RENOVATION DIGITAL TWIN FOR BUILDING RETROFIT MONITORING: A SOFTWARE PRODUCT AND AN ORGANIZATIONAL ECOSYSTEM

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Abstract

To meet the European energy-saving and decarbonisation goals, the delivery of renovation projects must be accelerated. Automated processes and software tools are crucial to facilitate and optimise the project execution and onsite monitoring by providing early warnings and notifications to the project team. Digital twins are one of the most promising approaches as they provide real-time data and use simulation to inform and speed up decision-making processes. This paper presents the design, development, and deployment of a Renovation Digital Twin (RDT) that enables monitoring of the retrofitting progress and the provision of feedback to the project stakeholders. The RDT aims at addressing a set of seven design requirements including compliance with the General Data Protection Regulation (GDPR) while sensing building data. The RDT integrates 13 Key Performance Indicators (KPIs) allocated to five application domains: quality, cost, scheduling, safety, and environment.

Introduction

To achieve the energy-saving and decarbonisation goals of the European Union, the delivery of renovation projects must be accelerated. The adoption of digital twining technologies in construction and renovation project is one of the most promising approaches. Digital twins (DTs) refer to the creation of exact digital replicas or virtual representation of an object or system that spans its lifecycle. Each replica possesses the properties and/or behaviours of a system in the physical world. These digital replicas are updated from real-time data, and use simulation to optimise decision-making processes (Tuhaise *et al.*, 2023).

DTs offer several advantages in the construction industry. They enable improved resource management by optimising energy usage, reducing the carbon footprint of buildings, and providing real-time access to as-built models, thus fostering harmonisation between current progress and future deliverables. Moreover, DTs enhance collaboration by enabling all stakeholders to access a shared digital representation of a project, improving communication and collaboration between engineers, architects, contractors, and other team members. Furthermore, they help minimise waste, reduce construction costs, and identify and mitigate potential safety hazards on construction sites, ultimately improving the efficiency, quality, and safety of construction projects while reducing costs (Tao *et al.*, 2018). Hence, in construction industry, DTs can be leveraged to reduce costs, accelerate delivery, enhance the safety, and provide efficient monitoring of projects throughout their lifecycle (Saback de Freitas Bello *et al.*, 2023).

Monitoring activities is a critical task in construction project management. DTs can be utilized to monitor onsite construction activities to offer real-time insights and predictive capabilities. By integrating various data sources such as 3D models, IoT (Internet of Things) sensor data, and building information, DTs enable the continuous monitoring of construction processes, allowing for the early detection of potential issues and the optimization of resource utilization. This proactive approach enhances safety, risk management, and contributes to improved efficiency and quality of construction project (Greif *et al.*, 2020). As a result, the adoption of DTs for onsite monitoring has a great potential to be a valuable tool for construction project management and execution.

Decarbonization and energy-saving are global and urgent goals of the construction industry. Onsite monitoring of renovation activities is crucial to approach these goals as it supports accelerated project delivery. Although DTs is a promising technology in approaching these goals, only a few research has been conducted so far, to effectively demonstrate the design, development, and usage of such technologies. The situation is more challenging in building retrofit where existing tools are usually lacking or adapted from new build construction tools. Hence, this paper aims to present the design, development, and deployment of a Renovation Digital Twin (RDT) that enables monitoring of the retrofitting progress and the provision of feedback to the project stakeholders.

The remainder of the paper is structured as follows. Section 2 summarises research works and gaps related to the topic being addressed by the research. Section 3 presents the research methodology implemented to achieve the research objectives, and introduces the solution proposed which includes the digital twin developed for renovation projects monitoring, integrating a set of KPIs identified with the help of the RINNO project's industrial partners. Conclusions, limitations and future works are finally outlined in Section 4.

Previous Works

The concept of DTs in the context of building renovation and onsite retrofitting works has garnered increasing attention within the architecture, engineering, construction, and operations (AECO) industry. Pan, et al. (Pan *et al.*, 2023) discuss the emerging and anticipated benefits of DTs in the building deep renovation life cycle, emphasizing their potential to reshape the process of assets' construction and maintenance through decision encoding. The authors highlight that while the applications of DTs are still at an early stage, they hold promise for various stakeholders involved in AECO, provided that their full potential is effectively exploited (Pan *et al.*, 2023).

In a similar vein, a systematic review by Opoku et al. (Opoku *et al.*, 2021) delves into the status, evolution, and key applications of digital twins in the construction industry. The review provides insights into six areas of application in the lifecycle phases of a construction project, shedding light on the diverse contexts in which DTs can be leveraged within the construction domain. These application areas include building information modelling, structural system integrity, facilities management, monitoring, logistics processes, and energy simulation (Opoku *et al.*, 2021). Similarly, Tuhaise et al. (Tuhaise *et al.*, 2023) identified key technologies, research gaps, and future research directions, focusing on technologies in data transmission, interoperability, data integration, data processing, and visualization. From a different perspective, Ammar et al. (Ammar *et al.*, 2022) conducted a study that explored the applications and challenges in construction through interviews. Their analysis identified 40 applications and uncovered 34 implementation challenges. The study also presents a case study that exemplifies the practical implementation of DTs in a construction setting, underscoring the potential for different information pipelines from the site to decision-making processes (Ammar *et al.*, 2022).

Research Gaps and Contribution

Managing a renovation project presents several challenges for project stakeholders and policymakers, such as disruption to, and by occupants, which usually lead to more time and cost overruns, more health and safety hazards, and worse quality performance when compared to new-built construction projects (Doukari, Wakefield, *et al.*, 2024). The literature review conducted collectively underscores the transformative potential of DTs in synchronising and enhancing the performance of construction activities and ensuring better control of the cost, time, safety, and quality of construction projects. Despite that, the use of DTs in building renovation and onsite retrofitting works was noticed to be limited in this literature body, and no comprehensive framework has been yet proposed. Hence, implementing this technology in building renovation should offer valuable insights into their evolving role and improve the efficiency of monitoring onsite retrofitting activities.

The contribution of this paper is twofold: (i) present a novel RDT solution (i.e., product system) that enables monitoring of the retrofitting progress and the provision of feedback to the project stakeholders; and (ii) provide detailed descriptions of the Research and Development (R&D) methodology implemented (i.e., organizational system) which includes the design, development, and deployment processes as well as the technological ecosystem required for the software product development.

Renovation Digital Twin – RDT

The RDT platform is developed to enable monitoring of the retrofitting progress and the provision of feedback to

Table 1: Renovation Project KPIs

Application	Description	Calculation	Representation
Quality	1- Number of quality incidents 2- Monitoring the quality controls 3- Number of customer complaints 4- Identification and alerts on recurring quality issues	1- Number of opened quality incident forms 2- Quality controls to be done in the next 10 days 3- Number of customer complaints 4- The 5 most recurrent quality issues	1- Line chart 2- List 3- Line chart 4- List
Cost	5- Cost savings 6- Cost overruns	5- Sum of the registered savings 6- Sum of the registered overrun costs	5- Line chart 6- Line chart
Scheduling	7- Delay monitoring 8- Milestones monitoring 9- Duration for resolving issues	7- Difference between days worked and days scheduled 8- % of achieved, ongoing and upcoming tasks 9- Average duration between opening and closing issues	7- Line chart 8- Pie chart 9- Line chart
Safety	10- Identification and alerts on recurring safety issues 11- Number of safety incidents 12- Monitoring safety incidents control	10- The 5 most recurrent safety issues 11- Number of safety issues 12- Stakeholders involved in safety issues	10- List 11- Line chart 12- List
Environment	13- Monitoring waste	13- Number of recorded waste containers	13- Line chart

the project stakeholders. Its main role is to: (i) gather onsite information about weekly project safety, quality, cost, completion of tasks and delays, and information related to waste management; and (ii) provide the project stakeholders with timely insights to take appropriate actions if needed.

Methodology

The research and development methodology implemented to achieve the research objectives is based on a 5-step process (Figure 1):

- First, workshops with onsite construction workers, project and site managers and engineers are organised in order to identify the most relevant information they need to be regularly reported during the retrofitting phase of a renovation project. For two days, fourteen participants from the RINNO project's industrial partners contributed to the identification of renovation project stakeholders' needs and system requirements in terms of onsite information and progress notification;
- Second, this input was categorised into different application domains, including quality, cost, scheduling, safety, and environment to facilitate KPIs identification;
- Third, for each application domain, a list of KPIs for retrofitting works monitoring is defined, and their sources of data, calculation formulas, representation formats, and frequency of measurement are detailed (Table 1);

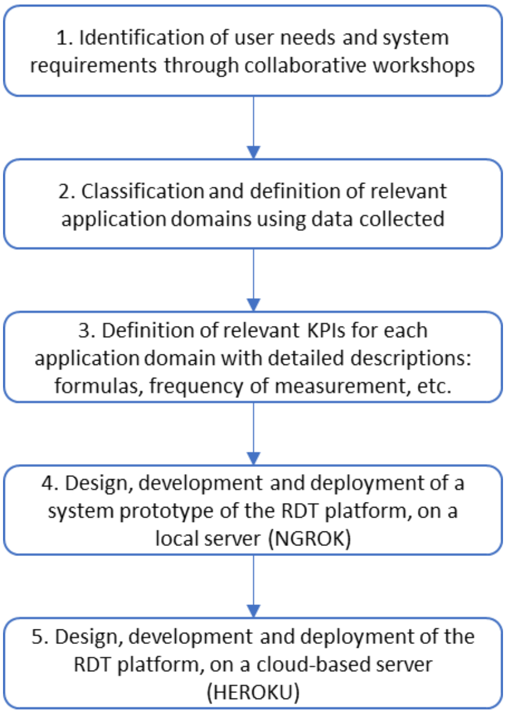

Figure 1: Research and development methods.

- Fourth, a system prototype, including main functionalities and user interfaces, is developed so as to enable both testing and validation with site managers and workers. This first version is deployed on a local machine, and remote access for testing purposes, is enabled using NGROK (NGROK, 2024);
- Fifth, a final version of the RDT platform is developed enabling the integration of the BIM model of the building being renovated along with a set of friendly graphical user interfaces (GUIs) for project KPIs visualisation and user notifications. This final version is deployed on HEROKU (HEROKU, 2024).

Design Requirements

The starting point of the RDT platform development is the set of design requirements (DR), including components and high-level functionalities, that have been identified with the RINNO project's industrial partners (Point 1, Figure 1). As presented in Table 2, seven requirements must be met to develop a suitable digital twin platform for renovation projects.

Table 2: Design requirements of the RDT platform.

DR1: Regularly provide relevant project KPIs regarding quality, cost, scheduling, safety, and environment (Table 1).
DR2: Store historical project KPIs during the retrofitting phase.
DR3: Simulate project KPIs and their progress overtime.
DR4: Provide a user-friendly interface through integrating BIM and relevant charts and/or graphs.
DR5: Enable stakeholders' notification when project KPIs exceed specific thresholds.
DR6: The RDT platform should be accessible anywhere and at any time for all project stakeholders through internet.
DR7: Comply with regulations, such as General Data Protection Regulation (GDPR), while sensing building data.

System Architecture

The RDT platform architecture presented in Figure 2 shows seven main components that help meet and implement the seven design requirements identified in Table 2. The RDT components and their relationships to the design requirements can be summarised as follows:

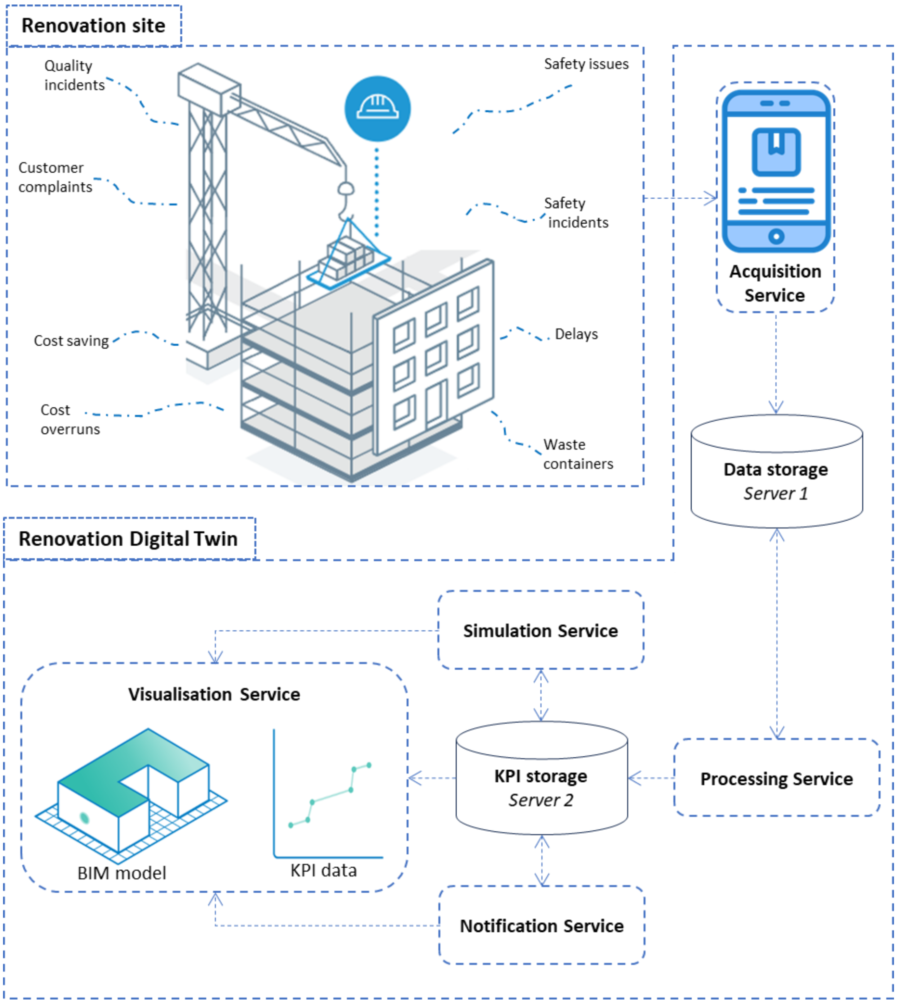

Figure 2: Renovation Digital Twin – RDT System Architecture.

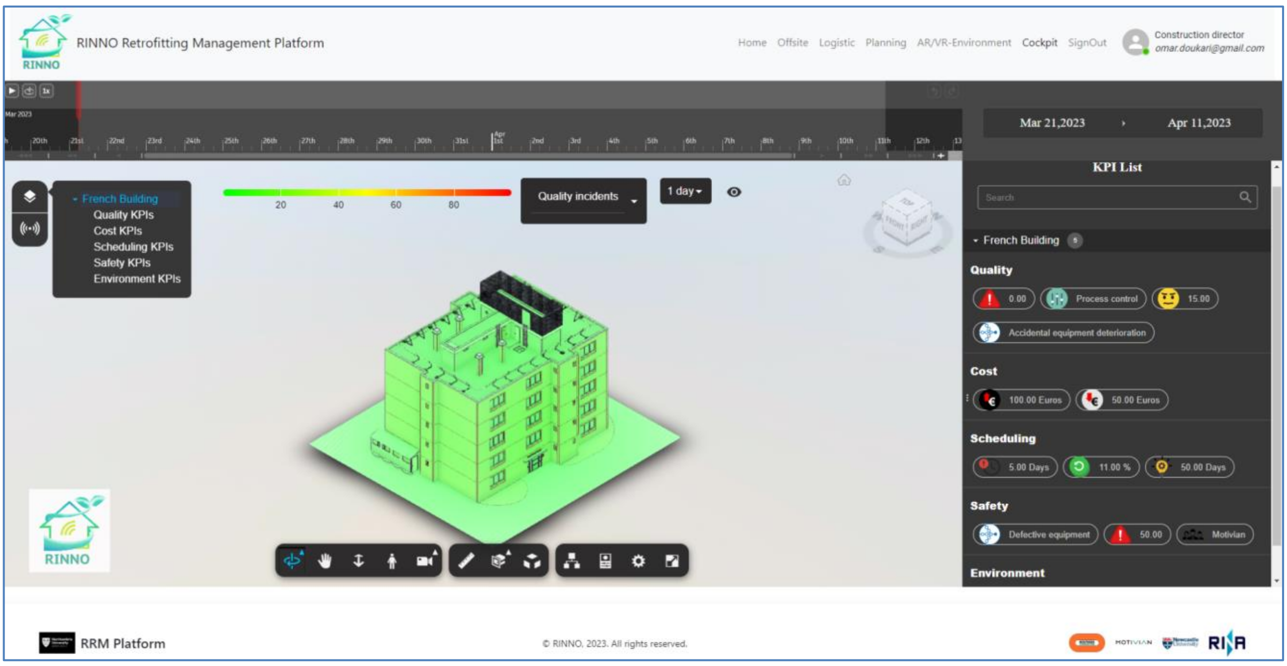

Figure 3: Renovation Digital Twin – RDT main UI.

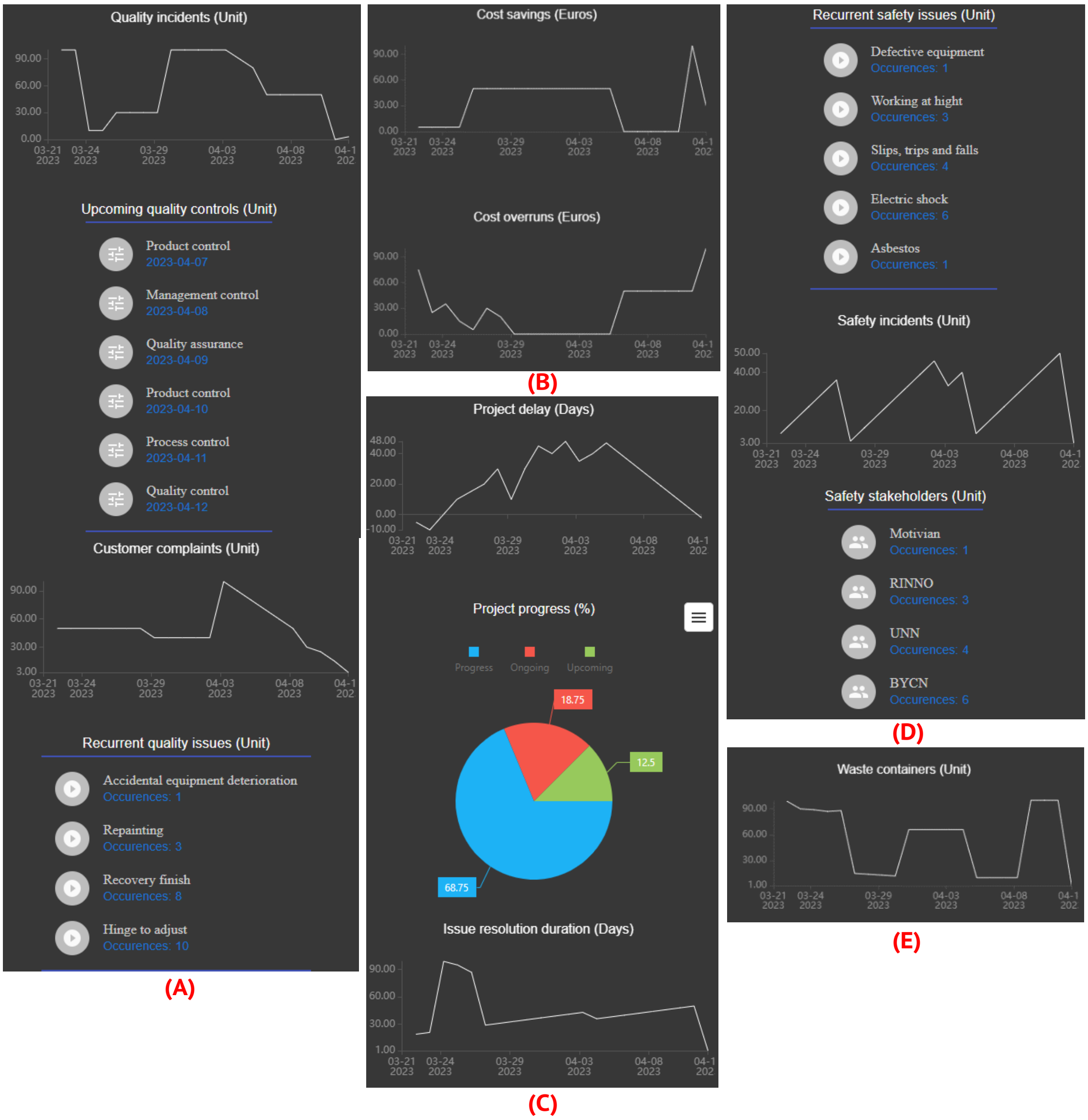

Figure 4: The RDT platform KPIs' dashboard for (A) Quality (B) Cost (C) Scheduling (D) Safety (E) Environment.

- Acquisition service: enables collecting raw data (ex. quality incidents, complaints, safety issues, etc.) from the onsite execution of the renovation project, and sending them back to be stored into the Data storage server. To comply with the GDPR regulation as stipulated by **DR7**, the Acquisition service is implemented as a mobile application instead of installing smart sensing devices such as sensors, which may need occupants and operators consent to data access (Doukari, Seck, Greenwood, *et al.*, 2022). The mobile application is used by the project manager to collect daily data related to the project progress and execution.

- Data storage: consists of a Structured Query Language (SQL) Server that stores daily project data collected through the Acquisition service. It also provides raw data for the 'Processing service' so that project KPIs can be calculated and stored as required by **DR1**.

- Processing service: enables calculating project KPIs using project's raw data stored into the Data storage component. It uses simple SQL queries to fetch data from Server 1, calculates the project KPIs, and then stores them into the KPI storage component (Server 2). As such, the Processing service helps meet requirement **DR1**.

- Notification service: consists of a 'background process' that runs continuously as a 'KPI Watcher' and triggers notifications when KPI threshold values are reached or exceeded. For each KPI in Table 1, min and max values are defined. While the min values are set to check data quality and consistency, the max values help trigger notifications via color-coded information displayed through the Visualisation service. The Notification service addresses requirement **DR5**.

- Simulation service: consists of simulating historical KPI values which are stored in Server 2 and their progress overtime. The result is visualised through a 'Timeliner' implemented and integrated into the Visualisation service. The KPI values are also simulated as shading and color-coded data into the BIM model elements using Forge APIs (Application Programming Interfaces). As such, the Simulation component enables '4D BIM simulation' (Doukari, Seck and Greenwood, 2022) aiming to meet requirement **DR3**.

- **KPI storage**: consists of a second SQL Server that stores project KPIs calculated by the Processing service. It feeds all RDT services (i.e., Simulation, Notification, and Visualisation) with KPI values through responding to SQL queries. This component implements **DR2**.

- **Visualisation service**: implements the main component where all visualisation, simulation and notification are displayed. The service integrates the BIM model of the building being renovated through Forge APIs, so as to allow end-users to access and easily visualise data related to current and/or historical project KPIs regarding quality, cost, scheduling, safety and some environmental aspects such as waste. This includes visualisations as shading created on top of the BIM model, 4D BIM simulations using the Timeliner, and through charts and graphics as illustrated in Figures 3 and 4. The Visualisation service answers requirement **DR4**.

Finally, to comply with requirement **DR6** and enable project stakeholders to access data anywhere and at any time, the RDT platform's architecture is designed and developed as a web-based application.

Development & Deployment

The RDT is developed using JavaScript for the backend, and React library (React, 2022), CSS and HTML technologies for the frontend (Figures 3 and 4). Particularly, MUI library (MUI, 2022) is used in order to ensure simplicity, clarity and responsiveness of the user interface (UI) components implemented, and so enable visualisation in different contexts (onsite and offsite) and on several device types with different hardware and software specifications, including smartphones, tablets and laptops. The RDT integrates Forge APIs and its main

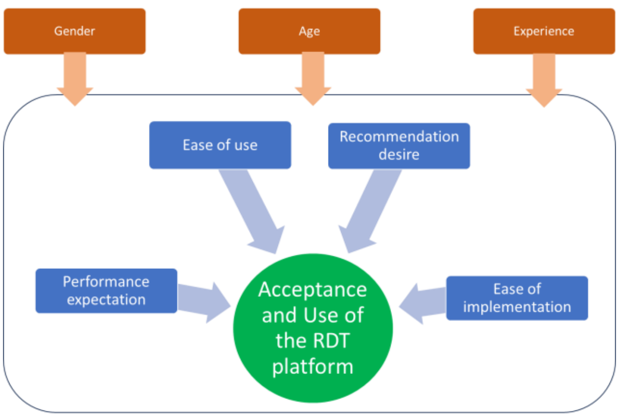

Figure 5: UTAUT model adapted to test and evaluate the acceptance of the RDT platform.

UI was inspired by a previous prototype version developed and shared by Autodesk (Sample Application, 2023).

As for the RDT deployment, it is processed following a 2-step process. First, for testing purposes, the platform is deployed on a local machine through NGROK (NGROK, 2024) and made accessible to the RINNO project's industrial partners so as to demonstrate its design and validate its functionalities. Second, the RDT is finally deployed on a permanent basis through HEROKU which is a cloud-based platform providing publication services for third-party web-based applications (HEROKU, 2024). A short demonstration video of the RDT platform in action can be visualised at (Doukari, 2024). The developed platform integrating the BIM model of the French demonstration site, which is one of the RINNO project's case studies (Doukari *et al.*, 2021), can be accessible online at (Doukari, 2023).

Conclusion, Limitations, and Perspectives

Despite the clear and obvious added values that DTs can provide to the construction industry, only little research have been conducted to showcase practical development and use of such technologies. The situation is more complex in renovation projects because of the dearth of digital tools and automated processes which are often adapted from new build construction tools, while such technologies are much more needed in building retrofit in order to expedite the delivery of renovation projects and meet the European energy-saving and decarbonisation goals by 2050 as per the EU commitment. In addition, specific requirements, such as complying with the GDPR regulation, may need to be addressed while conducting retrofitting works. To overcome these challenges, this paper introduced a Renovation Digital Twin (RDT) platform to enable monitoring of the retrofitting works and so accelerate the rate and amount of renovation projects in Europe. The adopted approach included the design, development and deployment of the RDT so as to document the process implemented and so enable reproducibility of the results. However, the research presents some limitations which can be summarised as follows: (i) the BIM model integration through the 'Visualisation service' is based on a semi-automatic process where the digital mock-up of the building under renovation first needs to be created and uploaded in the cloud, and then related (hosting) data must be updated within the RDT. To enable an efficient lean-based renovation project management as described in (Doukari, Kassem, *et al.*, 2024), a smooth and automatic BIM data preparation needs to be adopted; (ii) the 'Simulation service' enables 4D BIM simulation but only to visualise historical KPI values. There should certainly be much more benefits for the project participants if the simulation capabilities could be extended to predict future KPI trends using machine learning techniques (Rogage and Doukari, 2024) and/or a scenario-driven approach (Doukari, Wakefield, *et al.*, 2024); and finally (iii) future extensions of the research should investigate the acceptance and use of the RDT by end-users through its application and implementation within a real-world renovation project. An adapted version of the UTAUT model (Unified Theory of Acceptance and Use of Technology) (Dwivedi *et al.*, 2019) will be used to evaluate the RDT's performance and overall suitability for the management and delivery acceleration of renovation projects (Figure 5).

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