Way ANOVA test results

SUMMARY						
Groups	*Count*	*Sum*	***Average***	*Variance*		
Without DT	4	175	**43.75**	106.25		
With DT	4	75	**18.75**	6.25		
ANOVA TEST						
Source of Variation	*SS*	*ddl*	*MS*	***F***	***P-value***	***F crit***
Between Groups	1250	1	1250	**22.222**	**0.003**	**5.987**
Within Groups	337.5	6	56.25			
Total	1587.5	7				

The ANOVA test shows that $F > F_{critical}$, which means the null hypothesis H_0 can be rejected. Moreover, $p - value < 0.05$. Thus, **the difference in the means is significant enough**. This verifies the results from the t-test.

Table D-15 Experiment 1 - Case 3 - Conclusion

	Case 3 - IT users - Without DT vs. With DT
F-test	H0: $\sigma_1^2 \neq \sigma_2^2$
t-test	H0: $\mu_1 \neq \mu_2$
One-way ANOVA test	H0: $\mu_1 \neq \mu_2$
Conclusion	The use of the digital twin for IT users cause a significant enough difference in experiment 1.

As a result of the analysis, the digital twin has a considerable impact on the time spent to identify the failure in experiment 1 which is represented in Figure D-1 below.

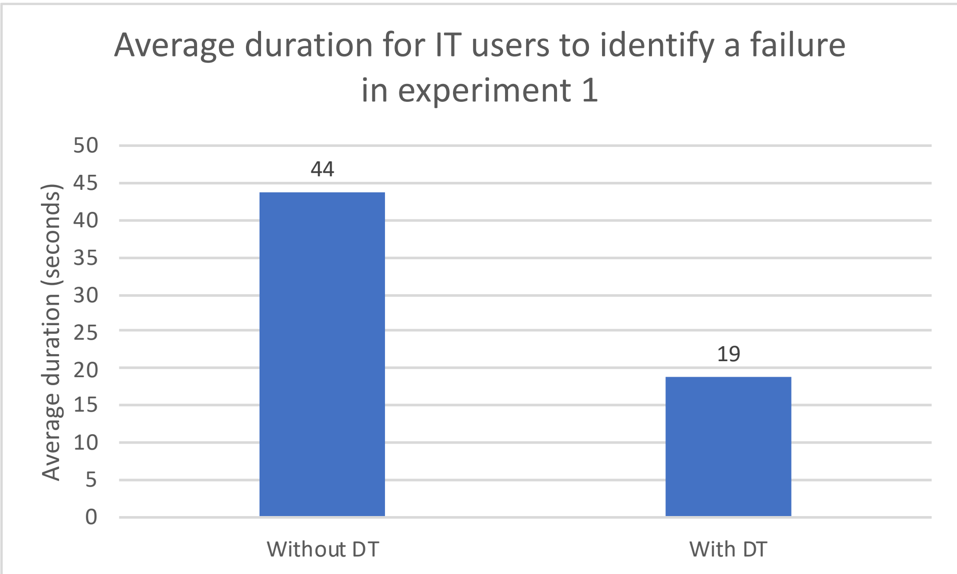

Figure D-1 Experiment 1 - Case 3 - Benefits of the digital twin prototype for IT users

As a conclusion, for IT users, **the digital twin prototype saves an average of 57% of time**.

Calculations are as follows:

$$\%\,Time\ saved = \frac{(t_{Without\ DT} - t_{With\ DT})}{t_{Without\ DT}}$$

$$\%\,Time\ saved = \frac{(44-19)}{44} = 57\%$$

D.2.4 Experiment 1 - Case 4 “Non-IT profile” - Samples “Without DT vs. With DT”

Now, the same study is realised for non-IT users.

The values analysed are shown in

Table D-16 below.

Table D-16 Experiment 1 - Case 4 - Groups values

Experiment 1 - non-IT users - Duration (seconds)	
With DT	**Without DT**
40	30
15	30
30	45
30	30

Table D-17 below shows the results of the F-test.

Table D-17 Experiment 1 - Case 4 - F-test results

F-TEST	*With DT*	*Without DT*
Mean	**28.75**	**33.75**
Variance	**106.25**	**56.25**
Observations	4	4
Degree of freed	3	3
F	**1.889**	
P(F<=f) one-tail	0.307	
F Critical one-ta	**9.277**	

Table D-17 above shows that $F < F_{critical\ one-tail}$. This means that the null hypothesis H_0 cannot be rejected and thus variances are equal.

Table D-18 below shows the results of the t-test assuming equal variances.

Table D-18 Experiment 1 - Case 4 - t-test results

T-TEST	*With DT*	*Without DT*
Mean	**28.75**	**33.75**
Variance	**106.25**	**56.25**
Observations	4	4
Pooled Variance	81.25	
Hypothesized Mean Difference	0	
Degree of freedom (dF)	6	
t Stat	**-0.784**	
P(T<=t) one-tail	0.231	
t Critical one-tail	1,943	
P(T<=t) two-tail	0.463	
t Critical two-tail	**2.447**	

The **t-test** shows that $|t_{Stat}| < |t_{Critical\ two-tail}|$. This means that the null hypothesis H_0 cannot be rejected and the means are equal. In other words, it means **there is not a significant difference between the two groups**.

Table D-19 below shows the results of the ANOVA test.

Table D-19 Experiment 1 - Case 4 - One-Way ANOVA test results

SUMMARY						
Groups	*Count*	*Sum*	***Average***	*Variance*		
With DT	4	115	**28.75**	106.25		
Without DT	4	135	**33.75**	56.25		
ANOVA TEST						
Source of Variation	*SS*	*ddl*	*MS*	***F***	***P-value***	***F crit***
Between Groups	50	1	50	**0.615**	**0.463**	**5.987**
Within Groups	487.5	6	81.25			
Total	537.5	7				

The **ANOVA test** shows that $F < F_{critical}$which means the null hypothesis H_0 cannot be rejected. Moreover, $p - value > 0.05$ which means that **the difference in the means is not significant enough**. This verifies the results from the t-test.

Table D-20 Experiment 1 - Case 4 - Conclusion

	Case 4 -Non-IT users - Without DT vs. With DT
F-test	$H_0: \sigma_1^2 = \sigma_2^2$
t-test	$H_0: \mu_1 = \mu_2$
One-way ANOVA test	$H_0: \mu_1 = \mu_2$
Conclusion	The use of the digital twin for non-IT users does not cause a significant enough difference in experiment 1.

D.2.5 Experiment 1 - Case 5 “Mix profiles” - Samples “Without DT vs. With DT”

Here, the impact of the digital twin prototype is analysed in Experiment 1 for both non-IT and IT users.

The values analysed are shown in Table D-21 below.

Table D-21 Experiment 1 - Case 5 - Groups values

Experiment 1 - Mixed users - Duration (seconds)	
Without DT	**With DT**
30	20
30	40
30	20
45	15
45	30
45	20
55	15
30	30

Table D-22 below shows the results of the F-test.

Table D-22 Experiment 1 - Case 5 - F-test results

F-TEST	*Without DT*	*With DT*
Mean	**38.75**	**23.75**
Variance	**98.214**	**76,786**
Observations	8	8
Degree of freedom (dF)	7	7
F	**1.279**	
P(F<=f) one-tail	0.377	
F Critical one-tail	**3,787**	

Table D-22 above shows that $F < F_{critical\ one-tail}$. This means that the null hypothesis H_0 cannot be rejected and thus variances are equal.Table D-23 below shows the results of the t-test assuming equal variances.

Table D-23 Experiment 1 - Case 5 - t-test results

T-TEST	*Without DT*	*With DT*
Mean	**38.75**	**23.75**
Variance	**98.214**	**76.786**
Observations	8	8
Pooled Variance	87.5	
Hypothesized Mean Difference	0	
Degree of freedom (dF)	14	
t Stat	**3.207**	
P(T<=t) one-tail	0.003	
t Critical one-tail	1.761	
P(T<=t) two-tail	0.006	
t Critical two-tail	**2.145**	

The **t-test** shows that $|t_{Stat}| > |t_{Critical\ two-tail}|$. This means that the null hypothesis H_0 can be rejected and the means are unequal. In other words, it means **there is a significant difference** between the two groups.

Table D-24 below shows the results of the ANOVA test.

Table D-24 Experiment 1 - Case 5 - One-Way ANOVA test results

SUMMARY

Groups	*Count*	*Sum*	***Average***	*Variance*
Without DT	8	310	**38.75**	98,2142857
With DT	8	190	**23.75**	76,7857143

ANOVA TEST

Source of Variation	*SS*	*ddl*	*MS*	***F***	***P-value***	***F crit***
Between Groups	900	1	900	**10.286**	**0.006**	**4.600**
Within Groups	1225	14	87.5			
Total	2125	15				

The **ANOVA test** shows that $F > F_{critical}$ which means the null hypothesis H_0 can be rejected. Moreover, $p - value < 0.05$ which means that **the difference in the means is significant enough**. This verifies the results from the t-test.

Table D-25 Experiment 1 - Case 5 - Conclusion

	Case 4 - Mixed users - Without DT vs. With DT
F-test	H0: $\sigma_1^2 = \sigma_2^2$
t-test	H0: $\mu_1 \neq \mu_2$
One-way ANOVA test	H0: $\mu_1 \neq \mu_2$
Conclusion	The use of the digital twin for mixed users causes a significant enough difference in experiment 1.

Thus, the analysis shows that the digital twin has a considerable impact on the time spent to identify the failure in experiment 1, which is represented in Figure D-2 below.

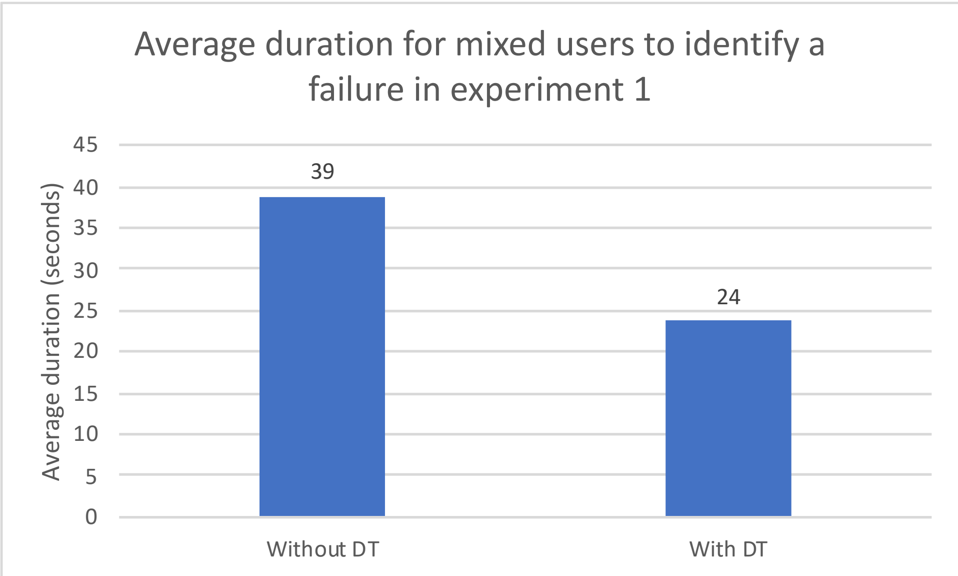

Figure D-2 Experiment 1 - Case 5 - Benefits of the digital twin prototype for mixed users

As a conclusion, for IT users, **the digital twin prototype saves an average of 38%**.

D.3 Experiment 2

D.3.1 Experiment 2 - Case 1 “Without Digital Twin prototype” - Samples “Non-IT” vs. “IT”

Here, the background of the testers in analysed in Experiment 2 without digital twin to evaluate its impact.

The values analysed are shown in Table D-26 below.

Table D-26 Experiment 2 - Case 1 - Groups values

Experiment 2 - Without DT - Duration (seconds)	
Non-IT	**IT**
260	25
227	25
135	40
	15
	40

Table D-27 below shows the results of the F-test.

Table D-27 Experiment 2 - Case 1 - F-test results

F-TEST	*Non-IT*	*IT*
Mean	**207.333**	**29**
Variance	**4196.333**	**117.5**
Observations	3	5
Degree of freedom (dF)	2	4
F	**35.713**	
P(F<=f) one-tail	0.003	
F Critical one-tail	**6.944**	

Table D-27 above shows that $F > F_{critical\ one-tail}$. This means that the null hypothesis H_0 can be rejected and thus variances are unequal.Table D-28 below shows the results of the t-test assuming unequal variances.

Table D-28 Experiment 2 - Case 1 - t-test results

T-TEST	*Non-IT*	*IT*
Mean	**207.333**	**29**
Variance	**4196.333**	**117.5**
Observations	3	5
Hypothesized Mean Difference	0	
Degree of freedom (dF)	2	
t Stat	**4.729**	
P(T<=t) one-tail	0.021	
t Critical one-tail	2.920	
P(T<=t) two-tail	0.042	
t Critical two-tail	**4.303**	

The **t-test** shows that $|t_{Stat}| > |t_{Critical\ two-tail}|$. This means that the null hypothesis H_0 can be rejected and the means are unequal. In other words, **there is a significant difference between the two groups**.

Table D-29 below shows the results of the ANOVA test.

Table D-29 Experiment 2 - Case 1 - One-Way ANOVA test results

SUMMARY						
Groups	*Count*	*Sum*	***Average***	*Variance*		
Without DT	3	622	**207.333**	4196.333		
With DT	5	145	**29**	117.5		
ANOVA TEST						
Source of Variation	*SS*	*ddl*	*MS*	***F***	***P-value***	***F crit***
Between Groups	59630.208	1	59630.208	**40.369**	**0.001**	**5.987**
Within Groups	8862.667	6	1477.111			
Total	68492.875	7				

The **ANOVA test** shows that $F > F_{critical}$ which means the null hypothesis H_0 can be rejected. Moreover, $p - valu < 0.05$ which means that **the difference in the means is significant enough.** This verifies the results from the t-test.

Table D-30 Experiment 2 - Case 1 - Conclusion

	Case 1 - Without DT - Non-IT vs. IT
F-test	H0: $\sigma_1^2 \neq \sigma_2^2$
t-test	H0: $\mu_1 \neq \mu_2$
One-way ANOVA test	H0: $\mu_1 \neq \mu_2$
Conclusion	The difference between the non-IT and the IT is significant enough when not using the digital twin in experiment 2.

Thus, the analysis shows that the background has a considerable impact on the time spent to identify this failure. Figure D-3 below shows this difference of time.

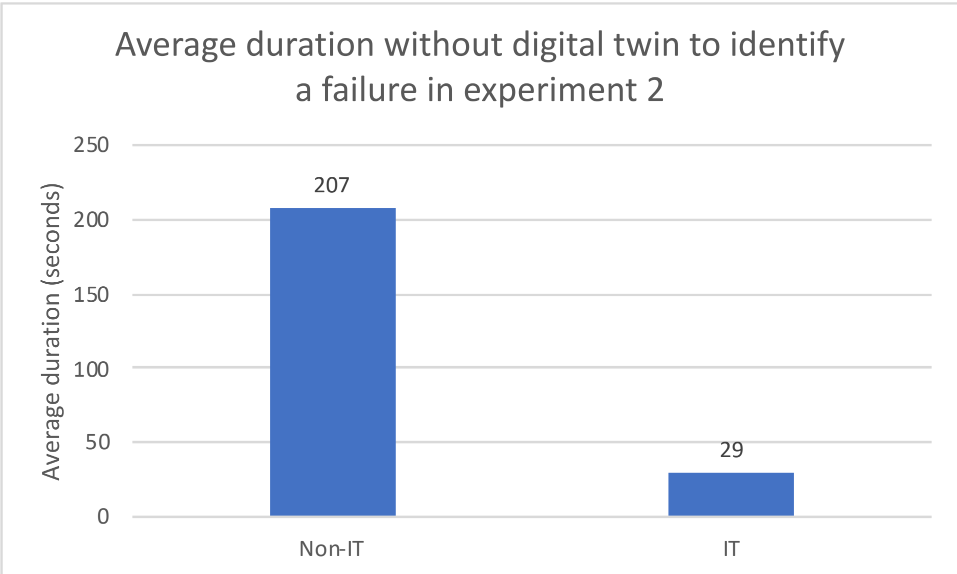

Figure D-3 Experiment 2 - Case 1 - Benefits of the background of the users without digital twin

As a conclusion, for IT users, **having an IT background enables them to save an average of 86%** in identifying the failure in experiment 2.

D.3.2 Experiment 2 - Case 2 “With Digital Twin prototype” - Samples “Non-IT" vs. IT”

Now, the same study is achieved with the digital twin prototype.

The values analysed are shown in Table D-31 below.

Table D-31 Experiment 2 - Case 2 - Groups values

Experiment 2 - With DT - Duration (seconds)	
Non-IT	**IT**
2	25
16	5
40	3
40	
14	

Table D-32 below shows the results of the F-test.

Table D-32 Experiment 2 - Case 2 - F-test results

F-TEST	*IT*	*Non-IT*
Mean	**22.4**	**11**
Variance	**286.8**	**148**
Observations	5	3
Degree of freedom (d	4	2
F	**1.938**	
P(F<=f) one-tail	0.368	
F Critical one-tail	**19.247**	

The F-test shows that $F < F_{critical\ one-tail}$. This means that the null hypothesis H_0 cannot be rejected and thus variances are equal.

Table D-33 below shows the results of the t-test assuming equal variances.

Table D-33 Experiment 2 - Case 2 - t-test results

T-TEST	IT	Non-IT
Mean	**22.4**	**11**
Variance	**286.8**	**148**
Observations	5	3
Pooled Variance	240.533	
Hypothesized Mean Difference	0	
Degree of freedom (dF)	6	
t Stat	**1,007**	
P(T<=t) one-tail	0,177	
t Critical one-tail	1.943	
P(T<=t) two-tail	0.353	
t Critical two-tail	**2.447**	

The **t-test** shows that $|t_{Stat}| < |t_{Critical\ two-tail}|$. This means that the null hypothesis H_0 cannot be rejected and the means are equal. In other words, it means **there is no significant difference between the two groups**.

Table D-34 below shows the results of the ANOVA test.

Table D-34 Experiment 2 - Case 2 - One-Way ANOVA test results

SUMMARY						
Groups	*Count*	*Sum*	***Average***	*Variance*		
Without DT	5	112	**22.4**	286.8		
With DT	3	33	**11**	148		
ANOVA TEST						
Source of Variation	*SS*	*ddl*	*MS*	***F***	***P-value***	***F crit***
Between Groups	243.675	1	243.675	**1.013**	**0.353**	**5.987**
Within Groups	1443.2	6	240.533			
Total	1686.875	7				

The **ANOVA test** shows that $F < F_{critical}$which means the null hypothesis H_0 cannot be rejected. Moreover, $p - value > 0.05$ which means that **the difference in the means is not significant enough.** This verifies the results from the t-test.

Table D-35 Experiment 2 - Case 2 - Conclusion

	Case 2 - With DT - Non-IT vs. IT
F-test	H_0: $\sigma_1^2 = \sigma_2^2$
t-test	H_0: $\mu_1 = \mu_2$
One-way ANOVA test	H_0: $\mu_1 = \mu_2$
Conclusion	The difference between the non-IT and the IT users is not significant enough when using the digital twin in experiment 2.

D.3.3 Experiment 2 - Case 3 “IT profile” - Samples “Without DT vs. With DT”

Here, the impact of the digital twin prototype is analysed in Experiment 1 for IT users.

The values analysed are shown in Table D-36 below.

Table D-36 Experiment 2 - Case 3 - Groups values

Experiment 2 - IT users - Duration (seconds)	
With DT	**Without DT**
2	25
16	25
40	40
40	15
14	40

Table D-37 below shows the results of the F-test.

Table D-37 Experiment 2 - Case 3 - F-test results

F-TEST	*With DT*	*Without DT*
Mean	**22.4**	**29**
Variance	**286.8**	**117.5**
Observations	5	5
Degree of freedom (dF)	4	4
F	**2.441**	
P(F<=f) one-tail	0.204	
F Critical one-tail	**6.388**	

The F-test shows that $F < F_{critical\ one-tail}$. This means that the null hypothesis H_0 cannot be rejected and thus variances are equal.Table D-38 below shows the results of the t-test assuming equal variances.

Table D-38 Experiment 2 - Case 3 - t-test results

T-TEST	*With DT*	*Without DT*
Mean	**22.4**	**29**
Variance	**286.8**	**117.5**
Observations	5	5
Pooled Variance	202.15	
Hypothesized Mean Difference	0	
Degree of freedom (dF)	8	
t Stat	**-0.734**	
P(T<=t) one-tail	0.242	
t Critical one-tail	1.860	
P(T<=t) two-tail	0.484	
t Critical two-tail	**2.306**	

The **t-test** shows that $|t_{Stat}| < |t_{Critical\ two-tail}|$. This means that the null hypothesis H_0 cannot be rejected and the means are equal. In other words, it means **there is not a significant difference between the two groups.**

Table D-39 below shows the results of the ANOVA test.

Table D-39 Experiment 2 - Case 3 - One-Way ANOVA test results

SUMMARY						
Groups	*Count*	*Sum*	***Average***	*Variance*		
With DT	5	112	**22.4**	286.8		
Without DT	5	145	**29**	117.5		
ANOVA TEST						
Source of Variation	*SS*	*ddl*	*MS*	***F***	***P-value***	***F crit***
Between Groups	108.9	1	108.9	**0.539**	**0.484**	**5.318**
Within Groups	1617.2	8	202.15			
Total	1726.1	9				

The ANOVA test shows that $F < F_{critical}$which means the null hypothesis H_0 cannot be rejected. Moreover, $p - value > 0.05$ which means that **the difference in the means is not significant enough.** This verifies the results from the t-test.

Table D-40 Experiment 1 - Case 3 - Conclusion

	Case 3 - IT users - Without DT vs. With DT
F-test	H0: $\sigma_1^2 = \sigma_2^2$
t-test	H0: $\mu_1 = \mu_2$
One-way ANOVA test	H0: $\mu_1 = \mu_2$
Conclusion	The use of the digital twin for IT users does not cause a significant enough difference in experiment 2.

D.3.4 Experiment 2 - Case 4 “Non-IT profile” - Samples “Without DT vs. With DT”

Now, the same study is achieved for non-IT users.

The values analysed are shown in Table D-41 below.

Table D-41 Experiment 2 - Case 4 - Groups values

Experiment 2 - non-IT users - Duration (seconds)	
With DT	**Without DT**
260	25
227	5
135	3

Table D-42 below shows the results of the F-test.

Table D-42 Experiment 2 - Case 4 - F-test results

F-TEST	*With DT*	*Without DT*
Mean	**207.333**	**11**
Variance	**4196.333**	**148**
Observations	3	3
Degree of freedom (dF)	2	2
F	**28.354**	
P(F<=f) one-tail	0,034	
F Critical one-tail	**19**	

The F-test shows that $F > F_{critical\ one-tail}$. This means that the null hypothesis H_0 can be rejected and thus variances are unequal.

Table D-43 below shows the results of the t-test assuming unequal variances.

Table D-43 Experiment 2 - Case 4 - t-test results

T-TEST	*With DT*	*Without DT*
Mean	**207.333**	**11**
Variance	**4196.333**	**148**
Observations	3	3
Hypothesized Mean Difference	0	
Degree of freedom (dF)	2	
t Stat	**5.159**	
P(T<=t) one-tail	0.0178	
t Critical one-tail	2.920	
P(T<=t) two-tail	0.036	
t Critical two-tail	**4.303**	

The **t-test** shows that $|t_{Stat}| > |t_{Critical\ two-tail}|$. This means that the null hypothesis H_0 can be rejected and the means are unequal. In other words, it means **there is a significant difference between the two groups.**

Table D-44 below shows the results of the ANOVA test.

Table D-44 Experiment 2 - Case 4 - One-Way ANOVA test results

SUMMARY

Groups	*Count*	*Sum*	***Average***	*Variance*
With DT	3	622	**207.333**	4196.333
Without DT	3	33	**11**	148

ANOVA TEST

Source of Variation	*SS*	*ddl*	*MS*	***F***	***P-value***	***F crit***
Between Groups	57820.167	1	57820.167	**26.619**	**0.007**	**7.709**
Within Groups	8688.667	4	2172.167			
Total	66508.833	5				

The ANOVA test shows that $F > F_{critical}$ which means the null hypothesis H_0 can be rejected. Moreover, $p - value < 0.05$ which means that **the difference in the means is significant enough.** This verifies the results from the t-test.

Table D-45 Experiment 1 - Case 4 - Conclusion

	Case 4 - Non-IT users - Without DT vs. With DT
F-test	H0: $\sigma_1^2 \neq \sigma_2^2$
t-test	H0: $\mu_1 \neq \mu_2$
One-way ANOVA test	H0: $\mu_1 \neq \mu_2$
Conclusion	The use of the digital twin for non-IT users causes a significant enough difference in experiment 2.

Thus, the analysis shows that the digital twin has a considerable impact on the time spent to identify this failure. Figure D-4 below shows this difference of time.

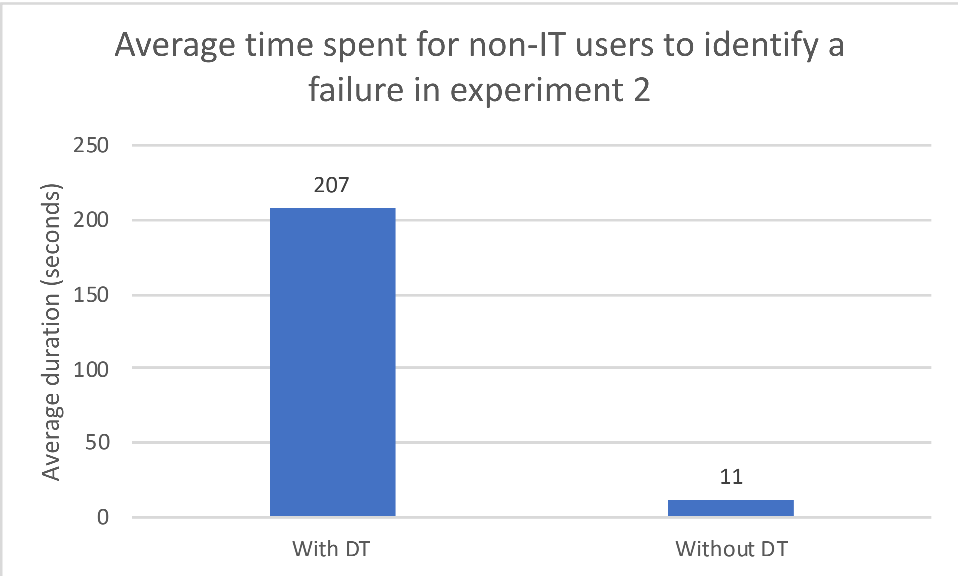

Figure D-4 Experiment 2 - Case 4 - Benefits of the digital twin prototype for non-IT users

As a conclusion, **for non-IT users, the digital twin prototype saves an average of 95% in experiment 2**.

D.3.5 Experiment 2 - Case 5 "Mix profiles" - Samples "Without DT vs. With DT"

Now, the same study is achieved for both non-IT and IT users.

The values analysed are shown in Table D-46 below.

Table D-46 Experiment 2 - Case 5 - Groups values

Experiment 2 - Mixed users - Duration (seconds)	
Without DT	**With DT**
260	25
227	5
25	2
25	16
40	40
15	40
40	14
135	3

Table D-47 below shows the results of the F-test.

Table D-47 Experiment 2 - Case 5 - F-test results

F-TEST	*Without DT*	*With DT*
Mean	**95.875**	**18.125**
Variance	**9784.696**	**240.982**
Observations	8	8
Degree of freedom (dF)	7	7
F	**40.603**	
P(F<=f) one-tail	3.826E-05	
F Critical one-tail	**3.787**	

The F-test shows that $F > F_{critical\ one-tail}$. This means that the null hypothesis H_0 can be rejected and thus variances are unequal.

Table D-48 below shows the results of the t-test assuming unequal variances.

Table D-48 Experiment 2 - Case 5 - t-test results

T-TEST	*Without DT*	*With DT*
Mean	**95.875**	**18.125**
Variance	**9784.696**	**240.982**
Observations	8	8
Hypothesized Mean Difference	0	
Degree of freedom (dF)	7	
t Stat	**2.196**	
P(T<=t) one-tail	0.032	
t Critical one-tail	1,895	
P(T<=t) two-tail	0.064	
t Critical two-tail	**2.365**	

The **t-test** shows that $|t_{Stat}| < |t_{Critical\ two-tail}|$. This means that the null hypothesis H_0 cannot be rejected and the means are equal. In other words, it means **there is not a significant difference between the two groups.**

Table D-49 below shows the results of the ANOVA test.

Table D-49 Experiment 2 - Case 5 - One-Way ANOVA test results

SUMMARY						
Groups	*Count*	*Sum*	***Average***	*Variance*		
Without DT	8	767	**95.875**	9784.696		
With DT	8	145	**18.125**	240.982		
ANOVA TEST						
Source of Variation	*SS*	*ddl*	*MS*	***F***	***P-value***	***F crit***
Between Groups	24180.25	1	24180.25	**4.824**	**0.045**	**4.6**
Within Groups	70179.75	14	5012.839			
Total	94360	15				

The **ANOVA test** shows that $F > F_{critical}$which means the null hypothesis H_0 can be rejected. Moreover, $p - value < 0.05$ which means that **the difference in the means is significant enough.** This is **contradictory** to the t-test.

Table D-50 Experiment 2 - Case 5 - Conclusion

	Case 4 -Mixed users - Without DT vs. With DT
F-test	H0: $\sigma_1^2 \neq \sigma_2^2$
t-test	H0: $\mu_1 = \mu_2$
One-way ANOVA test	H0: $\mu_1 \neq \mu_2$
Conclusion	The t-test and the ANOVA test are contradictory. More data needs to be measured in order to have more accurate analysis from statistical tests.

However, as the $|t_{Stat}|$ value is close to the $|t_{Critical\ two-tail}|$ value for the t-test, the result is not very significant to be interpreted without error. Thus, based on the ANOVA test, in case 4 the digital twin prototype may have an advantage in identifying this failure which is represented in Figure D-5 below. This would allow to reduce time by 81%.

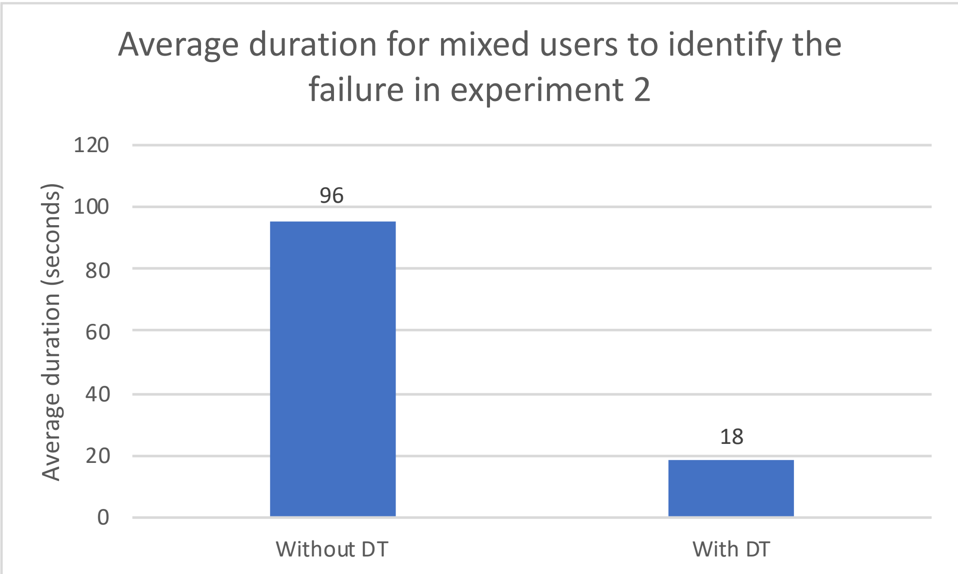

Figure D-5 Experiment 2 - Case 5 - Benefits of the digital twin prototype for mixed users

D.4 Survey results and analysis

The answers collected from the survey are shown in Table D-51 below.

Table D-51 Survey general results

QUESTION			TESTER												
			1	2	3	4	5	6	7	8	9	10	11	12	13
QUESTION	1. User-friendliness	Q 1.1	4	5	4	4	5	5	5	5	4	5	5	4	5
		Q 1.2	4	4	5	5	5	5	5	5	5	2	5	4	5
		Q 1.3	4	5	4	5	4	5	4	4	3	5	3	4	5
		Q 1.4	4	4	5	4	5	5	5	4	4	4	3	3	4
		Q 1.5	4	5	5	5	5	5	5	5	4	5	4	4	4
	2. Collection of data	Q 2.1	3	5	4	5	4	5	4	4	4	3	4	5	5
		Q 2.2	3	3	5	5	5	5	4	3	3	4	5	3	5
		Q 2.3	5	3	5	5	5	5	4	5	3	4	4	5	5

Analyses lead to the calculations of averages scores per question, per criterion and per tester represented in Table D-52 below.

Table D-52 Analysis of the answers collected from the survey

			TESTER													AVERAGE	
			1	2	3	4	5	6	7	8	9	10	11	12	13	Avg/Quest	Avg/Criteria
QUESTION	1. User-friendliness	Q 1.1	4	5	4	4	5	5	5	5	4	5	5	4	5	4,62	4,43
		Q 1.2	4	4	5	5	5	5	5	5	5	2	5	4	5	4,54	
		Q 1.3	4	5	4	5	4	5	4	4	3	5	3	4	5	4,23	
		Q 1.4	4	4	5	4	5	5	5	4	4	4	3	3	4	4,15	
		Q 1.5	4	5	5	5	5	5	5	5	4	5	4	4	4	4,62	
	2. Collection of data	Q 2.1	3	5	4	5	4	5	4	4	4	3	4	5	5	4,23	4,26
		Q 2.2	3	3	5	5	5	5	4	3	3	4	5	3	5	4,08	
		Q 2.3	5	3	5	5	5	5	4	5	3	4	4	5	5	4,46	
AVERAGE		Avg/Tester	3,88	4,25	4,63	4,75	4,75	5,00	4,50	4,38	3,75	4,00	4,13	4,00	4,75		