



**FREDERICO MIGUEL AFONSO FERREIRA**  
Bachelor in Computer Science and Engineering

# **DIGITAL TWINS IN THE CONTEXT OF DIGITAL TRANSITION FOR CLASSIC CARS RESTORING**

**CASE STUDY OF A CLASSIC CAR RESTORATION SHOP**

MASTER IN COMPUTER SCIENCE

NOVA University Lisbon  
September, 2024



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## **Digital twins in the context of Digital Transition for Classic Cars Restoring**

### **Case study of a classic car restoration shop**

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## ACKNOWLEDGEMENTS

I want to start by thanking Professor Vasco Amaral and Professor Fernando Abreu for their invaluable support, availability, and assistance throughout the development of this work. We held weekly meetings where we shared and discussed ideas, which greatly enriched the research process.

I would like to thank Raimundo Branco workshop and the workers as well, who were always available to help during my visits to the workshop and were very important during the validation phase.

I want to thank my entire family, without them, my university journey wouldn't have been possible. They supported me during both the good and bad times, always believing in me.

Finally, I want to thank my friends for all the good memories we've shared and the support they've provided throughout my years at university.

## ABSTRACT

Classic cars hold substantial value in the automotive industry, and the restoration process plays a pivotal role in increasing their worth. Ensuring the certification of these restoration processes is crucial, as is keeping owners well-informed about the ongoing procedures involving their cherished vehicles. By monitoring and controlling these restoration activities, and take into account the physical setting of the shop floor, classic car workshops can optimize operations, provide owners with relevant information, and preserve the authenticity of these vintage automobiles. To achieve this, we under-carried a digital transition process in a classic car restoration workshop, incorporating Industry 4.0 principles and Cyber-physical systems.

This research focuses on developing an advanced Digital Twin system for a classic car restoration workshop. The Digital Twin application enhances the management and monitoring of restoration and preservation processes, integrating with previously developed systems. The system enables workshop employees to manage car slot areas, track vehicle tasks, and assign these tasks to specific physical locations. It includes a 3D model of the workshop, allowing users to navigate, view vehicle locations, and interact with them. Classic car owners can monitor their vehicle's restoration progress and history. Additionally, the system supports process flow visualization and simulations.

In conclusion, the Digital Twin application streamlines workshop operations, enhances transparency between staff and owners, and preserves the authenticity of restoration processes. This research advances digital twin technology in classic car restoration, fostering improved management practices and enriching the overall experience for classic car owners.

**Keywords:** Digital Twin, Industry 4.0, IoT, Classic Cars, Smart restoration, Digital transition, Sensors, Cyber-physical system

## RESUMO

Os carros clássicos possuem um valor substancial na indústria automóvel, e o processo de restauro desempenha um papel fundamental no aumento do seu valor. Garantir a certificação desses processos de restauro é vital, assim como manter os proprietários bem informados sobre os procedimentos em curso nos veículos. Ao monitorizar e controlar as atividades de restauro, as oficinas de carros clássicos podem otimizar efetivamente as operações, fornecer aos proprietários informações pertinentes e preservar a natureza autêntica desses automóveis vintage. Por isso, ocorreu uma transformação digital numa oficina de restauro de carros clássicos, incorporando conceitos como a indústria 4.0 e sistemas ciber-físicos.

Este trabalho centra-se no desenvolvimento de um sistema de gêmeo digital para uma oficina de restauro de automóveis clássicos. Este sistema faz a gestão e monitorização dos processos de restauro e preservação, integrando-se com sistemas previamente desenvolvidos. O sistema permite aos funcionários da oficina gerir as áreas de trabalho dos automóveis, acompanhar as tarefas dos veículos e atribuir essas tarefas a locais específicos. Inclui um modelo 3D realista da oficina, permitindo aos utilizadores navegar, ver a localização dos veículos e interagir com eles. Os proprietários de automóveis clássicos podem monitorizar o progresso e o historial do restauro do seu veículo. Além disso, o sistema suporta a visualização e simulação de fluxos de processos e atividades.

Em conclusão, o gêmeo digital simplifica as operações da oficina, aumenta a transparência entre os trabalhadores e os proprietários, preservando a autenticidade dos processos de restauro. Esta investigação faz avançar a tecnologia de gêmeo digital no restauro de automóveis clássicos, promovendo melhores práticas de gestão e enriquecendo a experiência geral dos proprietários de automóveis clássicos.

**Palavras-chave:** Gêmeo Digital, Indústria 4.0, Internet das coisas, Carros clássicos, Restauro inteligente, Transformação inteligente, Sensores, Sistemas ciber-físicos

# CONTENTS

<b>List of Figures</b>	<b>viii</b>
<b>List of Tables</b>	<b>x</b>
<b>Acronyms</b>	<b>xi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Context and Description . . . . .	1
1.2 Problem Statement and Final Goals . . . . .	2
1.3 Challenges . . . . .	3
1.4 Scientific Methodology . . . . .	3
1.5 Expected Key Contributions . . . . .	4
1.6 Document Structure . . . . .	4
<b>2 Background</b>	<b>6</b>
2.1 Industry 4.0 . . . . .	6
2.1.1 Cyber Physical System . . . . .	6
2.2 Digital Twin . . . . .	6
2.2.1 Key Enabling Technologies . . . . .	8
<b>3 State of Art</b>	<b>10</b>
3.1 Rapid Systematic Review . . . . .	10
3.1.1 Planning the Research . . . . .	11
3.1.2 Conducting the Research . . . . .	12
3.2 Snowballing . . . . .	12
3.3 Discussion and analysis of the results . . . . .	13
3.4 Synthesis of the results . . . . .	15
3.5 Available Digital Twin Tools . . . . .	16
3.6 Previous Work . . . . .	19
3.7 Summary . . . . .	24

<b>4</b>	<b>Conceptualization and Implementation</b>	<b>25</b>
4.1	Software Requirements Engineering . . . . .	25
4.1.1	Stakeholders . . . . .	25
4.1.2	Functional Requirements . . . . .	26
4.2	Architecture . . . . .	28
4.2.1	Components . . . . .	29
4.2.2	Technologies . . . . .	31
4.3	Implementation . . . . .	32
4.3.1	Charter of Turin Monitor . . . . .	33
4.3.2	Digital Twin . . . . .	36
<b>5</b>	<b>Validation</b>	<b>50</b>
5.1	Overview . . . . .	50
5.2	Digital twin Validation . . . . .	51
5.2.1	Validation by Workshop Employees . . . . .	51
5.2.2	Validation by External Members . . . . .	56
5.3	Threats to Validity . . . . .	59
<b>6</b>	<b>Conclusions and Future Work</b>	<b>60</b>
6.1	Conclusions . . . . .	60
6.2	Future Work . . . . .	61
	<b>Bibliography</b>	<b>63</b>
	<b>Appendices</b>	
<b>A</b>	<b>Processes and Activities of Camunda</b>	<b>67</b>
<b>B</b>	<b>Questionnaire</b>	<b>70</b>

## LIST OF FIGURES

1.1	Action research cyclical process by "An Assessment of the Scientific Merits of Action Research" [26] . . . . .	3
2.1	Differences between digital model, shadow and twin by "Towards a Family of Digital Model/Shadow/Twin Workflows and Architectures" [19] . . . . .	7
3.1	Sensor box . . . . .	20
3.2	Component Diagram of the architecture developed by [22, 11] . . . . .	21
3.3	Charter of Turin Monitor application by [6] . . . . .	22
3.4	Camera Hub application by [6] . . . . .	22
3.5	Component Diagram of the architecture developed by [6] . . . . .	23
4.1	Use case diagram of the Digital Twin system . . . . .	26
4.2	Component Diagram of the system . . . . .	30
4.3	API methods for the virtual map locations . . . . .	33
4.4	API methods for the activities and location history of a classic car . . . . .	35
4.5	Unity System Structure . . . . .	37
4.6	Existing Ground floor 2D Plan of the workshop . . . . .	38
4.7	New Ground floor 2D Plan of the workshop . . . . .	38
4.8	3D Model of the workshop . . . . .	39
4.9	Processes and location mapping - Ground floor . . . . .	40
4.10	Processes and location mapping - First floor . . . . .	41
4.11	Login Page . . . . .	42
4.12	Main View . . . . .	42
4.13	Camera Controls . . . . .	43
4.14	Camera Controls . . . . .	43
4.15	Input name of location . . . . .	44
4.16	Place Location . . . . .	44
4.17	Location Details . . . . .	45
4.18	Projects list . . . . .	45

4.19	Projects last location . . . . .	46
4.20	Projects details . . . . .	47
4.21	Associate location to task . . . . .	47
4.22	Vehicle’s process flow . . . . .	48
4.23	Simulation Mode . . . . .	49
5.1	Diagram of steps followed in [14] . . . . .	52
5.2	Range of System Usability Scale (SUS) Scores in [13] . . . . .	57
5.3	SUS score Results . . . . .	58
5.4	Benchmark for the User Experience Questionnaire (UEQ) scales . . . . .	58
5.5	UEQ mean values by category . . . . .	59
A.1	Areas within the workshop . . . . .	67
A.2	Mapping of Processes and Activity Locations (1) . . . . .	68
A.3	Mapping of Processes and Activity Locations (2) . . . . .	69
B.1	Questionnaire for the Digital Twin validation (1) . . . . .	71
B.2	Questionnaire for the Digital Twin validation (2) . . . . .	72

## LIST OF TABLES

3.1	PICOC table . . . . .	11
3.2	Results summary table . . . . .	16
3.3	Digital twin tools comparison . . . . .	18
5.1	Workers characterization . . . . .	52
5.2	Answers to the questionnaire . . . . .	54

## ACRONYMS

<b>ACP</b>	Automóvel Club de Portugal ( <i>p. 2</i> )
<b>AI</b>	Artificial Intelligence ( <i>pp. 7, 12</i> )
<b>API</b>	Application Programming Interface ( <i>pp. 16, 17, 19, 31, 33–36</i> )
<b>ASE</b>	Automated Software Engineering ( <i>p. 2</i> )
<b>BLE</b>	Bluetooth Low Energy ( <i>p. 19</i> )
<b>BPMN</b>	Bussiness Process Model and Notation ( <i>pp. 19, 22, 31</i> )
<b>CPS</b>	Cyber-Physical System ( <i>pp. 6, 11, 13–15</i> )
<b>DT</b>	Digital twin ( <i>pp. 1–11, 13–17, 19, 24–26, 28, 31–36, 39, 41, 42, 50, 51, 53–56, 59–61</i> )
<b>DT-CPPS</b>	Digital Twin based Cyber Physical Production System ( <i>pp. 13, 14</i> )
<b>FIVA</b>	Fédération Internationale des Véhicules Anciens ( <i>pp. 1, 22</i> )
<b>GUI</b>	Graphical User Interface ( <i>pp. 22, 31, 36, 41</i> )
<b>IoT</b>	Internet of Things ( <i>pp. 6, 8, 15, 19</i> )
<b>KPI</b>	Key Performance Indicator ( <i>p. 13</i> )
<b>ML</b>	Machine Learning ( <i>pp. 7, 8, 14</i> )
<b>RFID</b>	Radio Frequency Identification ( <i>pp. 13, 62</i> )
<b>RR</b>	Rapid Review ( <i>pp. 10, 15, 24</i> )
<b>SLR</b>	Systematic literature review ( <i>p. 10</i> )
<b>SRE</b>	Software Requirements Engineering ( <i>pp. 25, 32–34</i> )
<b>SUS</b>	System Usability Scale ( <i>pp. ix, 56–58</i> )

**UEQ**      User Experience Questionnaire (*pp. ix, 56, 58, 59*)

# INTRODUCTION

*This chapter will introduce the context and description of this dissertation, institutional context, expected challenges, problem description and final goals to achieve. It is presented the Scientific methodology used in this work, expected key contributions and the structure of this work.*

## 1.1 Context and Description

Classic cars hold immense historical and cultural significance and are regarded as works of art by collectors and enthusiasts. Consequently, the classic car market experiences high demand, rendering these vehicles highly valuable. Restoring classic cars is essential to preserving their authenticity and ensuring continued value.

The Charter of Turin [10], established by the [Fédération Internationale des Véhicules Anciens \(FIVA\)](#) <sup>1</sup> sets forth the principles and guidelines for the preservation, use, and promotion of historic vehicles worldwide. It outlines FIVA's commitment to safeguarding the cultural heritage represented by historic vehicles. It emphasizes the importance of maintaining originality, historical accuracy, and technical authenticity by avoiding inappropriate modifications, destruction, and misuse.

Classic car restoration processes are typically intricate, time-consuming, and involve multiple stakeholders, making it challenging for workshop floors to manage, control, and monitor them effectively. It is expected that the benefits of the Industry 4.0 revolution to create more efficient, flexible, and intelligent restoration shops.

This project builds upon a system developed in previous works [22, 11, 6] within the digital transition of a classic car restoration shop and aims to contribute to facilitating optimization, decision-making, simulation, testing, monitoring, and control, improving efficiency, reducing costs, and enhancing quality within the workshop environment. This will be achieved by creating a [Digital twin \(DT\)](#) for this system, which is novel in this domain.

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<sup>1</sup>FIVA, <https://fiva.org/en/fiva-home/>, Last accessed in 30/09/2024

The work described in this paper originates from a collaboration between the [Automated Software Engineering \(ASE\)](#) group of NOVA-LINCS <sup>2</sup>, ISTAR's Software Systems Engineering group <sup>3</sup>, and Raimundo Branco <sup>4</sup>. The latter is a classic car restoration shop that aims to benefit from the fourth industrial revolution described before. Additionally, [Automóvel Club de Portugal \(ACP\)](#) <sup>5</sup>, the largest automobile association in Portugal, and BASF <sup>6</sup>, a German multinational company specializing in chemical production, including Glasurit's <sup>7</sup> product line used for painting classic cars, are participating in this collaborative effort.

## 1.2 Problem Statement and Final Goals

As mentioned, this work is part of an ongoing project to digitally transform a classic car restoration shop. As we will see later on, there is no Digital Twin technology applied in this domain that allows for monitoring and control of the restoration processes inside the shop floor. Therefore, in this work, we aim to answer the following question:

**How can we design and implement a Digital Twin that combines existing business processes with the physical processes of a classic car restoration shop to be able to monitor and control them, as well as support simulations and what-if scenarios?**

To get there, we must follow the following steps:

- Determine the current best practices, methodologies, architectures and technologies in *DT* for similar cases to ours by carrying on a Rapid Systematic Literature review;
- Choose the relevant properties of the domain to be represented in the digital twin, devise the relevant Use Case scenarios (to monitor, control and make simulations), and design the architecture of the digital twin solution;
- Implementation of the digital twin using the identified tools;
- Validation of the proposed solution.

In the end, a functional *DT* solution of the classic car restoration shop will be available. Making available information such as classic car locations and identification of ongoing processes through the database management system, and, lastly, a connection with a Charter of Turin monitor application, systems already developed. The *DT* will be the center of the system, able to monitor, control, simulate, test and improve efficiency in the classic cars workshop.

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<sup>2</sup>Nova-LINCS, <https://nova-lincs.di.fct.unl.pt/>, Last accessed on 30/09/2024

<sup>3</sup>ISTAR-SSE, <https://ciencia.iscte-iul.pt/centres/istar-iul/groups/sse>, Last accessed on 30/09/2024

<sup>4</sup>Raimundo Branco, <https://www.facebook.com/raimundo.joaquim.branco>, Last accessed on 30/09/2024

<sup>5</sup>ACP, <https://www.acp.pt/inicio>, Last accessed on 30/09/2024

<sup>6</sup>BASF, <https://www.basf.com/pt/pt.html>, Last accessed on 30/09/2024

<sup>7</sup>Glasurit, <https://www.glasurit.com/en-int>, Last accessed on 30/09/2024

### 1.3 Challenges

Firstly, there is a wide plethora of tools to create a *DT*, so it will be necessary to study and assess the different options available to this case study. Another challenge is the architecture of our solution. It will be necessary to research and analyze to build a reliable solution that is scalable, secure, extensive and efficient. As mentioned before, several systems have already been built in the workshop for the purpose of digital transition in this domain. Therefore, combining all the systems and keeping the data consistent will be a complex task.

The successful implementation of a *DT* requires the overall usability of the application, a realistic physical model of the workshop, and useful features that cater to the needs of the workshop employees and follow the processes that happen inside the shop floor.

### 1.4 Scientific Methodology

The research method used in this work is action research. In this methodology, the research is actively and systematically engaged in the problem.

According to the literature "An Overview of the Methodological Approach of Action Research" [17], the definition of action research is the following: "aims to contribute both to the practical concerns of people in an immediate problematic situation and to further the goals of social science simultaneously. Thus, there is a dual commitment in action research to study a system and concurrently to collaborate with members of the system in changing it in what is together regarded as a desirable direction.".

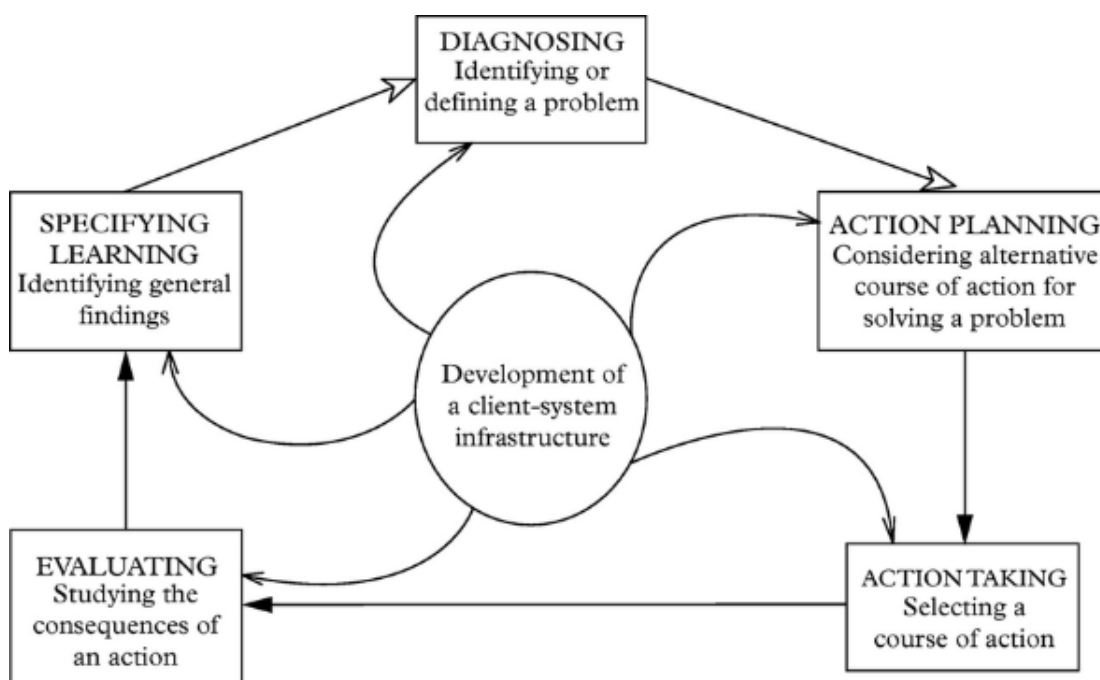


Figure 1.1: Action research cyclical process by "An Assessment of the Scientific Merits of Action Research" [26]

This methodology has a cycle with five different phases according to “An Assessment of the Scientific Merits of Action Research” [26], as it is possible to observe in figure 1.1.

- **Diagnosis** - In this phase, the problem to be solved is defined. In this case, our initial problems are mentioned in section 1.2.
- **Action planning** - This phase is the search for all the possible solutions to solve our problem. All these solutions will be studied and compared, and the best fit will be chosen.
- **Action taking** - The solution chosen in the previous phase will be implemented in this phase.
- **Evaluating** - In this phase, the outcome of the solution implemented will be analyzed and, consequently, evaluated if the solution solves the problem.
- **Specifying learning** - In the last phase, with the evaluation already made, the researcher concludes the results of the solution implemented and what was learned in the process.

### 1.5 Expected Key Contributions

With this work, several key contributions were made:

- Create and implement a digital twin of the classic car restoration shop;
- Being possible to monitor, control, simulate, decision-making, and testing in the shop floor with the DT, as well as space organization and layout optimization;
- Classic car owners can track the processes and tasks performed in their vehicles within the workshop.

### 1.6 Document Structure

This document is structured as follows:

- **Chapter 1 - Introduction:** In this chapter, we present the context and description of our work, expected challenges, problem statement and goals to achieve with the proposed solution.
- **Chapter 2 - Background:** In this chapter, there is crucial concepts for a better understanding of this work, such as the definition, features and key enabling technologies of a Digital twin.
- **Chapter 3 - State of the art :** This chapter contains previous works related to this dissertation’s theme and concepts.

- **Chapter 4 - Conceptualization and Implementation:** This chapter outlines the development process of this work. It begins by detailing the software requirements of our DT application, including the identification of stakeholders and functional requirements. Next, we present the system architecture, highlighting the key components and technologies used. Lastly, the chapter covers the implementation process.
- **Chapter 5 - Validation:** This chapter focuses on validating our system by presenting the methodologies used for validation and discussing the results obtained.
- **Chapter 6 - Conclusions:** The final chapter summarises the entire work and outlines potential future developments for this project.

## BACKGROUND

*This chapter gives insight into crucial concepts in this document. Industry 4.0 concept and enabling technologies, such as definition and features of a Digital Twin, key enabling technologies used, Internet of Things, cloud computing and machine learning.*

### 2.1 Industry 4.0

The industry 4.0 concept is an “end-to-end digitisation and the integration of digital industrial ecosystems by seeking completely integrated solutions” [29]. The main focus of Industry 4.0 is the digital transformation and automation of industries, allowing them to improve efficiency and productivity.

There are several key technologies to make industry 4.0 possible, like [Cyber-Physical System \(CPS\)](#), [Internet of Things \(IoT\)](#) and cloud computing according to [29]. All these technologies combined have the potential to create an industry 4.0 system.

#### 2.1.1 Cyber Physical System

[CPS](#) is a main element in Industry 4.0. [CPS](#) refers to the integration of physical systems and virtual systems. It uses sensors and machines to gather real-time information from the physical world, relying on communication networks. [CPS](#) has functionalities of controlling, monitoring and coordinating processes and operations in a system [21].

### 2.2 Digital Twin

The basic concept of a [DT](#) means a virtual representation of a physical real object.

A [DT](#) is often confused with the digital model and digital shadow concept. These three concepts differ in how data flow interacts between physical and virtual objects. In a digital model, the data flow is manual. Changes in the physical object are manually made to the virtual object, and vice-versa. In a digital shadow, the data flow is automated between physical objects and virtual objects, but manually vice-versa. Lastly, in a [DT](#) exists an

automatic bi-directional data flow between the two objects [19] as it is possible to observe in the figure 2.1.

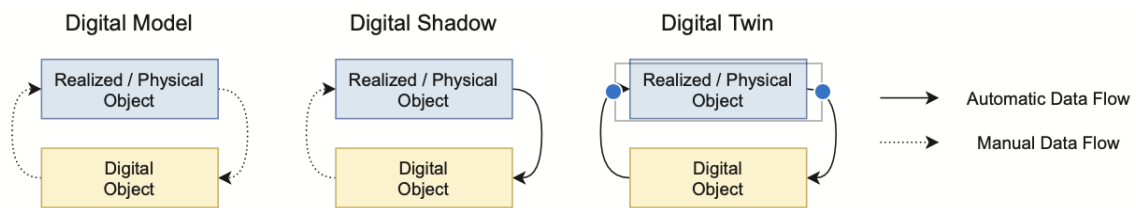


Figure 2.1: Differences between digital model, shadow and twin by "Towards a Family of Digital Model/Shadow/Twin Workflows and Architectures" [19]

A more detailed definition of a **DT** is a “virtual construct that represents a physical counterpart, integrates several data inputs with the aim of data handling and processing, and provides a bi-directional data linkage between the virtual world and the physical one” [27]. This data is usually collected through sensors, and synchronization is important.

A **DT** have a lot of important features and purposes, according to the literature [7]:

- **Data visualization** - visual interfaces to visualize virtual models in 2D or 3D, as plots of different data in the **DT** through the sensors.
- **Modelling and Calibration** - In a **DT**, it is possible to create models and representations of the behaviour of something, and it is important for a model to be faithful to his physical system. Calibration is an important process in the modelling and configuration of the parameters of a model.
- **State estimation** - With a **DT** can estimate the system’s state. These states change through various parameters.
- **Monitoring** - Monitoring and controlling the physical object or processes through the **DT** is possible.
- **What if simulation** - enables experimentation and testing with conditions and scenarios, what is the consequence of doing something, a virtual replica of the physical system. All this using the data captured by the **DT**.
- **Predictive maintenance** - predict when maintenance may be necessary for the physical object, identification of potential failures.
- **Self adaption** - Ability to adapt and optimize the **DT** usually through **Machine Learning (ML)** and **Artificial Intelligence (AI)**.

These features combined bring improved performance, cost savings, sustainability, increased safety, collaboration, and quality control to a physical system like a shop floor or a factory.

## 2.2.1 Key Enabling Technologies

In this section, it will explain various key enabling technologies to achieve the full definition of a DT, like IoT, cloud computing and ML. And how they are important in a DT.

### 2.2.1.1 Internet of Things

Here, the definition IoT and its importance in DT will be discussed. The definition of IoT “is the network of things, with device identification, embedded intelligence, and sensing and acting capabilities, connecting people and things over the Internet” [23], with multiple devices connected creating a network to exchange information. These devices can collect and control information from a physical object.

IoT is a crucial technology to a DT because it provides data to the system in real-time, which is used for the simulations. IoT also brings together the power of monitor and control devices and processes to a DT. The connection between physical objects and the digital system is a vital role for a DT.

Therefore, IoT is an enabler of many of the DT features identified in section 2.2.

### 2.2.1.2 Machine Learning

ML is also an important aspect of improving efficiency and enabling some features of a DT. ML algorithms allow advanced analysis, interpretation, and prediction capabilities upon the data coming from IoT.

ML algorithms may be used in the context of a DT for anomaly detection (i.e. finding deviations from expected behaviour), predictive analytics (i.e. making predictions about future behaviour), optimization and control (i.e. finding the best settings or control parameters to achieve desired outcomes), data imputation and reconstruction (when data is missing or incomplete), and what-if analysis through simulation (to analyze the impact of different scenarios and provide insights into the system’s behaviour under various conditions) [5].

### 2.2.1.3 Cloud Computing

Cloud computing delivers computing resources, including servers, data storage, databases, processing power, networking, and software, over the Internet.

Cloud computing is crucial in implementing and utilising DTs to grant scalability and resource management [3]. Since DTs usually require optimal performance to allow real-time response, cloud platforms can offer a scalable infrastructure to handle varying processing workloads efficiently. DTs often generate large amounts of data, calling for efficient data ingestion, organization, and retrieval to ensure that historical and real-time data is readily available for modelling and analysis. Cloud computing platforms offer those capabilities. The same can be said for facilitating collaboration among stakeholders involved in the DT ecosystem while enabling seamless data sharing and integration

between different systems. Cloud computing also provides powerful computational resources and pre-built tools for the ML features described in section [2.2.1.2](#).

Ultimately, it brings together an important environment for developing an efficient DT.

## STATE OF ART

*This chapter presents the state of the art of the topics in question in this work. The search methodology description, research questions, and the search string used. The analysis and study of the accepted papers. A section about the previous theses. Lastly, a comparison of DT tools found and a summary of the research.*

### 3.1 Rapid Systematic Review

The search methodology for this work's state of the art was the **Rapid Review (RR)** [2]. This method delivers the results in a faster review, with simple processes, compared to the **Systematic literature review (SLR)**, but maintains the rigour and quality of the search for scientific evidence. So the RR was the best choice due to the limited available time.

The search engine to find quality scientific papers was the Scopus<sup>1</sup>. And with the complement of Parsifal<sup>2</sup>, a tool to perform SLR, to document the whole process. The RR method will be divided into three stages during the research:

- **Planning the research** - It is defined the PICOC<sup>3</sup>, research questions, search string, sources and selection criteria;
- **Conducting the research** - Evaluation of the quality of the selected papers;
- **Discussion and analysis of the results** - Synthesis and analysis of the information collected in the selected articles.

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<sup>1</sup>Scopus, <https://www.scopus.com/>, Last accessed on 19/05/2023

<sup>2</sup>Parsifal, <https://parsif.al/>, Last accessed on 22/05/23

<sup>3</sup>Population, Intervention, Comparison, Outcome, and Context, a framework to describe the research scope

### 3.1.1 Planning the Research

#### 3.1.1.1 Research Questions

The PICOC method was used, as seen in table 3.1, before formulating the research questions and defining the search string.

Table 3.1: PICOC table

PICOC	
<b>Population</b>	Scientific papers
<b>Intervention</b>	Digital Twins in the Context of Digital Transition
<b>Comparison</b>	Digital Twins vs other systems
<b>Outcomes</b>	A systematic study of methodologies, practices, techniques, and tools that characterise the current state of the art in the identified context
<b>Context</b>	Industry 4.0 in the automotive industry

Our research questions are the following:

- How are digital twins integrated into the automotive industry?
- What architectures are being used?
- What technologies are being used?

#### 3.1.1.2 Search String

To achieve our goals, the search string in Scopus was the following:

- TITLE-ABS-KEY ( "digital twin" AND "industry 4.0" AND "cyber physical system" AND ( "automotive industry" OR "smart factory " OR "car industry" OR "shop floor" OR "smart manufacturing" ) )

With this search string, it is possible to find articles that the main focus is **DT**. One of the strings must be Industry 4.0 systems because the **DT** concept is entirely connected with the fourth industrial revolution. Another string is the **CPS**, a key component for the Industry 4.0, as mentioned before in section 2.1. As explained in section 1.1, the case study of this project is a classic car restoration shop, so the papers must be in the context of the automotive and car industry. Unfortunately, there are no sufficient papers only with these strings, therefore these strings were added: smart factory, shop floor and smart manufacturing.

Lastly, all these articles are in English, and their publication year is no earlier than 2015, as all the concepts in this research are relatively new.

The search engine returned 108 results.

## 3.1.2 Conducting the Research

### 3.1.2.1 Study Selection

After getting the potential articles, we read the abstract of all of them, and it was determined which ones were relevant. This process was also made with the help of Elicit<sup>4</sup>, an AI tool to search for articles, with the capacity to summarize information about the paper.

In this process, 30 articles were accepted.

### 3.1.2.2 Quality Assessment

The accepted articles were entirely read for quality assessment in the next phase.

These were the questions used to evaluate each article:

- Were the goals and research questions clearly stated?
- Were threats to validity exposed?
- Were negative findings presented?
- Was related work exposed and compared with claimed research results?
- Was the research design specified?
- Were the data used for validation adequately described and available?
- Were the research questions answered?
- Were the architecture and implementation of the proposed technology described?
- Is it applied in a case study?
- Is it applied in the automotive industry?

Each question is answered with one of the following *Strongly agree*, *Agree*, *Neither agree or disagree*, *Disagree* or *Strongly disagree*. With the values 4.0, 3.0, 2.0, 1.0 and 0.0, respectively.

In this phase, eight articles were accepted.

## 3.2 Snowballing

The snowballing approach was also used to find more relevant articles from the articles accepted in section 3.1.2.2. The reference list is reviewed in backward snowballing to find new relevant papers. In forward snowballing, the papers that cited the initial papers are reviewed [28]. Both these techniques were applied in the research of this work.

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<sup>4</sup>Elicit, <https://elicit.org/>, Last accessed in 23/05/2023

### 3.3 Discussion and analysis of the results

In [9], the case study is the Volkswagen AutoEuropa, in Palmela, Portugal, and the main goal was to produce a big data platform for data analytics, visualization and control of a logistics-based digital twin. The designed architecture for this case has three entities, the physical factory, the big data infrastructure and the DT. The physical factory sends data to the other entities. The big data infrastructure has five layers: Data collection and ingestion layer, Data storage layer, Data processing layer, Data analytics layer and Data visualization layer. Lastly, this entity has bidirectional communication with the DT tool chosen, the Visual Components simulation environment. For the validation of this work, the DT simulation quality was tested and compared with the logistics processes in real life. The second validation was a “*What if scenario*” to solve an optimization problem. Both these tests required a comparison with **Key Performance Indicator (KPI)**.

In [12], a DT and manufacturing simulation integrated platform with the main purpose of monitoring and simulation is proposed. The architecture comprises a CPS Bus, transmits data, a Physical shop-floor, the machines, a Shop-floor Service System, controls and monitors the shop-floor, and the DT. The construction of the digital twin used Unreal Engine, a game engine. It used a five-dimensional (Geometry, Physics, Capabilities, Behaviour and Rules) architecture to build the DT by [1]. A simulation of two production line configurations was conducted for validation to determine which configuration is the most efficient.

The paper [4], studies a framework for a **Digital Twin based Cyber Physical Production System (DT-CPPS)**, which is composed of two parts, physical and cyber shop floor. The physical shop floor is the sensors and the network connectivity needed to collect the data. And the cyber shop floor is the DT of the physical shop floor, as tools, it is recommended to use Plant Simulation by Siemens or Demo 3D. It presents this DT operating flow with the information interaction between the two parts. The data processing of the DT-CPPS is also explained in two phases, local and global data processing. Finally, the predictive machine sequencing model is shown to find the best sequence for a certain process learned from historical data and responsive production scheduling strategies. It is possible to create a production plan Gantt Chart through the real-time data, and then a scheduling strategy is made. This architecture is applied on a shop floor with several machines and industrial robots, with the purpose of monitoring, simulation, prediction and feedback control of operations.

In [18], a DT based on both product and process twins. For this is proposed a six-layer framework:

- **Integrated physical assets** - All the entities like sensors and **Radio Frequency Identification (RFID)** that collects data;
- **Integrated faithful product/process virtual models** - A virtual model must be faithful to its physical object. The more similar, the more accurate and precise the

digital twin becomes;

- **Intelligent layer** - This layer has artificial intelligence and ML algorithms to make decisions in the DT;
- **Data layer** - In this layer, all the data generated from the physical assets are stored and processed;
- **Enterprise layer** - This is responsible for services, business models, decision making, event and rule handling.

This framework was studied at the Festo cyber-physical smart factory, with the main goal of prognostic and diagnostic analyses, simulation, control, monitoring and optimization. The Siemens NX tool created the 3D CAD model of the factory, and the DT tool was the Plant simulation by Siemens.

This study [20], it was presented a DT-CPPS framework to overcome the performance and efficiency of personalized production. The system has five services: production planning, automated execution, real-time monitoring, abnormal situation and dynamic response services. The DT-CPPS is a four-layered architecture, device, network, service and application. The service layer contains a product, process, plan, plant, and resource (P4R) information database. There are five applications in the DT-CPPS: the DT, context-aware, advanced planning, advanced scheduling and device control. The case study of this work was a micro smart factory, and as a simulation engine tool, DMWorks was used by ezRobotics. With the results presented, we can assume that this solution has fast execution and responses compared to normal production.

In the article [15], it was proposed a DT based on configuration, motion, control and optimization (CMCO) for flow-type smart manufacturing systems.

- **Configuration design** - refers to physical static design;
- **Motion planning** - refers to motion path of actuator;
- **Control development** - refers to CPS;
- **Optimization** - refers to manufacturing execution engine;

The encapsulation of quad-play and the DT are the enablers of the CMCO model. As the case study, this architecture is tested in a hollow glass processing enterprise in China. The prototype was developed based on Unity 3D, a simulation engine. All four modules were implemented in the engine. Finally, the DT was tested with a study of the tempering furnaces' utilization rate, showing that the factory can save costs by managing the furnaces better. The final test was an optimization problem of the number of trays compared to two other algorithms, with the DT having better results.

The paper [30] presents a four-component DT architecture for production management and control, in shop floor. The layers are the physical shop floor, digital model of the shop

floor, big data storage and management platform, application platform services and lastly the DT. For this architecture to be possible, it is necessary four key technologies:

1. Real-time acquisition, organization, and management of the data - through constructing an IoT network in the shop floor.
2. Construction of the DT was built following three levels, element, construction of 3D geometric models of the machines in the shop floor. Behaviour, connections between elements, and tools recommended are FlexSim, Unity3D, and 3DVIA Composer. The rule consists of ensuring the operations of the DT match the physical shop floor mechanism.
3. DT and big data-driven prediction
4. DT based production management and control service

In the study [25], it was proposed a DT-based CPS applied in a production line of an automotive factory in the Republic of Korea. This work aims to have a system capable of predicting the operation and production, considering abnormal situations, and consequently, increasing system efficiency. This DT-based CPS is the connection between a DT and a web-based integrated platform. This framework has five components, the physical world, a legacy system, a web-based platform, the P4R<sup>5</sup> information model and the DT. The data comes from the physical world through sensors, and it is transmitted to the web-based platform, where it is transformed into P4R model and transmitted to the DT. Lastly, the new data and predictions in the DT return to the web-based platform. This framework comprises a three-layered architecture, communication, information and application layer. As a simulation engine for the DT was used the Plant simulation by Siemens. For the validation of the DT-based CPS, an experiment was carried out to calculate the prediction accuracy ratio between the predicted production volume (calculated by the DT) and actual production volume (produced on the production line). All the different processes on the production line had over 95% average prediction accuracy ratio.

### 3.4 Synthesis of the results

With our RR, it was possible to gather all the necessary information that we purpose to collect in the section 3.1.1.1, our research questions. Therefore, information was gathered in the selected papers about the main goals of the proposed DTs, architectures and technologies used in different contexts.

In the table 3.4, there is a summary of the eight selected papers that were analysed and studied, with the software to build the DT used, main goals, architecture type and context.

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<sup>5</sup>Product, Process, Plan, Plant and Resource

Paper	Software	Main goal	Architecture Type	Context
[9]	<i>Visual components</i>	Data analytics, visualization and control of a logistics-based	5 Layers	Automotive industry
[12]	<i>Unreal engine</i>	Monitoring and simulation	5 Dimensions	Smart factory
[4]	<i>Plant simulation, Demo 3D</i>	Monitoring, simulation, prediction and feedback control of manufacturing operations	2 Layers	Industrial robots
[18]	<i>Plant simulation</i>	Prognostic and diagnostic analyses, simulation, control, monitoring and optimisation	6 layers	Smart factory
[20]	<i>DMWorks</i>	Performance and efficiency	4 Layers based on services	Smart factory
[15]	<i>Unity 3D</i>	Cost saving and optimisation	Based on CMCO	Smart factory
[30]	<i>FlexSim, Unity3D, 3DVIA Composer</i>	Production management and control	4 Layers	Shop floor
[25]	<i>Plant simulation</i>	Predicting the operation and production, abnormal situations, and increase system efficiency	3 Layers based on P4R	Automotive industry

Table 3.2: Results summary table

It is possible to observe that there are several options in terms of software tools to build the DT, and a comparison of the different features between all the tools is necessary to find the option for our case study in the section 3.5. There are also several ways to design the architecture of a DT, different numbers of layers based on services, P4R and CMCO. Our system will not be built from the beginning. Therefore, the way the other systems were built will significantly impact our work, considering the information obtained.

### 3.5 Available Digital Twin Tools

In the section above, several software tools were used to create DT. Each software has its characteristics, other application areas, functionalities, scripting language, popularity in the community, may or may not have integrated [Application Programming Interface \(API\)](#) as documentation, and if it is the necessary commercial license or open access.

The summary of digital twin software:

1. *Visual Components Simulation Environment*<sup>6</sup> - A software platform for simulation and emulation, the main application area is the manufacturing and can design production systems.
2. *Unreal Engine*<sup>7</sup> - It is an open access 3D computer graphics game developed by Epic Games, with the capacity to create powerful DT, used mainly for architecture, real estate and build environment.
3. *Tecnomatix Plant Simulation*<sup>8</sup> - Software application developed by Siemens, the main area is industrial engineering, manufacturing and logistics. This application has the power to create models and simulate, helping to control DT.
4. *Demo 3D*<sup>9</sup> - It is a simulation software for manufacturing, with the power to create models, material handling systems and optimization.
5. *DMWorks*<sup>10</sup> - Simulation solution developed by EzRobotics used mainly in manufacturing, can model, simulate and process validation. This solution also has several features dedicated to managing and controlling robots in a production line.
6. *Unity 3D*<sup>11</sup> - Open access game engine platform, the primary purpose is not digital twins but has several features that are compatible, like 3D modelling and simulation powers.
7. *FlexSim*<sup>12</sup> - A software platform for Manufacturing, Material Handling, Healthcare, Warehousing and Supply chain. This solution has features like simulation modelling and analysis.
8. *3Dvia Composer*<sup>13</sup> - It is a software for 3D visualization and simulation, the main purpose of this application is 3D home design.

The table 3.3 is a summary with more information about these DT software, comparing main context, functionalities, scripting language, popularity, if it has an integrated API and documentation, and lastly if it is open access or if it requires a commercial license.

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<sup>6</sup>Visual Components, <https://www.visualcomponents.com/>, Last accessed on 12/06/2023

<sup>7</sup>Unreal Engine, <https://www.unrealengine.com/en-US/digital-twins>, Last accessed on 12/06/2023

<sup>8</sup>Plant Simulation, <https://plm.sw.siemens.com/en-US/tecomatix/>, Last accessed in 12/06/2023

<sup>9</sup>Demo 3D, <https://www.demo3d.com/>, Last accessed on 12/06/2023

<sup>10</sup>DMWorks, <https://www.ezrobotics.com/solution/dmwork.php>, Last accessed in 12/06/2023

<sup>11</sup>Unity 3D, <https://unity.com/solutions/digital-twins>, Last accessed in 12/06/2023

<sup>12</sup>FlexSim, <https://www.flexsim.com/>, Last accessed on 12/06/2023

<sup>13</sup>3DVIA Composer, <https://www.3ds.com/products/3dvia>, Last accessed on 12/06/2023

Digital twin Tools \Criteria	Main context	Functionalities	Scripting language	Popularity (1 - Little, 2 - Average, 3 - Great)	API	Open Access	Documentation
Visual Components	Manufacturing	3D Layout Configuration Statistical Analysis Process modeling Basic Virtual Commissioning Robot Programming and Control	Visual Components Script (VSC), based on .NET Framework and C#	1	Yes	No	Yes
Plant simulation	Industrial engineering, manufacturing and logistics	3D simulation environment, Object-oriented Modeling Dynamic Simulation Statistical Analysis Optimization and What-If Analysis Material Flow Analysis Resource Management	SimTalk	1	Yes	No	Yes
Demo 3D	Manufacturing	3D Visualization Simulation Control System analysis and optimization Realistic 3D Visualization	JScript and C#	1	Yes	No	Yes
Unreal Engine	Architectures, real state and build environment	Blueprint Visual Scripting Physics Simulation Data Integration and Visualization Multi Platform Deployment Level of Detail (LOD) Optimization	C++ and Blueprint	3	Yes	Yes	Yes
DMWorks	Manufacturing	3D Visualization Simulation Manufacturing Process Validation Robot Offline Programming Robot and Workcell Calibration		1	No	No	No
Unity 3D	Smart cities, facilities and products	3D visualization Physics Simulation Data Integration and Visualization Multi Platform Deployment Scripting and Programming Level of Detail (LOD) Optimization	C#	2	Yes	Yes	Yes
FlexSim	Manufacturing, Material handling, Healthcare, Warehousing and Supply chain	3D visualization Data integration Process modeling What if simulation	FlexScript, based on C++	1	Yes, C++	No	Yes
3DVIA Composer	3D Design	3D visualization Simulation	3DVIA Composer Scripting Language (3DSL)	1	Yes, C#	No	No

Table 3.3: Digital twin tools comparison

Only two open-access tools, *Unity 3D* and *Unreal Engine* were the best candidates. Both have robust physics engines that can handle simulations and interactions within the *DT*, and both offer *APIs*, tools for integration and 3D modelling. The main reasons why we chose *Unity 3D* were:

- *Unreal Engine* has a steeper learning curve than *Unity 3D* due to its advanced features and customization options for cutting-edge graphics capabilities and visual effects required in gaming, but not in a *DT*;
- *Unity 3D* has broader platform compatibility, including support for desktop, web, mobile, and VR/AR devices. *Unreal Engine* primarily focuses on desktop and high-end platforms, although it does support other platforms to some extent;
- *Unity 3D* has a larger and more established user community than *Unreal Engine*, which means there are extensive resources, tutorials, and reusable assets available;
- *Unity 3D* uses *C#* as programming language, simpler syntax compared to *C++*, used in *Unreal Engine*, and easier to learn and use.

## 3.6 Previous Work

This work is based on three other projects [22, 11, 6]. In the first one [22], the main goal was to create a system to monitor and control, capable of identifying stages of classic car restoration. The second [11] continued the first work, adding sensors and improving the system. In the third [6] work was developed a system capable of monitoring the progression of classic cars restoration and preservation processes with a *Business Process Model and Notation (BPMN)* approach.

Figure 3.2 illustrates the architecture of the system developed in [22, 11]. It implemented a *IoT Subsystem* responsible for several *IoT devices* (*Bluetooth Low Energy (BLE)* beacons, smart plugs with *WIFI* for metering the power consumption and a sensor box) in the workshop. The sensor box includes humidity, temperature and accelerometer (to detect vibrations) sensors connected to a *Raspberry Pi*. This sensor box is attached to a car through a magnet. As shown in figure 3.1. The *Cloud Service Provider* runs in a cloud-based virtual machine managed by *OpenStack*<sup>14</sup>. This subsystem digests *IoT sensors' data* and processes it, fingerprinting algorithms for identifying car positions and identifying the tools being used.

Lastly, there is a web application to monitor and control the workshop. It is possible to manage the sensors, add new ones, change configurations, check errors in the sensors, and track the processes being carried out in the cars. All these refer to the two first projects [22, 11] mentioned.

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<sup>14</sup>Open Stack, <https://www.openstack.org/>



Figure 3.1: Sensor box

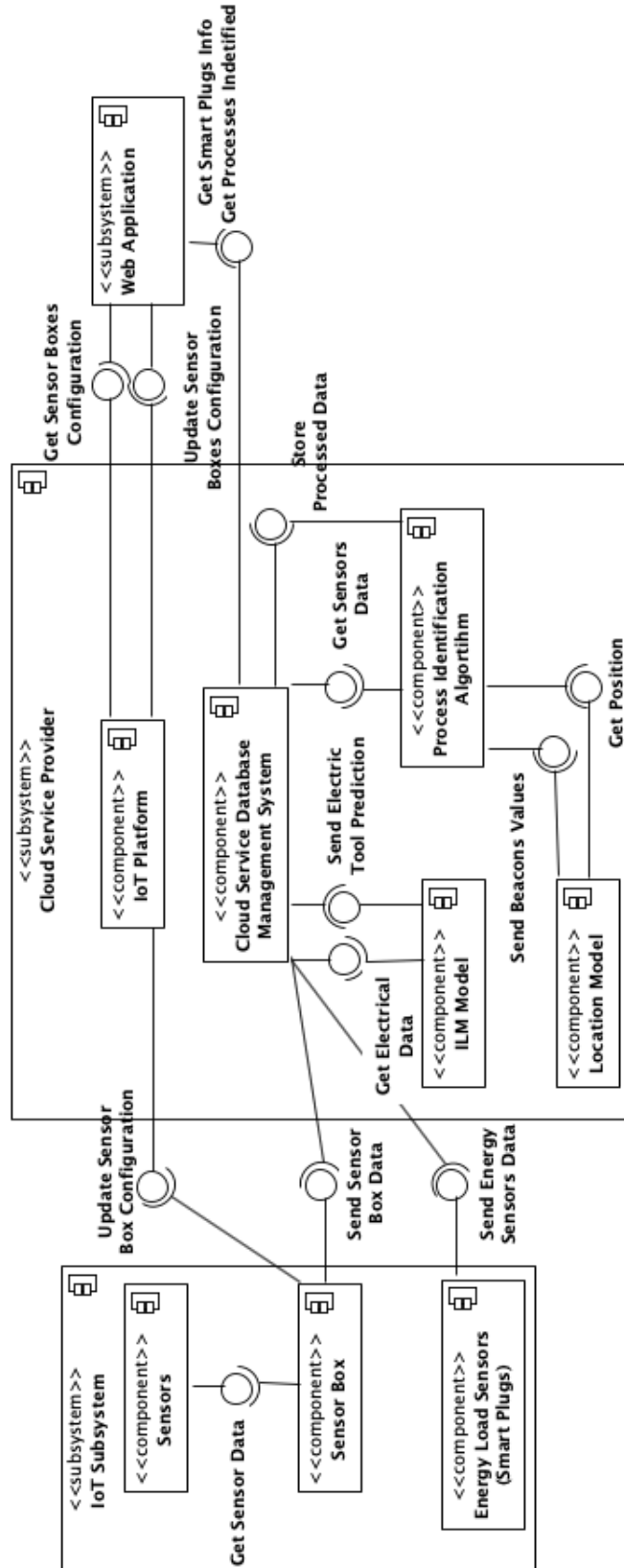


Figure 3.2: Component Diagram of the architecture developed by [22, 11]

The Charter of Turin Monitor is a process-aware subsystem fueled by a BPMN workflow engine. It is in charge of process monitoring and uses a process-aware Graphical User Interface (GUI) with a BPMN model matching FIVA’s Charter of Turin practices [10]. This process-aware GUI allows for associating media evidence with each restoration process activity for each classic car. A multimedia report (text, images, and videos) is generated at the end of each restoration process. Figure 3.3 shows the BPMN of a vehicle in the Charter of Turin Monitor application, keeping track of the processes and tasks performed.

## Ferrari F50 1975

Download Evidence PDF

Edit Project Delete Project

Licence Plate: xx1

Started on: 2024-09-11

Pinterest URL: <https://www.pinterest.com/fjbrancoaws/ferrari-f50-xx1-240911>

Task awaiting approval: Restoration Base/Restoration Repair/Restoration Repair Paint/Restoration Repair Paint Complete

Vehicle Card

Zoom out

Submit tasks

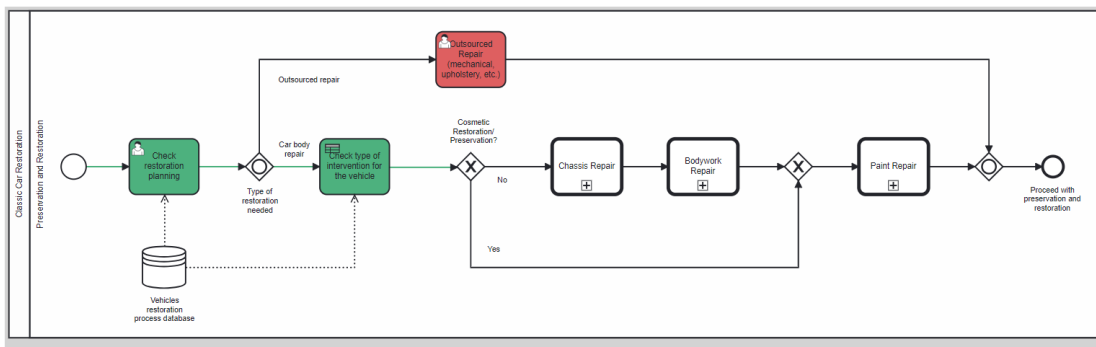


Figure 3.3: Charter of Turin Monitor application by [6]

Lastly, the Cameras Hub component allows classic car owners to remotely control cameras mounted on a showroom and record pieces of evidence at specific moments of the restoration process [6]. As shown in figure 3.4.

Figure 3.5 presents the architecture of the Charter of Turin monitor.



Figure 3.4: Camera Hub application by [6]

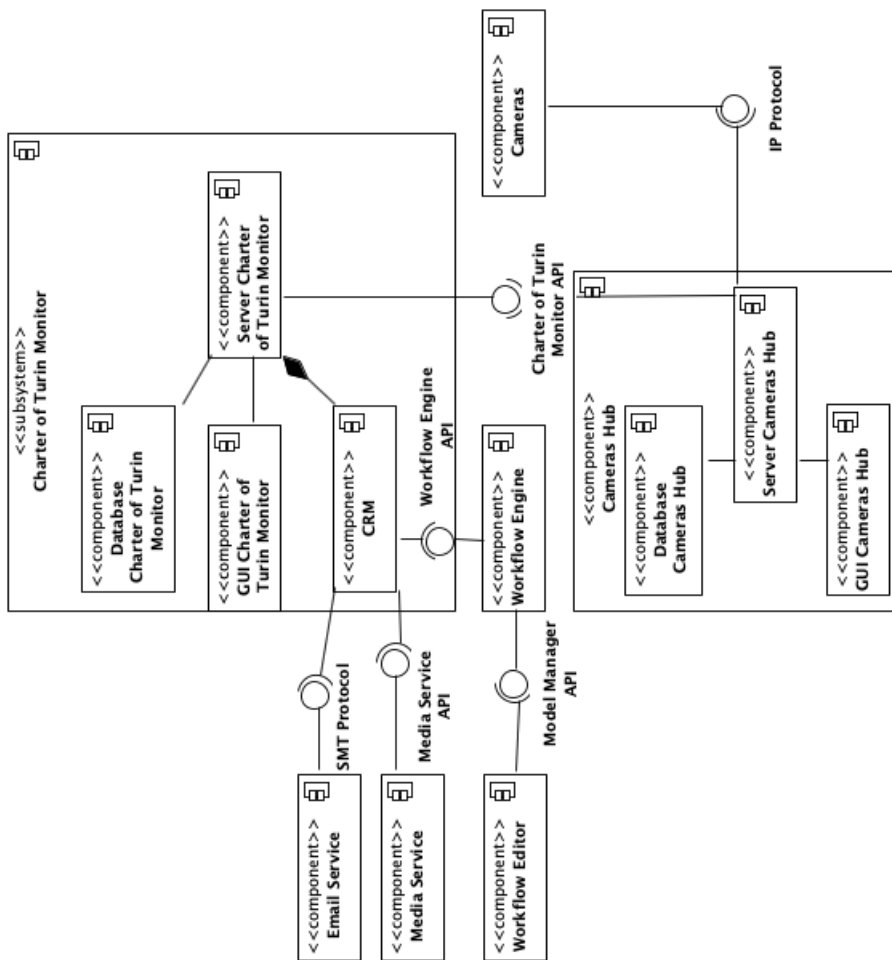


Figure 3.5: Component Diagram of the architecture developed by [6]

### 3.7 Summary

In this chapter, we performed a [RR](#) to help us identify and understand the main goals of a [DT](#) in the automobile industry and smart factories, as well as architectures and technologies used in the different studies.

Relevant research questions and the corresponding search string were presented in our context. Then, how the study selection was processed and the quality assessment of the selected papers. With the discussion and analysis of the studies, it was possible to make a list of the different software used to build the [DTs](#) in the projects. Therefore, a table was made to compare the features of these technologies to help us understand the best fit to our context. In the end, previous theses [[22](#), [11](#), [6](#)] were described and explained because they will be the base of our work. Now, we have all the materials to build the architecture of our solution.

In this chapter, we collected all the relevant information to build the architecture of our solution and its evaluation strategy.

# CONCEPTUALIZATION AND IMPLEMENTATION

*This chapter presents the conceptualization and implementation of our work. First, we identify the stakeholders and outline the functional and non-functional requirements. Next, we present the architecture, components, and technologies used in the system. Finally, the [DT](#) solution is presented.*

## 4.1 Software Requirements Engineering

[Software Requirements Engineering \(SRE\)](#) is a discipline that focuses on identifying, documenting, and managing the requirements of a software system.

The first step was to identify the stakeholders, those who can affect or are affected by our system. This step is crucial to ensure that the system would meet the needs and expectations of all stakeholders involved. The next step is the requirements, functional and non-functional, for the system's capabilities and performance.

### 4.1.1 Stakeholders

The stakeholders in the [DT](#) system are consistent with those in the Charter of Turin monitor application, which makes sense for our [DT](#), as it will rely on it for information. These stakeholders are categorized into three distinct types, each with specific access levels and responsibilities:

- Plant shop manager - These stakeholders are responsible for updating the system based on the work performed on the workshop floor associated with the classic cars. In the [DT](#), they ensure accurate tracking of tasks and corresponding locations of the vehicles.
- Administrative Manager - In the Charter of Turin Monitor application, these stakeholders hold administrative power over the system, allowing them to create and

delete user accounts and manage projects by creating, updating, and deleting them. In the DT, they are responsible for the creation, updating, and deletion of virtual map locations. Besides these, they have the same access privileges as the Plant Shop Manager.

- Classic car owner - These stakeholders can access the progress of the restoration or conservation processes of their classic cars, along with the specific locations within the workshop where the work is being carried out.

### 4.1.2 Functional Requirements

The functional requirements of the DT system are represented in Figure 4.1. The actors are those introduced in Section 4.1.1.

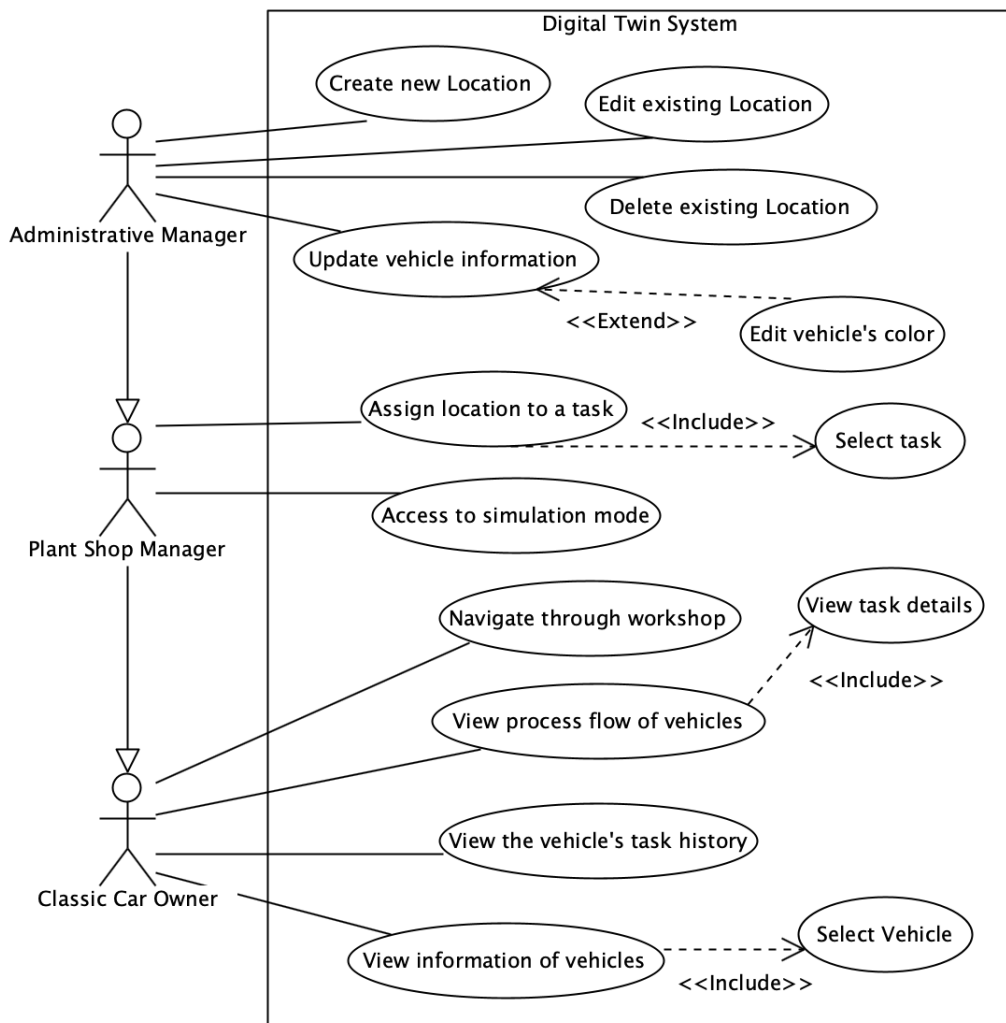


Figure 4.1: Use case diagram of the Digital Twin system

### 4.1.2.1 System Requirements

Several requirements describe what the system should be able to do by itself. The System should be able to:

- User Authentication - Allow the authentication of users via credentials;
- Component Communication - Allow the system communicate with other components;
- Data Acquisition Integration - Integration with the Charter of Turin Monitor application for information of the projects in the workshop;
- Process Management Integration - Integration with the Camunda, to keep the processes and tasks performed in the workshop updated;
- Interactive Visualization - Interactive 3D model visualization of the classic car workshop and of car models;
- Classic Car Owner aware - Owners can be aware of the latest changes to their vehicle's processes, tasks and location in the workshop.

### 4.1.2.2 Administrative requirements

- Create new locations within the workshop;
- Update locations;
- Delete locations;
- Update car information;
- Edit vehicle's color;
- Have access to all features accessible by Plant Shop Managers.

### 4.1.2.3 Plant Shop Manager Requirements

- Assign a location to a task;
- Select vehicle;
- Select a task;
- View information about the vehicles;
- View process flow of vehicles;
- View task details;

- Navigate through the workshop;
- Access simulation mode.
- View location of vehicles;
- View the vehicle's task history.

#### 4.1.2.4 Classic Car Owner Requirements

- View location of vehicles;
- View process flow of vehicles;
- View information about the vehicles;
- View the vehicle's task history;
- Navigate through the workshop.

#### 4.1.2.5 Non-Functional Requirements

- Have a response time that provides smooth performance under typical workloads;
- Be easy to use;
- Have high availability;
- Be fault-tolerant;
- Be robust and safe;
- Have a modular architecture for easy maintenance, updates and integration of new features;
- Compatibility with other systems.

## 4.2 Architecture

As mentioned, the basis of this work is the Charter of Turin component, which is responsible for the integration of the FIVA's guidelines used as reference for managing the restoration processes (business rules), and it will have a strong connection to the *DT* system. The project will depend on several components that have already been developed, as well as updating and adding some features to complement the needs of the *DT*.

So, to build our system's architecture, we will start with the Charter of Turin architecture and make updates.

### 4.2.1 Components

The figure [4.2](#) shows the updated system, with the additional components highlighted in yellow, which were necessary to complete the required system.

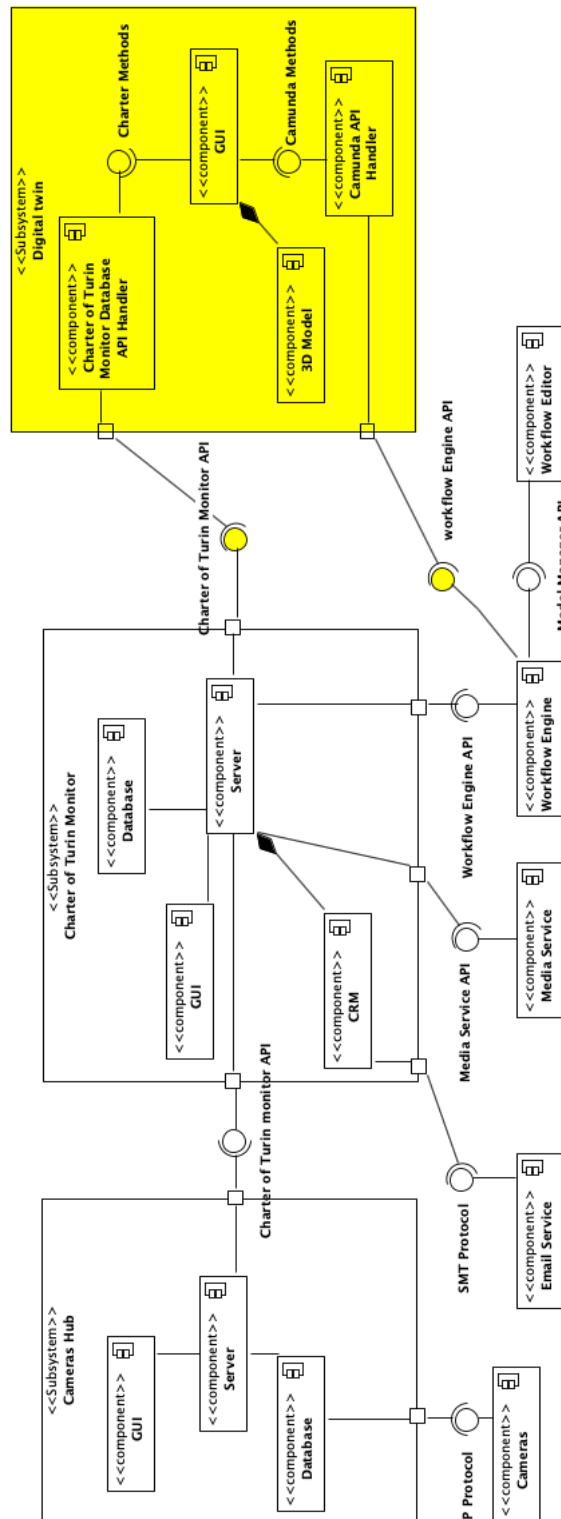


Figure 4.2: Component Diagram of the system

#### 4.2.1.1 Digital twin Component

The **DT** component is a newly integrated subsystem of the system, featuring a **GUI**. This **GUI** is composed of a 3D model of the workshop and is designed for workshop employees to interact with the facility, including viewing and managing the processes and locations of classic cars within the workshop. Additionally, the **GUI** enables classic car owners to track the progress and location of their vehicles.

The subsystem includes two **API** handlers: one interfaces with the Charter of Turin Monitor component for accessing project-related data from its database, and the other interacts with the Workflow Engine **API** to retrieve information about processes and tasks within the **BPMN** diagrams in Camunda.

#### 4.2.1.2 Charter of Turin Monitor Component

This component enables workshop employees to update the processes and tasks performed in the cars and allows classic car owners to monitor the progress of their vehicles. To support these functionalities, the database and server modules were enhanced to incorporate the necessary features. For our project requirements, new **APIs** were added and existing ones updated, which led to the creation of new collections and entities within the database.

#### 4.2.1.3 Workflow Engine and Workflow Editor Components

These two components are responsible for the **BPMN** diagrams. The Workflow Editor component is the editor of the **BPMN** diagrams. The Workflow Engine manages the workflows of these diagrams. It was also added a connection of the Workflow Engine to the **DT's GUI** to access the diagram's information.

### 4.2.2 Technologies

Here, the main technologies used in the development of our application, based on the architecture and requirements presented, will be explained.

#### 4.2.2.1 Unity

Unity<sup>1</sup> is a cross-platform game engine primarily used for developing 2D and 3D video games and simulations. Its main features include a real-time 3D rendering engine, a robust physics engine, and an extensive API for scripting in C#.

Unity was chosen because it supports multiple platforms, offers a powerful game engine, has strong community support, and can import and manage 3D models. Additionally, due to its scripting capabilities, it is a flexible and modular application. The scripting also supports asynchronous operations, networking, and integration with third-party services.

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<sup>1</sup>Unity, <https://unity.com/>, Last Access: 26/09/2024

#### 4.2.2.2 C#

C# is an open-source, object-oriented programming language used for developing a wide range of applications. As previously mentioned, Unity scripting is done in C#. Unity's scripting API is a collection of classes, methods, properties, and events that allow developers to interact with the Unity engine through code. This API helps in creating complex interactions and behaviours within Unity's UI.

#### 4.2.2.3 Revit

Revit <sup>2</sup> by Autodesk <sup>3</sup> is a Building Information Modelling (BIM) software, specifically BIM and building design, capable of creating and managing 3D models of digital representations of buildings, including architectural and structural.

It was chosen because it provides 3D modelling, integrates and interoperates with other BIM tools, and is compatible with several file formats. It also integrates 2D and 3D workflows. When a 3D model is created, the 2D drawings (plans, sections, elevations) are generated as well.

#### 4.2.2.4 AutoCAD

AutoCAD <sup>4</sup> by Autodesk, is a computer-aided design software, mainly used by architects and engineers for 2D and 3D model creation. It supports various file formats and integrates with other third-party software and tools. It's a simple, traditional and versatile tool.

#### 4.2.2.5 3ds Max

3ds Max <sup>5</sup> is a computer graphics program for 3d modeling, animations, images and games, developed by Autodesk. This tool is commonly used for game development of detailed 3D assets because of the advanced materials and textures available, as well as the high-end rendering power.

### 4.3 Implementation

In this section, the implementation of the DT system for the classic car workshop is detailed. The implementation phase translates the conceptual design and requirements outlined in the SRE into a functional system. This includes the integration of various components, the development of key features, and the modifications made to existing systems to support the new functionalities, with a focus on the technical aspects.

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<sup>2</sup>Revit, <https://www.autodesk.com/products/revit/overview?term=1-YEAR&tab=subscription>, Last Access: 26/09/2024

<sup>3</sup>Autodesk, <https://www.autodesk.com/>, Last Access: 26/09/2024

<sup>4</sup>Autocad, <https://www.autodesk.com/products/autocad/overview?term=1-YEAR&tab=subscription>, Last Access: 26/09/2024

<sup>5</sup>3ds Max, <https://www.autodesk.com/products/3ds-max/overview?term=1-YEAR&tab=subscription>, Last Access: 26/09/2024

### 4.3.1 Charter of Turin Monitor

The Charter of Turin Monitor serves as the foundational element of this system, as previously mentioned. To successfully develop the *DT* system in accordance with the specifications outlined in the *SRE*, several modifications and enhancements were necessary for the Charter of Turin Monitor. So, first, we needed to study the Charter of Turin Monitor system, not only in terms of architecture, as discussed in chapter 3.6, but also in terms of technology to understand how the system is built. This understanding was crucial for effectively adding new features and making changes in the best possible way.

More specifically, changes were made to the server to add new *APIs* and update existing ones, along with modifications to the database to incorporate new collections and entities required for the *DT* system.

#### 4.3.1.1 API Methods

One of the objectives outlined in the *SRE* was for our *DT* system to associate the processes and tasks performed on the classic cars with their physical locations in the workshop, a feature not originally present in the Charter of Turin Monitor.

For this reason, as shown in the 4.3 figure from OpenAPI <sup>6</sup>, *API* methods were created to manage the locations in the workshop where a classic car can be or where a process can be performed, along with the list of activities associated with each location.

VirtualMapLocations	
GET	/api/VirtualMapLocations
POST	/api/VirtualMapLocations
GET	/api/VirtualMapLocations/{id}
DELETE	/api/VirtualMapLocations/{id}
PUT	/api/VirtualMapLocations/{id}
GET	/api/VirtualMapLocations/activity/{activityId}

Figure 4.3: API methods for the virtual map locations

In the figure 4.3, there are six essential *API* methods that provide full CRUD (Create, Read, Update, Delete) functionality and enhance the system's ability to associate locations with specific activities.

1. **Get all the Virtual Map Locations:** This method returns the information about all the virtual map locations in the workshop.
2. **Create a Virtual Map Location:** This method allows the system to add a new location to the virtual map of the workshop.

<sup>6</sup>OpenAPI, <https://www.openapis.org/>, Last Access: 19/12/2024

3. **Get one Virtual Map Location:** This method retrieves information about a specific location, identified by its unique ID.
4. **Delete one Virtual Map Location:** This method deletes a specific location, identified by its unique ID.
5. **Update Virtual Map Location:** The update method enables the modification of existing locations on the virtual map.
6. **Get Virtual Map Locations, by activity:** The final method allows the system to retrieve all locations associated with a particular activity, identified by its *activityID*. This method is crucial for tracking where specific processes and tasks are performed within the workshop.

Together, these methods provide comprehensive management of virtual map locations, ensuring that the **DT** system accurately reflects the physical workshop environment and its associated processes. In addition to developing these **API** methods, it was necessary to add a new collection *VirtualMapLocations* to the MongoDB database of the Charter of Turin Monitor application. This new collection facilitates the storage and management of the virtual map locations data.

The *VirtualMapLocation* entity was designed to represent each location within the workshop and includes the following fields:

- **ID** - A unique identifier for each location.
- **Name** - The name of the location within the workshop.
- **CoordinateX, CoordinateY and CoordinateZ** - The spatial coordinates that define the location's position on the virtual map of the classic car workshop.
- **Vertices** - A list of coordinates representing the different vertices used to define the shape of the car slot area.
- **Color** - The color of the car slot area when instantiated.
- **Capacity** - The maximum number of cars that can fit in the car slot area.
- **ActivityIDs** - A list of activity identifiers associated with this location, indicating which tasks or processes can be performed at this location.

This structure ensures that all relevant information about each workshop location is stored and managed efficiently, supporting the dynamic needs of the **DT** system.

Another objective mentioned in the **SRE** was to maintain a history of the processes and tasks associated with the locations in the workshop for each classic car. This functionality allows us to effectively map the workflow and monitor the progress of each vehicle throughout its service journey.

Then, as shown in the figure 4.4 from Swagger, API methods were developed to manage the complete history of processes and locations for each classic car in the workshop, with an array of the activities associated with a location in the workshop where was performed.

ActivityAndLocationHistory	
GET	/api/ActivityAndLocationHistory
POST	/api/ActivityAndLocationHistory
GET	/api/ActivityAndLocationHistory/Car/{caseInstanceId}
GET	/api/ActivityAndLocationHistory/{id}
PUT	/api/ActivityAndLocationHistory/{caseInstanceId}/activities/{activityAndLocationId}

Figure 4.4: API methods for the activities and location history of a classic car

1. **Get the history of all classic cars:** This method retrieves the complete history of all classic cars currently in the workshop.
2. **Create the history of a classic car:** This method initializes and creates the history for a new classic car added to the workshop.
3. **Get the history of a classic car:** This method retrieves the complete history of a specific classic car in the workshop using its unique identifier, *caseInstanceId*.
4. **Get one history entry:** This method retrieves the complete history of a classic car by its unique *id*.
5. **Update the history of a classic car:** This method updates a specific activity and its associated location in the workshop for a classic car identified by *caseInstanceId*, using its unique identifier *activityAndLocationId*.

This ensures that the DT effectively tracks and reflects the complete service journey of each classic car, facilitating better monitoring and analysis of their associated activities and location. In the MongoDB database, a new collection *ActivityAndLocationHistory* was added to manage the history of processes and locations associated with each classic car, supporting the functionalities provided by the API methods.

The *ActivityAndLocationHistory* entity was designed to represent the history of activities and locations associated with each classic car within the workshop. It includes the following fields:

- **ID** - A unique identifier for each history record.
- **CaseInstanceId** - The unique identifier of the classic car associated with this history.
- **History** - An array of *ActivityAndLocation* entities, representing the history of processes and tasks along with their corresponding locations. Each *ActivityAndLocation*

entity contains an *Id* field, an *ActivityId* to identify the specific activity, and a *LocationId* to identify the associated *VirtualMapLocation*.

This structure guarantees the efficient storage and management of each classic car's complete history, ensuring that the DT system can adapt to evolving operational needs.

### 4.3.2 Digital Twin

In this section, we will delve into the implementation of the DT system, emphasizing its integration with the existing framework of the Charter of Turin Monitor. The Digital Twin acts as a dynamic virtual representation of the classic car workshop, enabling real-time monitoring and management of processes related to classic cars. By leveraging the API methods established in the previous section 4.3.1.1, we enhance the system's functionality.

First, a highly realistic 3D model was developed to visually represent the workshop environment, which is integrated into the DT's GUI.

Furthermore, a virtual map has been created to outline all tasks and processes performed within the workshop, along with their specific locations.

Additionally, the GUI is designed to facilitate intuitive navigation and interaction with the DT, enhancing user experience and accessibility.

The figure 4.5 presents the system structure in our unity application. Assets is the main directory of our work, which contains our C# scripts, the prefabs that includes all the 3D objects and screen views used in our project, as well as packages including libraries and imported classes.

The scripts are divided into four categories:

- API - Scripts responsible for the connection with the Charter of Turin Monitor application and the Camunda.
- Models - Data classes, they are the core entities of our system.
- Objects - Scripts that manage the interactions, behaviors and properties of game objects with the system, like dragging a car or moving the camera.
- UI - Scripts responsible for the user interface interactions, like listing all the locations and cars.

#### 4.3.2.1 3D Model

The 3D model plays a crucial role in the DT by enhancing realism and the overall visual experience, while also serving as a practical tool for monitoring and managing processes within the workshop. To achieve a highly realistic and accurate representation of the workshop environment, we developed a 3D model using Revit, AutoCAD, and 3ds Max, with final integration into Unity.

The steps taken to build the 3D model were:

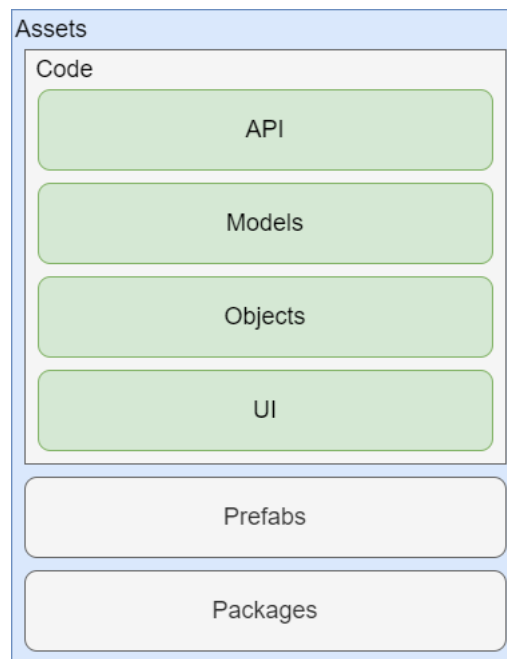


Figure 4.5: Unity System Structure

1. Initial Assessment and 2D Plan Update;
2. 3D Model Creation in Revit;
3. Model Optimization in 3ds Max;
4. Integration into Unity.

The development process began with existing 2D plans of the workshop, including various floor plans, elevations, and building sections, as shown in Figure 4.6. However, these initial plans did not fully align with the actual layout of the workshop. Consequently, it was necessary to conduct field measurements directly in the workshop to update and refine the 2D plans using AutoCAD 2024, as illustrated in Figure 4.7. This ensured that the 3D model would accurately and precisely reflect the real workshop layout.

For the development of the 3D model, we used Revit 2024. We began by integrating the revised 2D models and adjusting dimensions and details to accurately reflect the actual layout of the workshop in three dimensions. This process involved meticulously ensuring that all architectural elements, including walls, windows, and doors, were represented with precision.

Next, the model was imported into 3ds Max for optimization. It used 3ds Max 2024 to enhance the model's textures, lighting, and other visual elements, ensuring that it was both aesthetically realistic and optimized for real-time rendering. This step was crucial to ensure that the model not only appeared realistic but also performed efficiently within the Unity environment. The final result was the 3D model of the classic car workshop in figure 4.8.



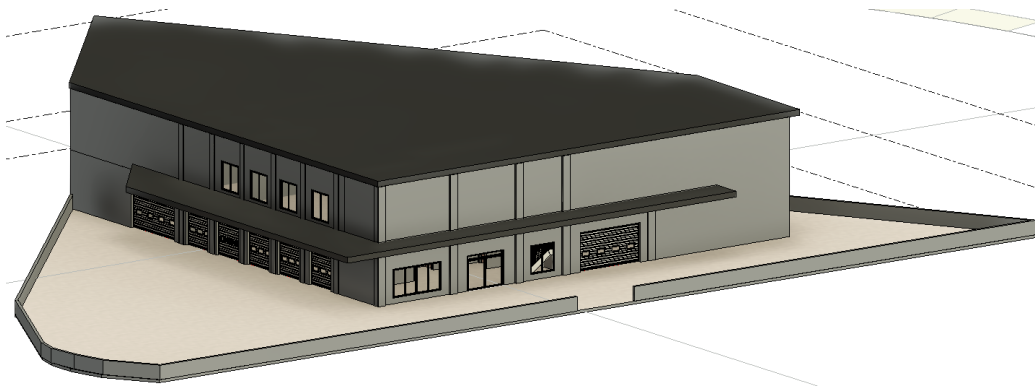


Figure 4.8: 3D Model of the workshop

The final step involved converting the optimized 3D model from 3ds Max into a format compatible with Unity. In Unity, the 3D model was fully integrated into the **DT** system, allowing it to be interactive and navigable within the GUI. This integration enabled users to explore the virtual workshop environment in real time, providing a comprehensive and immersive experience.

#### 4.3.2.2 Virtual Map of Processes and Activity Locations

In this section, we explore the creation of the Virtual Map of Processes and Activity Locations, a core feature of the **DT**. This map allows users to visualize the workflow of classic car servicing and maintenance. Each process and task is linked to its corresponding location in the workshop, offering a clear representation of where each task occurs in the workshop. By integrating this virtual map into the **DT**, users gain valuable insights into the operational dynamics of the workshop, facilitating more efficient management and informed decision-making.

First, we compiled a list of all the processes and tasks managed by Camunda, represented in the BPMN diagrams, that are performed on the classic cars. This initial step was crucial for understanding the scope of activities that occur within the workshop and for establishing a clear framework for mapping these processes to their respective physical locations.

We conducted on-site visits to the workshop and collaborated closely with the employees. Together, we delineated specific areas within the workshop to effectively organize and categorize the various processes and tasks. Each area was assigned a unique code along with a corresponding description:

- CB - Chemical Blasting
- CS - Coat & Styling
- DA - Disassembly & Assembly
- EX - Experimental Hub

- FO - Front Office
- FS - Filling & Sanding
- IO - check In & Out
- OC - Outsource Company
- PB - Paint Booth
- PF - Preservation and Finishing
- PL - Paint Lab
- PS - Parts Storage
- RM - Parts Repair & Manufacturing
- SB - Sand Blasting

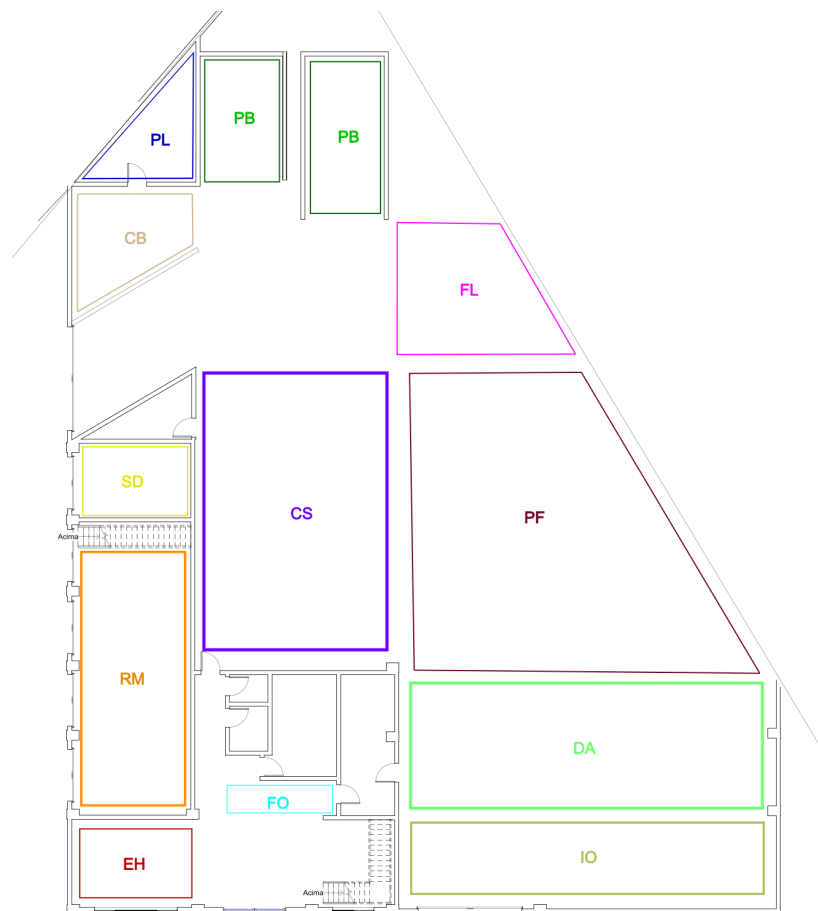


Figure 4.9: Processes and location mapping - Ground floor

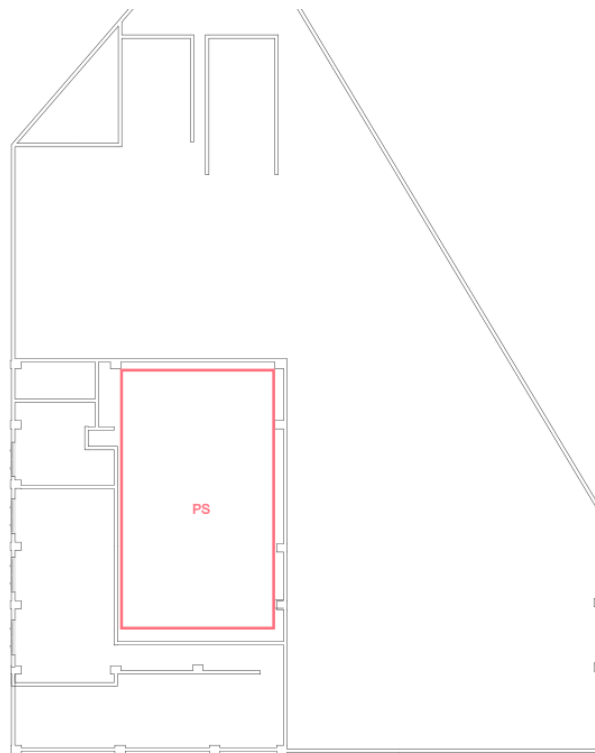


Figure 4.10: Processes and location mapping - First floor

The figure 4.9 illustrates the delineated areas within the workshop on the ground floor, while figure 4.10 depicts the layout of the first floor, which consists of a single area designated for vehicle parts storage.

After listing all the tasks and defining the areas, the final step was to map each task to one or more areas within the workshop. We used Excel to organize and manage this mapping process efficiently. The employees provided valuable insights, helping us understand that some tasks could be associated with multiple areas. They also clarified that tasks fall into two categories: those requiring the presence of the classic car or a part of it and those that do not. For instance, "Apply Paint" requires the classic car, whereas "Order replacement parts" does not. This information is crucial as it significantly impacts the development of the GUI in the DT system, guiding how tasks and processes are represented and interacted with within the digital environment.

#### 4.3.2.3 User Interface

The GUI of the DT was developed using Unity 2022, with C# scripts created in the Visual Studio 2022 IDE<sup>7</sup>. The SonarLint<sup>8</sup> extension was utilized to ensure clean code practices.

In Figure 4.11, the login page is displayed, allowing users to log in as the stakeholders described in section 4.1.1.

<sup>7</sup>Visual Studio 2022 IDE, <https://www.visualstudio.com/vs/>, Last Access: 02/09/2024

<sup>8</sup>SonarLint, <https://www.sonarsource.com/products/sonarlint/>, Last Access: 02/09/2024

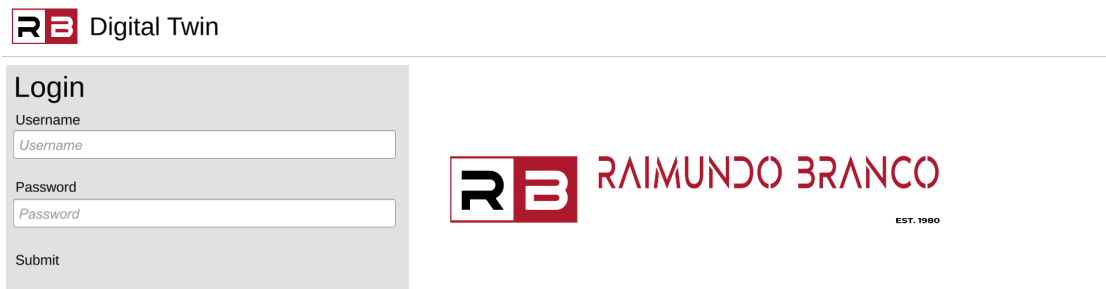


Figure 4.11: Login Page

After logging in, users are redirected to the main view of the DT app, as shown in figure 4.12. The main view features a 3D model of the workshop and a navigation bar with buttons for switching between screens and performing various actions. From here, users can explore the workshop.



Figure 4.12: Main View

In the "Camera Controls" button, located in the navigation bar, there is a list of action buttons designed to help users navigate through the 3D model, as shown in figure 4.13.

The available commands are:

- W - Move camera forward
- S - Move camera backwards
- L - Move camera left
- R - Move camera right
- Q - Rotate camera left
- E - Rotate camera right



Figure 4.13: Camera Controls

- T - Remove the roof from the workshop
- Space - Switch between top view and angled view
- 1 - Remove the first floor from the workshop

In terms of virtual map locations, if the "Locations" checkbox in the navigation bar is checked, a list of virtual map locations within the workshop appears. Each entry includes the location name, the assigned color, a checkbox to hide or show the car slot area, a pencil icon to edit information, and a trash icon to delete the location. Additionally, there is a "Virtual Map Grid" toggle. When it is turned on, the car slot areas are displayed within the workshop, as shown in figure 4.14. In the virtual map locations panel, there is also a button labelled "New Location" to create a new car slot area.

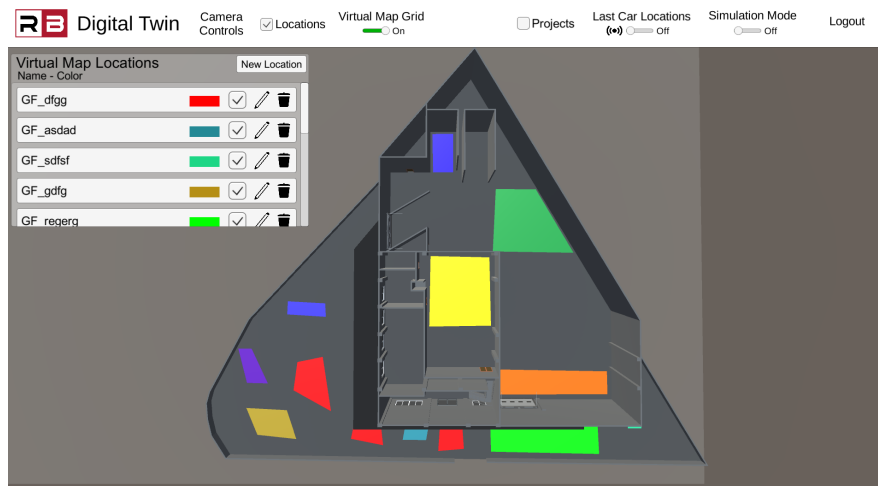


Figure 4.14: Camera Controls

When creating a new location, the first thing that appears is a panel prompting the user to enter the location's name, as shown in figure 4.15.

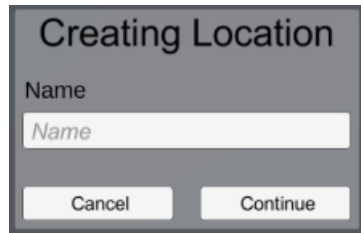


Figure 4.15: Input name of location

Then, as shown in view 4.16, after entering the location's name, the next step is to choose the location within the workshop by dragging the car slot area. You can also adjust its shape and size by dragging the spheres around the car slot area. Additionally, there's a dropdown that allows you to choose whether the car slot area is placed on the ground floor or the first floor in the 3D workshop model.



Figure 4.16: Place Location

The last step in creating a location involves setting details such as the color of the car slot area, which helps users visualize different spots in the workshop. You can also specify whether a classic car is required for the processes and tasks associated with this location and if the location requires a specific car capacity. On the right side of the screen, there is a dropdown list of all the processes and tasks performed in the workshop, allowing users to check off the tasks relevant to this location, as shown in figure 4.17. Finally, you complete the creation process by clicking the "Confirm Creation of Car Slot" button.

The "Projects" checkbox displays a list of classic cars currently in the workshop, along with cars that have previously been serviced when the "Closed" button is pressed. Basic information about each car is shown, and if there are any pending actions for a car, the number of pending tasks is displayed, as seen in figure 4.18.

### 4.3. IMPLEMENTATION



Figure 4.17: Location Details

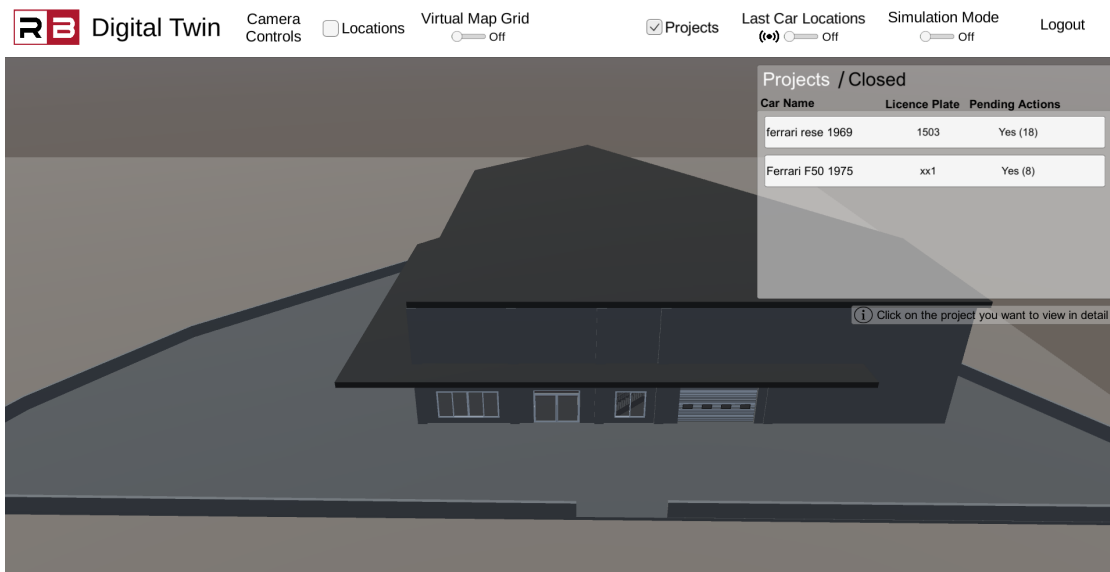


Figure 4.18: Projects list

In figure 4.19, when the "Last Car Locations" toggle is activated, the active classic cars are instantiated at their last known locations within the workshop.



Figure 4.19: Projects last location

If a car from the projects list is clicked, details about that vehicle will be displayed. Similarly, if an instantiated classic car in the 3D model of the workshop is clicked, the details for that car will also be shown, as illustrated in figure 4.20. The details include basic information about the vehicle, such as the license plate, chassis number, engine number, the date it entered the workshop, the Pinterest URL with pictures associated with the project, and the link to the project in the Charter of Turin monitor app. Additionally, in the "Change Color" button, a color picker and binary code can be used to select the specific color of the car, which is reflected in the display.

Additionally, there is a list of the vehicle's activity history, which includes the processes and tasks performed, associated locations, start dates, and end dates. Tasks that have an associated location are marked with a green check icon to indicate that the location has already been assigned. In contrast, tasks awaiting user association with the location where they were performed are highlighted in yellow. To associate one of these tasks with a location, the chosen task must be selected from the available list. When a task is selected, the app displays the information shown in figure 4.21.

After the task is selected, the locations associated with this task will be displayed within the workshop. The classic car can then be dragged to the appropriate location or selected by clicking on the location where the vehicle performed the task. On the left side of the screen, information about the task is provided, while details about the available and occupied locations are shown on the right side. One important aspect to consider is the occupancy of the car slot areas by other vehicles within the specified date interval of the task, as well as the capacity of that location. If a location is not available, it will appear

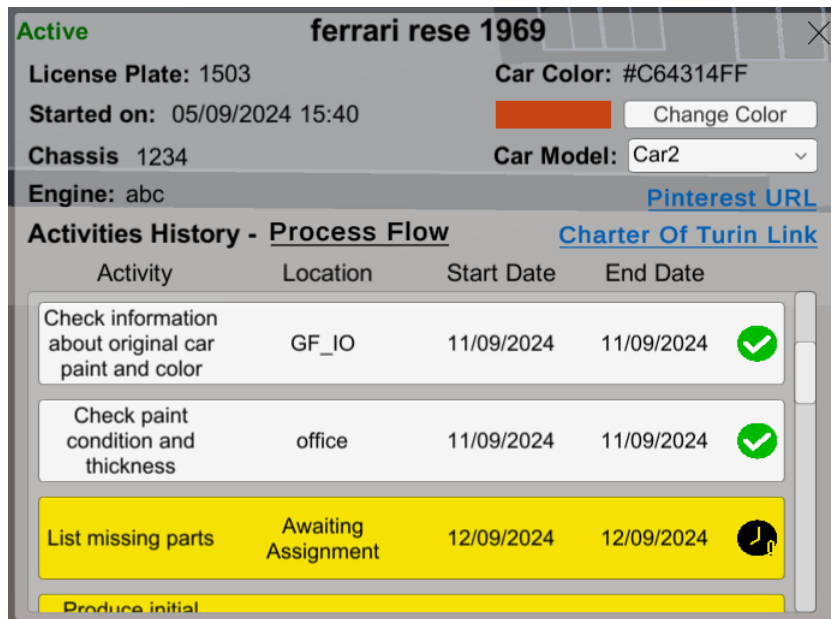


Figure 4.20: Projects details

in black, indicating that it cannot be associated with the car. To confirm the location, the "Confirm Car Location of Task" button must be pressed.



Figure 4.21: Associate location to task

In the project details, as illustrated in figure 4.20, there is a "Process Flow" button that, when pressed, displays the timeline of tasks performed on the car. This timeline is accompanied by classic cars instantiated in their respective locations within the workshop, offering a visual representation of the car's movement and activities throughout its stay in the workshop, as shown in figure 4.22. This feature enables users to track the car's progress and review the sequence of tasks in an intuitive, visual format.

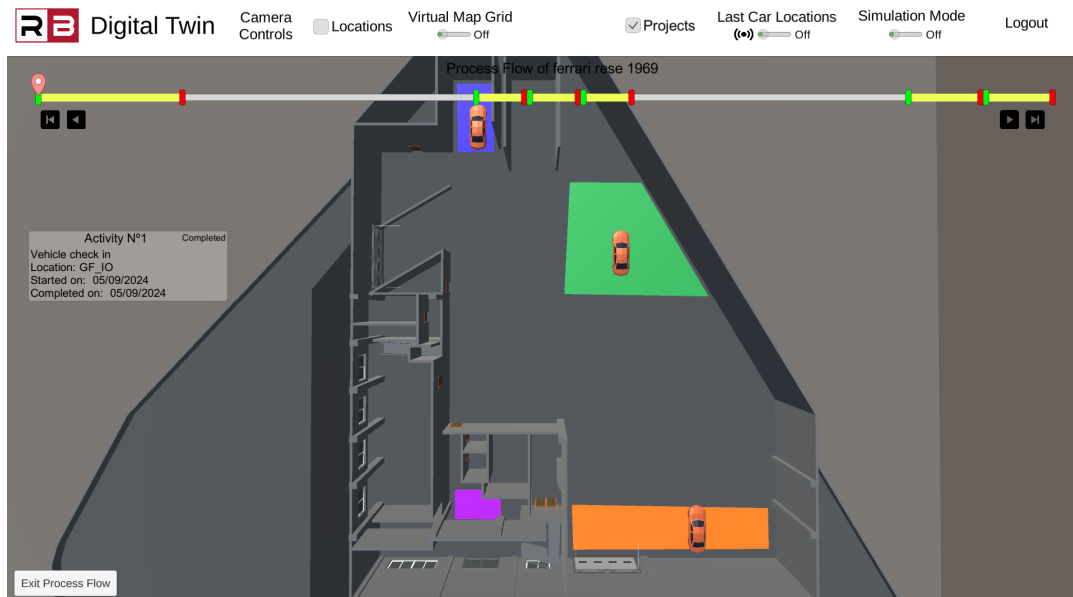


Figure 4.22: Vehicle's process flow

At the top of figure 4.22, a timeline displays all processes and tasks performed on the car that have an associated location. A green marker indicates the start of a task, while a red marker signifies task completion. A yellow bar illustrates the duration of each task, helping users understand the time spent on various activities within the workshop's timeline. Gray gaps represent periods when the vehicle was not involved in any activities. To enhance clarity, tasks and gaps larger than two days are represented with a maximum size equivalent to two days, preventing excessively large gaps that may cause confusion.

Additionally, four navigation buttons allow users to move through the timeline: one to move forward, another to go back, one to jump to the first task, and another to jump to the last task. When any of these buttons are pressed, the system focuses on the car's location for the current task. Information about the task and its associated location, including start and end dates, is always displayed on the left side of the screen, providing detailed insights into the currently selected task.

The last feature is the simulation mode, which can be activated by turning on the toggle switch. This mode allows users to freely add several cars into the workshop, enabling a more flexible exploration of the workspace, figure 4.23. Users can observe how different vehicles interact with the available car slot areas and visualize the potential workflow dynamics within the workshop. The "Add Car" button facilitates the addition of vehicles, allowing users to drag and position them freely within the workshop. Additionally, the "Delete All Cars" button eliminates all cars that have been previously instantiated, providing a way to reset the simulation as needed.



Figure 4.23: Simulation Mode

## VALIDATION

*In this chapter, we delve into the validation process of the digital twin application developed for the classic car workshop. We begin with an overview of the entire validation process, outlining the methodologies and criteria used to assess the application's performance and reliability. Following this, we provide detailed insights into the validation of the digital twin application itself, discussing specific tests conducted, user feedback collected, and the outcomes of these evaluations. Finally, we address potential validation threats encountered throughout the process, highlighting challenges and considerations that may impact the validity of our findings.*

### 5.1 Overview

As mentioned in section 1.4, the scientific methodology chosen for the development of this work was Action Research, meaning that continuous validation took place throughout the development process of the DT. This validation and feedback primarily came from the workshop employees, who are the main users of the application and have a deep understanding of the workshop's needs. The close collaboration with these workers throughout the process ensured that the final result closely aligns with their practical requirements and addresses their real-world challenges. Additionally, feedback was gathered from classic car owners to ensure that the features they use also meet their expectations and enhance their experience.

During the course of this work, a paper [8] was published in the International Conference on Industry 4.0 and Smart Manufacturing (ISM 2023)<sup>1</sup>. The focus of this conference is Industry 4.0 and smart manufacturing, which aligns closely with the subject of our work, making it a suitable venue for our submission. The paper outlined the design architecture of the proposed system and highlighted some features that, in the meantime, were fully implemented.

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<sup>1</sup>ISM 2023, <https://www.msc-les.org/ism2023/>, Last Access: 26/09/2024

Lastly, this work was included and mentioned in a interview of "Jornal dos Clássicos: A Excelência do Restauro"<sup>2</sup>.

The following sections provide a detailed account of the validation processes and the results obtained for the various components of the system.

## 5.2 Digital twin Validation

The initial validation process was carried out with the workshop staff, concentrating on the interface and functionalities of the DT application.

### 5.2.1 Validation by Workshop Employees

For the validation of our system by the workshop employees, we followed the expert panel methodology, similar to the approach used in [14]. This validation methodology is an established process for assessing and improving the quality and credibility of a system by consulting a panel of experts. These experts review, critique, and validate key components of the project.

This approach was deemed suitable for our case because the users of the DT application need to possess a deep understanding of the previously developed system, the Charter of Turin monitor, as well as knowledge of preservation and restoration processes, and the overall workshop operations. In the figure its possible to observe the steps followed by [14].

Based on these steps, our validation was separated into five steps;

1. Identification of the key features in our system that we wanted to validate;
2. Selection of the expert panel, ensuring participants had relevant knowledge and experience;
3. Creation of the questionnaire to be presented to the experts;
4. Collection of the questionnaire responses during a meeting with the experts;
5. Discussion and analysis of the results.

The initial step in this validation process involved identifying the key features of our platform, which subsequently became the focal point of our validation efforts. The primary features selected for validation include:

- Navigation within the 3D model of the workshop;
- Management of car slot areas, including creation, updates, and deletion, as well as their representation within the application;

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<sup>2</sup>Interview, [https://www.youtube.com/watch?v=W7Dg\\_MgC7Ys](https://www.youtube.com/watch?v=W7Dg_MgC7Ys), Last Access: 26/09/2024

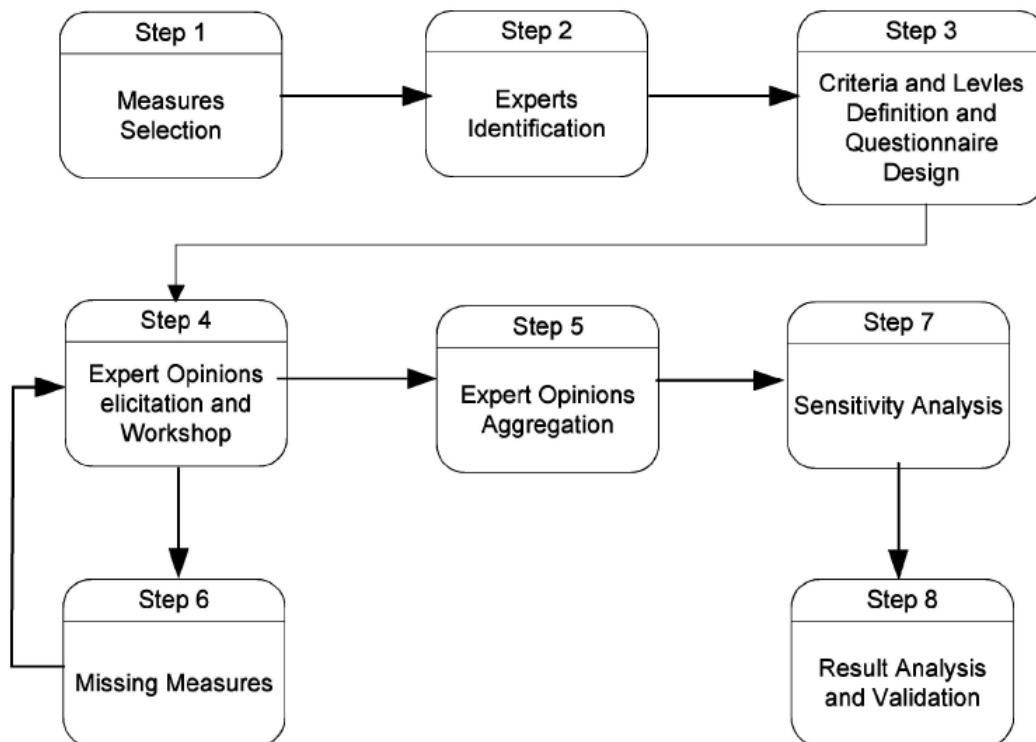


Figure 5.1: Diagram of steps followed in [14]

- Representation of vehicles in the workshop along with their details;
- Management of tasks and locations associated with the vehicles;
- Visualization of vehicle process flows and history;
- Simulation capabilities.
- General performance of the application.

Following the identification of these key features, the next step was to select the appropriate experts to participate in the questionnaire. The experts needed to have a solid understanding of the usual operations of the Charter of Turin monitoring application, as both applications are interconnected. The experts chosen for the validation were two employees from the workshop, and their characterization is presented in Table 5.1.

Profession	Years of Experience
Manager	20
Secretary	15

Table 5.1: Workers characterization

The next step was to develop the questionnaire, presented in appendix B, which consisted of several questions aimed at gauging the workers' opinions on the main features

of our application. Responses were rated on a scale ranging from "Strongly Disagree" to "Strongly Agree".

The questions included the following:

- The 3D model of the workshop is easy to navigate.
- It is easy to assign a location to a task.
- It is easy to track cars and their last known locations.
- Car slot areas are clearly defined and easy to understand.
- Car slot areas are easy to create and to edit.
- The process flow for each car is easy to follow and understand.
- The car details (e.g., status, tasks, etc.) are well-presented.
- The simulation feature is intuitive and easy to use.
- The app is responsive with minimal delays or lag.

There was one final question: "What features could be added in the future?" The aim of this question was to identify any missing functionalities that the workers believed could be incorporated into the DT application as future improvements. This question allowed the employees to provide open-ended responses.

#### 5.2.1.1 Questionnaire Results

We gathered with the employees to present the DT application, allowing them to freely explore all its features and details for a period of time. Afterwards, the questionnaire was introduced, and each employee filled out the questions individually. Once all responses were collected, we held a discussion to review each question and their answers, encouraging open feedback and further insights.

The responses to the questionnaire provided valuable insights into the usability and functionality of the DT application. The gathered feedback helped identify areas of strength and potential improvement. Below is table 5.2, which summarizes the answers provided by the employees to each question. This data offers a clear overview of their perceptions and experiences with the system.

The summary of the discussion of the results:

- **The 3D model of the workshop is easy to navigate** - the 3D model allows users to explore the workshop environment, moving freely through various areas. A camera system is integrated to provide smooth navigation, allowing users to pan, zoom, and switch viewpoints to effectively interact with the workshop layout. The feedback from employees was positive; they noted that the 3D model closely resembles the actual workshop and that the camera controls are intuitive and easy to use.

Questions	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The 3D model of the workshop is easy to navigate.	0	0	0	0	2
It is easy to assign a location to a task.	0	0	0	0	2
It is easy to track cars and their last known locations.	0	0	0	0	2
Car slot areas are clearly defined and easy to understand.	0	0	0	0	2
Car slot areas are easy to create and to edit.	0	0	0	0	2
The process flow for each car is easy to follow and understand.	0	0	0	0	2
The car details (e.g., status, tasks, etc.) are well-presented.	0	0	0	1	1
The simulation feature is intuitive and easy to use.	0	0	0	1	1
The app is responsive with minimal delays or lag.	0	0	0	1	1

Table 5.2: Answers to the questionnaire

- **It is easy to assign a location to a task** - In the [DT](#) application, employees can assign processes and tasks performed on a vehicle to specific locations within the workshop. The feedback was positive, with all employees agreeing that assigning a location to a task is straightforward and simple.
- **It is easy to track cars and their last known locations** - The system tracks each car's movements and displays all vehicles at their last known locations within the workshop. Employees provided very positive feedback on this feature, appreciating how it offers a clear overview of each vehicle's position. This capability significantly reduces the time spent searching for cars, streamlining operations and enhancing overall efficiency in the workshop.
- **Car slot areas are clearly defined and easy to understand** - Here, we aimed to assess whether the car slot areas within the workshop were clearly defined, with distinct boundaries that made it easy for employees to identify and differentiate between one another. Employees appreciated the representation of the car slot areas, noting that the ability to personalize them with different colors enhanced their visibility and made it easier to distinguish between slots.
- **Car slot areas are easy to create and to edit** - We aimed to assess whether the process of creating and editing a car slot area was intuitive for the employees, particularly regarding the definition of dimensions, format, location and some details. Employees appreciated that the car slot areas could be defined as polygons with varying dimensions instead of being restricted to pre-fabricated objects. This flexibility enabled them to create customized spaces that better fit the unique layout of the workshop. This aspect was discussed during development, as the initial

design involved uniform areas that were the same size, which did not accommodate the specific needs of the workshop.

- **The process flow for each car is easy to follow and understand** - This question assessed whether the employees were satisfied with the process flow and the timeline of tasks associated with each vehicle within the workshop. The goal was to ensure that the visual representation of the sequence of tasks and events for each car was clear and easy to comprehend. Employees gave positive feedback, stating that the process flow was intuitive.
- **The car details (e.g., status, tasks, etc.) are well-presented** - In the [DT](#) application, users can view various details about each vehicle, including basic information such as the make, model, and year, along with the status, tasks performed, and links to relevant resources like a Pinterest board for restoration ideas or the Charter of Turin monitor. Employees provided positive feedback, noting that all the essential information was available but could be better organized and easier to read.
- **The simulation feature is intuitive and easy to use** - This question aimed to gather feedback on the simulation mode in the application. Employees responded positively, stating that the feature was easy and intuitive to use. They also noted that it could be particularly useful for organizing areas within the workshop.
- **The app is responsive with minimal delays or lag** - The application's responsiveness is crucial for smooth navigation and interaction with the 3D model, as well as for instantiating different objects in the workshop. The feedback from both employees was generally positive. However, one employee noted that when the application is tasked with instantiating several objects simultaneously, there can be a noticeable delay before all objects are fully instantiated. Despite this, the overall performance was considered satisfactory.
- **What features could be introduced in the future?** - The goal of this question was to understand the employees' perspectives on which features, details, or integrations might be missing and could further enhance their day-to-day work within the [DT](#) application. This feedback aimed to guide future improvements and ensure the system continues to meet the evolving needs of the workshop. One key suggestion was the ability to assign one or multiple workers to tasks performed on the vehicles and track the hours worked on each task. This feature would improve task management and accountability, making it easier to monitor individual contributions and work efficiency. Another aspect was possibly integrating with other applications, such as car repair management systems. The workshop utilizes these systems to track the repair history of each vehicle, including parts and budgets, while they are in the workshop. Employees mentioned that integration with these applications would enhance information organization and accessibility. A simple suggestion was to

provide a direct link to one of these systems, making access easier and faster. Another suggestion regarding application integration was connecting with systems related to processes and tasks performed on a vehicle outside the workshop, particularly for outsourced jobs. The conclusion of integrating multiple systems is to maintain a more organized and cohesive collection of all existing information about a single vehicle, eliminating the uncertainty of where specific information about a car is located. These were the key topics addressed in this question.

### 5.2.2 Validation by External Members

In this phase of validation, we utilized two questionnaires, the [SUS](#) as described in [13], and the [UEQ](#) as outlined by [24].

For the validation, we contacted six former students involved in the workshop's digital transformation. Most of them currently work in the automotive industry, which provides them with substantial knowledge in this domain. However, we only received three responses to the questionnaires. The [DT](#) system was introduced to the participants through a demonstration, after which they completed the questionnaires.

The [SUS](#) is a straightforward questionnaire designed to evaluate the usability of a system. It consists of a ten-item questionnaire with five possible answers, ranging from "Strongly Disagree" to "Strongly Agree."

For our validation, the standard version of the [SUS](#) statements was used, which includes the following items:

- I think that I would like to use this system frequently.
- I found the system unnecessarily complex.
- I thought the system was easy to use.
- I think that I would need the support of a technical person to be able to use this system.
- I found the various functions in this system were well integrated.
- I thought there was too much inconsistency in this system.
- I would imagine that most people would learn to use this system very quickly.
- I found the system very awkward to use.
- I felt very confident using the system.
- I needed to learn many things before I could get going with this system.

The [UEQ](#) is designed to assess the overall user experience of a product. This questionnaire consists of pairs of contrasting attributes with 26 items, and users respond on

a scale ranging from 1 to 7, with 1 indicating a strong preference for one attribute and 7 indicating a strong preference for the opposite attribute.

The categories evaluated here are:

- Attractiveness
- Perspicuity
- Efficiency
- Dependability
- Stimulation
- Novelty

### 5.2.2.1 Results

First, the results of the [SUS](#) questionnaire provide a final score ranging from 0 to 100 for each participant. This score represents a grade for the system's usability, as depicted in [Figure 5.2](#), based on the grading scale presented in [\[13\]](#).

**Table 1.** The Sauro–Lewis CGS.

SUS Score range	Grade	Percentile range
84.1–100	A+	96–100
80.8–84.0	A	90–95
78.9–80.7	A–	85–89
77.2–78.8	B+	80–84
74.1–77.1	B	70–79
72.6–74.0	B–	65–69
71.1–72.5	C+	60–64
65.0–71.0	C	41–59
62.7–64.9	C–	35–40
51.7–62.6	D	15–34
0.0–51.6	F	0–14

Figure 5.2: Range of [SUS](#) Scores in [\[13\]](#)

Our final scores for each participant are presented in [Figure 5.3](#). Based on the grading table referenced above, Participant 1's score translates to an A+, indicating excellent usability, while Participant 2's score corresponds to a B+, and Participant 3's score is C, reflecting good usability with some room for improvement.

These results give an average score of 80, corresponding to an A- grade. Based on these results, we can infer that the users were positive about our system, indicating that it offers good usability. However, there is still room for improvement to further enhance the overall user experience.

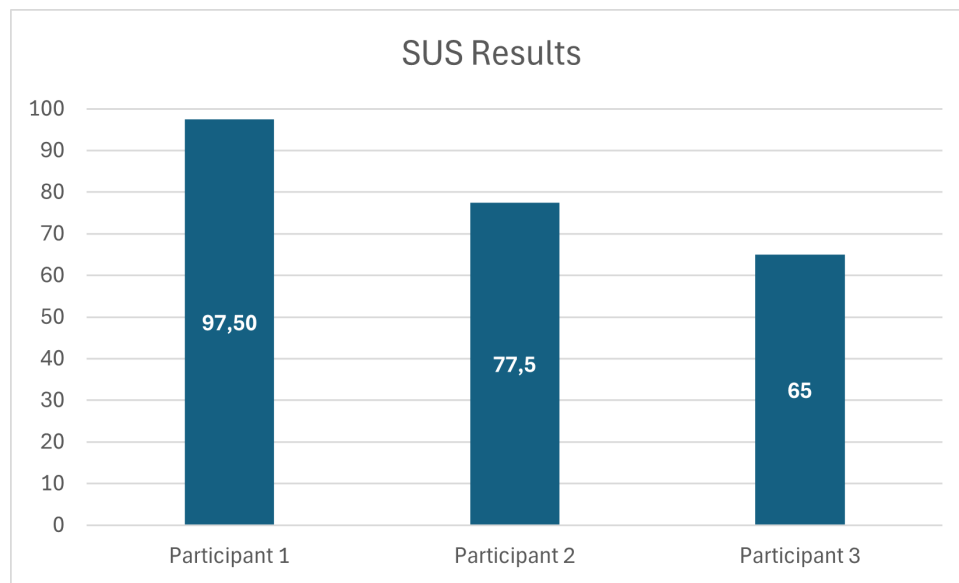


Figure 5.3: SUS score Results

Lastly, the results from the UEQ questionnaire show that each of the 26 items belongs to one of the categories outlined in section 5.2.2, contributing to the mean score of that category. Depending on the mean value, the evaluation result of each category can fall into one of five ratings: Bad, Below Average, Above Average, Good, or Excellent, as presented in figure 5.4 by [24].

	<b>Att.</b>	<b>Eff.</b>	<b>Per.</b>	<b>Dep.</b>	<b>Sti.</b>	<b>Nov.</b>
<b>Excellent</b>	$\geq 1,72$	$\geq 1,64$	$\geq 1,82$	$\geq 1,6$	$\geq 1,50$	$\geq 1,34$
<b>Good</b>	$\geq 1,50$ $< 1,72$	$\geq 1,31$ $< 1,64$	$\geq 1,37$ $< 1,82$	$\geq 1,4$ $< 1,6$	$\geq 1,31$ $< 1,50$	$\geq 0,96$ $< 1,34$
<b>Above average</b>	$\geq 1,09$ $< 1,50$	$\geq 0,84$ $< 1,31$	$\geq 0,90$ $< 1,37$	$\geq 1,06$ $< 1,40$	$\geq 1,00$ $< 1,31$	$\geq 0,63$ $< 0,96$
<b>Below average</b>	$\geq 0,65$ $< 1,09$	$\geq 0,50$ $< 0,84$	$\geq 0,53$ $< 0,90$	$\geq 0,70$ $< 1,06$	$\geq 0,52$ $< 1,00$	$\geq 0,24$ $< 0,63$
<b>Bad</b>	$< 0,65$	$< 0,50$	$< 0,53$	$< 0,70$	$< 0,52$	$< 0,24$

Figure 5.4: Benchmark for the UEQ scales

The results of the validation are presented in figure 5.5. Stimulation was the highest-scoring category, reflecting that users felt in control during their interactions with the system. The category with the lowest score was Novelty, which suggests that while users found the system reliable, there may be room for introducing more innovative features.

Dependability, stimulation and novelty scored Excellently. Attractiveness and efficiency had a good. And Perspicuity is Above average. Overall, these results are positive.

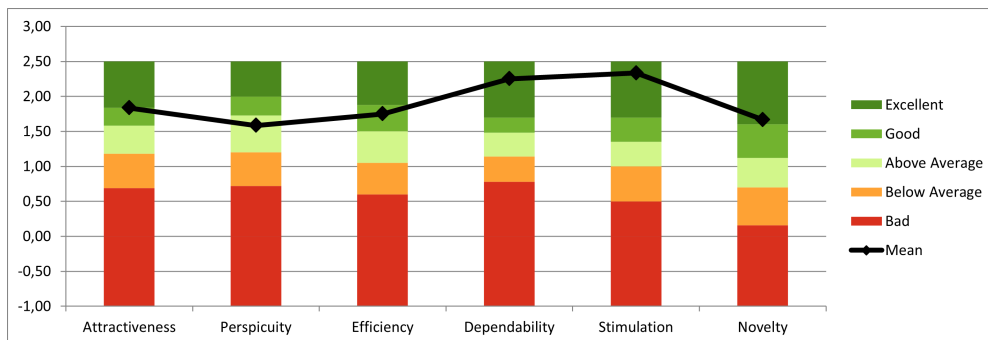


Figure 5.5: UEQ mean values by category

Both validation methods had great results, with good feedback and general interest from the participants in the developed DT system, with potential improvements that can be made.

### 5.3 Threats to Validity

A validation threat is that the expert panel had limited time to explore the application before completing the questionnaire. The brief exposure to the system may have impacted the depth of their feedback. Ideally, the users should have had a few weeks to use and interact with the system in real-world conditions as part of their everyday activities. This would allow for a more thorough assessment of the application's interface, usability, and functionalities.

Another validation threat is the small sample of both validations, which is made up of workshop employees and external participants. A limited number of participants reduces the amount of feedback and weakens the results. A larger group of participants would provide stronger results, offering more feedback and diverse insights into the system. Nevertheless, the workshop employees represent the universe of users that will use the system in the repair shop.

In the external members' validation of the system's usability, the participants did not use the application; they just saw a demonstration, which may have impacted the results.

## CONCLUSIONS AND FUTURE WORK

*This chapter concludes our work by summarizing the developed solution and highlighting its contributions to the field. We reflect on the key findings and the impact of the digital twin application. Additionally, we discuss potential future directions for enhancing the system and identifying areas for further research and development.*

### 6.1 Conclusions

The main objective of our work was to build a **DT** system capable of managing and monitoring the restoration and preservation processes of classic cars in the workshop, combining them with the physical information of the shop floor and ensuring effective communication between workshop employees and car owners. [Here is the link to the GitHub repository.](#) [And the link to the demonstration video on YouTube.](#)

To achieve this, we developed a **DT** application following an action research methodology, incorporating constant feedback from workshop employees to enhance the implementation of the entire system. We aimed to integrate previously developed systems, specifically the Charter of Turin Monitor application and Camunda. These systems were studied and analyzed to ensure seamless communication with our new system. To meet the requirements of the **DT** application, we introduced new API methods and updated existing ones. As a result, we modified the Charter of Turin Monitor system's database, adding new collections and entities. With these changes, we were able to manage locations and track the history of processes and their associated locations for each vehicle in the workshop.

One of the main requirements of the **DT** application was to have a realistic 3D model of the workshop. Using existing 2D plans and conducting field measurements, a 3D model was developed with AutoCAD, Revit, and 3ds Max. Additionally, a virtual map was created to represent processes and activity locations, including designated areas where similar tasks are performed and a precise depiction of where each task occurs within the workshop.

In the end, the user interface of the digital twin (DT) was developed using Unity, along with the other features previously presented.

The system's validation received positive feedback regarding its usability and the available features.

Our system is capable of managing locations, vehicles, and processes, and it has garnered interest from all stakeholders involved. Additionally, several companies that collaborate with the workshop have expressed interest, recognizing the value that such a system can bring to daily operations in any workshop and within the automotive industry as a whole.

We believe this work has made valuable contributions to the DT field, as well as to Industry 4.0 and cyber-physical systems. We developed a solution to enhance process management within a workshop by integrating multiple technologies and systems. This work demonstrates the potential of a DT system, providing insights and inspiration for other industries seeking to leverage similar approaches.

## 6.2 Future Work

In terms of future work related to the DT system developed, there are opportunities for improvements and the addition of new components to enhance the system.

Our system's management of processes, task history, and vehicle information is currently based solely on the Charter of Turin Monitor application. Integrating data collected from sensors placed in the workshop could significantly enhance the system by providing real-time vehicle locations and identifying tasks being performed. Additionally, incorporating corresponding models of the machines used in the workshop into the 3D model would be beneficial. With the support of smart plugs, we could monitor the usage of these machines, ensuring predictive maintenance and aiding in the identification of processes and tasks.

The workshop has a camera hub system interconnected with the Charter of Turin Monitor application, as presented earlier in section 3.6. Integrating these cameras into the DT and enabling control over them would facilitate real-time video monitoring of the workshop, thereby enhancing the system's functionality. If this equipment could be controlled, classic car owners would be able to observe their vehicles from various angles.

During the validation process with the workshop employees, they suggested a feature for managing workers, assigning them to tasks, and tracking their hours worked. Additionally, they emphasized the need for integration with other systems used in the workshop, such as the car repair management system, which tracks the repair history of each vehicle, with a particular focus on parts and budgets. They also proposed establishing connections to external systems for managing outsourced jobs performed on the vehicles.

One problem identified during the visits to the workshop was the parts storage on the first floor, which was disorganized and confusing, with many parts lacking proper identification. A potential future feature could be implementing a storage management

system using markers such as QR codes or [RFIDs](#) to help identify and track the objects. Assigning these objects to specific vehicles would also be beneficial, especially since the old parts are returned to the owner after the restoration and preservation processes are completed. In this case, the Digital Twin would be an essential tool to help the technical staff locate the parts of the vehicles more easily.

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## PROCESSES AND ACTIVITIES OF CAMUNDA

<b>CODE</b>	<b>DESCRIPTION</b>
CB	Chemical Blasting
CS	Coat & Styling
DA	Disassembly & Assembly
EH	Experimental Hub
FO	Front Office
FS	Filling & Sanding
IO	check In & Out
OC	Outsource Company
PB	Paint Booth
PF	Preservation and Finishing
PL	Paint Lab
PS	Parts Storage
RM	parts Repair & Manufacturing
SB	Sand Blasting

Figure A.1: Areas within the workshop

## APPENDIX A. PROCESSES AND ACTIVITIES OF CAMUNDA

AREA CODE	AREA DESCRIPTION	AREA CODE	AREA DESCRIPTION	TASKS	OBSERVATIONS
				<b>Process - Restoration Base</b>	
IO	check In & Out			Task: Vehicle check in	
IO	check In & Out			Task: Collect vehicle information (schemes, data and paint)	
				<b>Process - Restoration Evaluation</b>	
				<b>Process - Restoration Evaluation General State</b>	
FO	Front Office			Check car registration	
IO	check In & Out			Evaluate the general state and damaged areas	
IO	check In & Out			Check information about original car paint and color	
IO	check In & Out			Check paint condition and thickness	
IO	check In & Out			Outsource specialist advice	
IO	check In & Out			Task: List missing parts	
FO	Front Office			Task: Produce initial estimate of cost and timeframe	
FO	Front Office			Task: Send budget and timeframe to customer	
FO	Front Office			Task: Receive customer response	
FO	Front Office			Task: Void budget proposal	
				<b>Process - Restoration Disassembly</b>	
FO	Front Office			Task: Check and/or update vehicle file	
OC	Outsource Company			Task: Outsource disassembly (mechanical, upholstery, etc.)	
				<b>Process - Restoration Disassembly Part</b>	
DA	Disassembly & Assembly			Task: Photograph/film the part before removal (body and chassis)	
DA	Disassembly & Assembly			Task: Produce sketches with relevant dimensions dimensions	
DA	Disassembly & Assembly			Task: Disassemble part	
DA	Disassembly & Assembly			Task: Photograph/film the part after removal	
PS	Parts Storage			Task: Label and properly store the part in container	
PS	Parts Storage			Task: Record disassembled parts	
				<b>Process - Restoration Re-Evaluation</b>	
				<b>Process - Restoration Re-Evaluation Body Pickling</b>	
DA	Disassembly & Assembly			Task: Body pickling: Evaluate the state of the body sheet	
SB	Sand Blasting			Task: Body pickling: Physical stripper	
CB	Chemical Blastin CS	Coat & Styling		Task: Body pickling: Apply chemical stripper	
DA	Disassembly & Assembly			Task: Re-evaluate damage to the body	
FO	Front Office			Task: Report car condition	
				Task: Identify the parts that need to be replaced	
FO	Front Office			Task: Produce updated estimate of cost and timeframe	
FO	Front Office			Task: Send budget and timeframe to customer	
FO	Front Office			Task: Receive customer support	
FO	Front Office			Task: Order replacement parts	
				<b>Process - Task: Restoration Repair</b>	
FO	Front Office			Task: Check restoration planning	
OC	Outsource Company			Task: Outsourced Repair (mechanical, upholstery, etc.)	
				<b>Process - Restoration Repair Chassis</b>	
RM	parts Repair & Manufacturi			Task: Chassis: Thorough cleaning	
RM	parts Repair & Manufacturi			Task: Chassis: Check specifications for measurements and layout	
RM	parts Repair & Manufacturi			Task: Chassis: Check position of mounting brackets	
RM	parts Repair & Manufacturi			Chassis: Remove flaws using traction equipment	
				<b>Process - Restoration Repair Bodywork</b>	
				<b>Process - Restoration Repair Bodywork Part</b>	
RM	parts Repair & Manufacturi			Task: Bodywork: Identify part to repair	
RM	parts Repair & Manufacturi			Task: Bodywork: Choose correct material and thickness	
RM	parts Repair & Manufacturi			Task: Bodywork: Use English Wheel to form compound curves in metal sheet	
RM	parts Repair & Manufacturi			Task: Bodywork: Use Bending Machine to bend metal sheet	

Figure A.2: Mapping of Processes and Activity Locations (1)

RM	parts Repair & Manufacturi		Task: Bodywork: Use Bead Roller to add rigid lines in metal sheet
RM	parts Repair & Manufacturi		Task: Bodywork: Use Calender to finish or smooth a sheet of metal
RM	parts Repair & Manufacturi		Task: Bodywork: Use Stretcher to stretch a sheet of metal
RM	parts Repair & Manufacturi		Task: Bodywork: Manual work
RM	parts Repair & Manufacturi		Task: Bodywork: Weld identifying plate
RM	parts Repair & Manufacturi		Task: Bodywork: Validation of the measurements with the original
RM	parts Repair & Manufacturi		Task: Bodywork: Validation of the measurements with the original
		Gather evidence of the overall bodywork repair process	
			<b>Process - Restoration Repair Bodywork Coating</b>
PB	Paint Booth		Task: Coat and Style: Application of anti-rust primer coat with cure at 60° C for
FS	Filling & Sanding	PB Paint Booth	Task: Coat and Style: Application of sprayable and/or manual filler and sanding
FS	Filling & Sanding		Task: Coat and Style: Application of anti-infiltration compound in joints
PB	Paint Booth		Task: Coat and Style: Application of paint primer coat with cure at 60° C for 30
CS	Coat & Styling		Task: Coat and Style: Evaluation of style lines, gaps and thickness (<500 µm)
CS	Coat & Styling		Task: Gather evidence of the overall coating and styling process
			<b>Process - Restoration Repair Paint</b>
CS	Coat & Styling		Task: Paint: Evaluate damages to paint
			<b>Process - Restoration Repair Paint Complete</b>
PL	Paint Lab		Task: Paint: Search for the authentic production color of the vehicle
EH	Experimental Hub		Task: Paint: Compare the authentic color with the current color
FO	Front Office		Task: Paint: Choose color to be used
PL	Paint Lab		Task: Paint: Choose paint system with suitable features
PL	Paint Lab		Task: Paint: Prepare paint technique to be used
PL	Paint Lab		Task: Paint: Check application method during production
PL	Paint Lab		Task: Paint: Choose appropriate paint dilution for desired effect
CS	Coat & Styling	CB Chemical Blasting	Task: Paint: Use high temperatures while drying the paint
PL	Paint Lab		Task: Paint: Choose appropriate tip to achieve the desired effect
PL	Paint Lab		Task: Paint: Choose appropriate paint dilution for desired effect
PB	Paint Booth		Task: Paint: Apply paint
PB	Paint Booth		Task: Paint: Use glossing techniques
PB	Paint Booth		Task: Paint: Use patination techniques
PB	Paint Booth		Task: Paint: Use mottling techniques
PB	Paint Booth		Task: Paint: Use normal paint technique
CS	Coat & Styling		Task: Paint: Wash and clean paint
CS	Coat & Styling		Task: Paint: Decontaminate paint using a clay bar
PF	Preservation and Finishing		Task: Paint: Polish paint
PF	Preservation and Finishing		Task: Paint: Apply wax to the paint
			<b>Process - Restoration Repair Paint Additional</b>
PB	Paint Booth		Task: Paint: Paint part
FO	Front Office		Task: Paint: Assign Glasurit's quality warranty
DA	Disassembly & Assembly	Task: Reassembly	
IO	check In & Out	Task: Deliver original damaged removed parts	
IO	check In & Out	Task: Vehicle check out	

Figure A.3: Mapping of Processes and Activity Locations (2)

| B

## QUESTIONNAIRE

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Validation questions:

**1. Navigation and Layout:**

- The 3D model of the workshop is easy to navigate.
  - Strongly Disagree |  Disagree |  Neutral |  Agree |  Strongly Agree

**2. Task Management:**

- It is easy to assign a location to a task
  - Strongly Disagree |  Disagree |  Neutral |  Agree |  Strongly Agree
- It is easy to track cars and their last known locations.
  - Strongly Disagree |  Disagree |  Neutral |  Agree |  Strongly Agree

**3. Car Slot Management:**

- Car slot areas are clearly defined and easy to understand.
  - Strongly Disagree |  Disagree |  Neutral |  Agree |  Strongly Agree
- Car slot areas are easy to create and to edit
  - Strongly Disagree |  Disagree |  Neutral |  Agree |  Strongly Agree

**4. Process Flow and History:**

- The process flow for each car is easy to follow and understand.
  - Strongly Disagree |  Disagree |  Neutral |  Agree |  Strongly Agree

**5. Car Information and Simulations:**

- The car details (e.g., status, tasks, etc.) are well-presented.
  - Strongly Disagree |  Disagree |  Neutral |  Agree |  Strongly Agree
- The simulation feature is intuitive and easy to use.
  - Strongly Disagree |  Disagree |  Neutral |  Agree |  Strongly Agree

**6. Performance:**

- The app is responsive with minimal delays or lag.

Figure B.1: Questionnaire for the Digital Twin validation (1)

## APPENDIX B. QUESTIONNAIRE

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- Strongly Disagree |  Disagree |  Neutral |  Agree |  Strongly Agree

What features could be introduced in the future?

Figure B.2: Questionnaire for the Digital Twin validation (2)





Original Investigator's Research