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A DISTRIBUTED COLLABORATIVE PLATFORM FOR MULTI-STAKEHOLDER MULTI-LEVEL MANAGEMENT OF RENOVATION PROJECTS

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SUMMARY*: To meet European energy-saving and decarbonisation goals, the annual renovation rate of buildings requires to be at least twice its current level; an aspiration to which the use of innovative and automated solutions can contribute. This paper presents such a solution, the RINNO Retrofitting Manager (RRM) which is part of a large, ambitious research and development project (RINNO) that aims to provide an augmented intelligence-enabled framework for deep, energy-focused retrofitting of buildings. The RRM uses web-service technologies to rationalise the retrofitting process and optimise the delivery of renovation works, while making data readily accessible through an integrated set of role-based user interfaces. The RRM is designed and developed as an open distributed system, that is extensible and portable, by implementing a collaborative research and development approach. The RRM platform implements a multi-level, multi-stakeholder planning approach. It addresses the dearth, insufficiency, and isolation of existing renovation tools by enhancing collaboration, interoperability, and data security, and avoiding information loss and misunderstanding. Employing the Unified Theory of Acceptance and Use of Technology (UTAUT) model, tests conducted with users from independent construction organisations confirmed the RRM's satisfactory performance, ease of deployment, and overall suitability for the management of renovation projects. While this research provides a free collaborative platform for managing renovation projects that can be used by all building retrofit stakeholders in Europe, it also introduces a set of web-services that can be easily reused by third-party developers and integrated into their software tools.*

KEYWORDS*: Renovation projects, multi-level planning, RINNO Retrofitting Manager, web-service technologies, distributed systems.*

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1. INTRODUCTION

Recent research shows that 77% of European residential buildings were built prior to 1990 (*EU Buildings Database*, 2016), 35% of buildings are over 50 years old (*EU Buildings Database*, 2016), 75% are energy-intensive and inefficient (*Energy Efficient Buildings*, 2022), yet up to 80% will still be in use by the year 2050 (Menna et al., 2022). Inefficient buildings negatively impact both humans and the environment (UN, 2021). It has been forecast that a renovation rate of at least 3% annually is required to accomplish the EU's energy efficiency and environmental objectives in a cost-effective way (European Commission, 2022). However, at current renovation rates, which range between 0.4 and 1.2% depending on the EU country, it would take more than 100 years to renovate all EU buildings (European Commission, 2022).

Several studies have attempted to identify the main barriers and constraints that hinder building renovation in Europe (D'Oca et al., 2018; Palm & Reindl, 2018). They highlight a lack of normalised and improved workflows, and practical software tools that facilitate renovation procedures (particularly true for retrofitting, when the space is shared between occupants and project teams) (Amorocho & Hartmann, 2021). Furthermore, issues such as occupant disruption to onsite productivity are frequently neglected (Designing Buildings, 2022). To address these issues and enable the acceleration of renovation works, Killip et al. (Killip et al., 2013) propose the consideration of three dimensions of innovation. First, innovative products or new technologies to enhance the performance of building components. Second, best practices which represent the most appropriate ways of achieving specific tasks and activities. Third, optimised processes that allow the renovation teams to plan, manage and execute efficiently the renovation tasks. In particular, project participants require dedicated tools and methods to communicate and collaborate to enhance the performance of their activities and better control renovation projects in terms of cost, time, safety and quality (Amorocho & Hartmann, 2021; Caixeta & Fabricio, 2013; Egbu, 1997; Egbu et al., 1998; Naaranoja & Uden, 2007; Swan & Brown, 2013). Although innovative products are very important for the success of a renovation project, they should not be the main focus to solve the problem (Killip et al., 2013). Moreover, most project participants use specific software tools that are fragmented, isolated, and cannot communicate with each other. Such software present significant obstacles to interoperability which lead to a limited use of digital platforms, especially for collaboration and coordination purposes (Lynn et al., 2021).

Technological advancements, such as web technologies have provided a new way of representing and exchanging data between interoperable and distributed systems, and so uncovered opportunities to streamline and improve information project management processes in the architecture, engineering, construction and facilities management (AEC-FM) industry (Schraw, 1998). Due to the nature of a renovation project as an information-intensive process involving many stakeholders and systems as well as applications, web-services present a real advantage to resolve the complex and multifaceted challenges faced. Web-service technologies have been used by several researchers to improve interoperability between digital tools and optimise information exchange processes (Borgo et al., 2015; Pauwels & Terkaj, 2016; Terkaj & Šojić, 2015); facilitate linking and synchronising information across various AEC-FM domains (Lima et al., 2005, 2012); and produce new information based on the knowledge explicitly gathered and represented (de Farias et al., 2016; Pauwels et al., 2011). However, none of the existing works have considered demonstrating the potential application of web-service technologies as a comprehensive framework to seamlessly structure and manage retrofitting processes in order to accelerate the rate and amount of renovation projects.

This paper presents the development of such an application - the RINNO Retrofitting Manager (RRM) platform – that has the long-term aim of accelerating the rate and amount of renovation projects and improving their effectiveness. The RRM platform has been conceptualised, designed, and implemented within the large European 'RINNO' research and development project that aims to optimise and accelerate building renovation in Europe (Doukari et al., 2021). The project has 19 partners from 10 different EU countries with dispersed multidisciplinary research teams working concurrently across Europe and includes work that focuses on innovative products and technologies as well as optimised project delivery. This last is the main purpose of the RRM platform; that is to streamline the onsite execution of the retrofitting process by implementing a practical Lean approach, while making data easily accessible through an integrated set of role-based user interfaces. The RRM is designed and implemented as an open distributed web-based retrofitting platform that helps optimise, execute, analyse, and monitor the renovation process as well as guide and train the workforce onsite. Ultimately, the proposed platform is expected to address the lack and isolation of renovation tools as well as enhance collaboration, interoperability, and data security, and avoid information loss and misunderstanding among renovation project stakeholders.

The remainder of the paper is structured into six main sections that follow this introduction. Section 2 summarises the research background, in terms of the prevailing problems, gaps, and consequent contributions. Section 3 presents the research approach adopted to design and develop the RRM platform. Section 4 explains the process of requirement capture and the requirements that emerged. Section 5 describes the development of the RRM platform, starting with a general overview, and then more detail on the RRM engine components, their main functionalities and the methodologies that enabled their development and integration. Section 6 presents the testing and evaluation of the RRM platform through its demonstration to representatives of independent construction organisations and discusses their evaluation. Finally, conclusions and perspectives, including future extensions of the proposed framework, are given in Section 7.

2. RESEARCH BACKGROUND

2.1 Lean planning

Enhancing productivity and accelerating project delivery have always been the main motivation for research in the construction project management domain (Dixit et al., 2019). The scheduling of renovation works represents an important part of the management of the retrofitting process. It determines the sequence of work, facilitates the allocation of resources to project activities over time, and so ensures the completion of the project on time and within budget (Conlin & Retik, 1997). Hence, it plays a central role in a renovation project's success (Doukari et al., 2022). Moreover, planning and scheduling deficiencies have been identified as main causes that can lead to project delays and cost overruns (Flyvbjerg, 2014) and ultimately to claims and disputes (Aravindhan et al., 2021).

Several conventional planning and scheduling methods are identified in the literature review (Doukari et al., 2022). They are 8 classes, including (i) the Critical Path method, (ii) the Line-of-Balance method, (iii) the Program Evaluation and Review Technique (PERT), (iv) simulation methods, (v) Artificial Intelligence (AI)-based methods, (vi) visualisation methods, (vii) Critical Chain scheduling, and (viii) location-based scheduling. The previous methods have shown more than 50% average plan failure in terms of project productivity and delays (G. Ballard & Howell, 1998). Therefore, Lean methodology has been adopted in construction by applying the Toyota Production System (Adamu et al., 2012; Alarcón et al., 2002; Alsehaimi et al., 2009; Babalola et al., 2019; H. G. Ballard, 2000; Howell, 1999; Murguia et al., 2016; Womack et al., 2007). The aim of Lean-based planning methods is to continuously improve the added value of the construction tasks with the goal of enhancing the overall profitability of the project. The principle of continuous improvement is crucial in Lean which is usually implemented using a four-step process 'Plan-Do-Check-Act' known as Kaizen model. The essence of Kaizen is to divide the manufacturing process into small and continuous positive changes, which are easy to implement and less costly, so as to achieve significant improvements.

The integration of Lean philosophy in construction is beneficial for the optimisation and management of production processes, and has shown significant benefits to efficiently: managing waste; reducing consumption of resources, water and energy; reducing times and costs; and improving quality (Carvajal-Arango et al., 2019; Du et al., 2023). Research has explored the integration of Lean principles in construction, resulting in various frameworks and applications such as the transformation, flow and value theory (Koskela, 1992, 2000), multi-process construction applications (Babalola et al., 2019), sustainable development (Carvajal-Arango et al., 2019), and integration with Building Information Modelling (BIM) technologies (Saieg et al., 2018; Schimanski et al., 2021). Furthermore, nine Lean planning techniques have been identified in the construction industry (Babalola et al., 2019), and the Last Planner System© (LPS) is one of the most used and implemented Lean techniques in construction (Heigermoser et al., 2019). The LPS implements a collaborative planning process enabling incorrect planning analysis and update. It focuses on short-term project planning at crew level while integrating a multi-level planning approach that includes 'Baseline', 'Look-ahead', and 'Commitment' schedules. The Baseline schedule represents the project long-term planning. It is defined by the upstream management systems and adjusted as needed to specify what should be done. The Look-ahead schedule aims at making long-term project schedule more realistic by decomposing and detailing construction activities from Baseline level to operations level. It is used to identify constraints, allocate resources and prepare information, and communicate workflow processes (Heigermoser et al., 2019). The Commitment schedule, which is defined at a weekly basis, indicates the most detailed construction tasks that will be done, and the interdependences between the project participants.

2.2 Service-Oriented Computing

The advent of digitisation in the construction industry through BIM, Digital Twin and Artificial Intelligence (AI) has dramatically increased the quality, quantity, and usability of project data. A wide variety of technologies can leverage these data to provide novel solutions and perform traditional tasks more innovatively. A prominent example is Service-Oriented Computing (SOC), where computational units, named web-services, provide functionalities to other applications remotely across the network by using standard Internet technology, such as Simple Mail Transfer Protocol (SMTP), Hypertext Transfer Protocol (HTTP), and File Transfer Protocol (FTP) (Papazoglou, 2003). A web-service can be defined as an autonomous, interoperable and adaptive building block that satisfies three fundamental properties: accessibility through a common technology, loose coupling with its 'client', and discoverability on the network (Mezni, 2023). Web-service functionalities range from simply granting access to stored data, to executing complex processes and analyses so that valuable information can be produced. In addition, web-services can be interconnected, manually or automatically (Sheng et al., 2014) to integrate different sources of information as well as to automate and compose complex workflows and processes, while clients (humans or applications) still believe they are dealing with a single service.

The three types of web-services commonly referred to in the literature are SOAP, RESTFUL, and Event-Oriented services. SOAP services use Simple Object Access Protocol (SOAP) and are described using Web-Service Description Language (WSDL) (Huf & Siqueira, 2019). RESTFUL services are built over HTTP protocol, Uniform Resource Identifiers (URI) and JSON (JavaScript Object Notation) format. They must comply with the Representational State Transfer (REST) system architecture requirements (Fielding & Taylor, 2002). Finally, Event-Oriented services are capable of delivering events representing state changes or relevant facts (Eugster et al., 2003).

Distributed applications and systems relying on web-service technologies provide significant advantages over monolithic architectures and desktop-based applications (Bietz et al., 2017; van Steen & Tanenbaum, 2016). These include better scalability, decoupling of components, and in particular easier development, testing, deployment, and maintenance (van Steen & Tanenbaum, 2016). Two communicating web-services can be provided by different service providers, implemented in different languages and with different system specifications, and distributed over different geographic locations (Sadeghiram et al., 2023). Being independent (thus avoiding installation issues) they are capable of storing and providing access to large amounts of data and automated processes by responding to multiple client requests through easy-to-use interfaces. Therefore, they ensure high levels of interoperability among software systems, flexibility, higher usability and reusability of services, and a more intuitive application behaviour (Bietz et al., 2017; Nacer & Aissani, 2014). Such technologies have been used to develop a variety of system architectures, whose objectives have included: detecting abnormal energy consumptions in residential buildings (Meléndez et al., 2018); industrial image recognition using SOC and the Business Process Execution Language (BPEL) (Rudorfer & Krüger, 2018); building surroundings analysis in early planning and design phase (Li et al., 2019); and efficient urban water management for storm events providing real-time computing functionalities, including hydrological and hydraulic status information (Zeng et al., 2021). Studies that investigated the various benefits of using web-services in construction have included: (i) improving interoperability between digital tools and optimising information exchange processes (Borgo et al., 2015; Pauwels & Terkaj, 2016; Terkaj & Šojić, 2015); (ii) linking and synchronising information across various AEC-FM domains (Lima et al., 2005, 2012); and (iii) producing new information and data based on explicit representations of knowledge (de Farias et al., 2016; Pauwels et al., 2011).

2.3 Research gaps and contribution

To meet the EU's energy efficiency and environmental objectives, the annual renovation rate requires to at least double from its current level. Therefore, project participants need to efficiently communicate and collaborate in order to synchronise and enhance the performance of their activities and better control the cost, time, safety and quality of renovation projects (Amorocho & Hartmann, 2021; Caixeta & Fabricio, 2013; Egbu, 1997; Egbu et al., 1998; Naaranoja & Uden, 2007; Swan & Brown, 2013). However, investigation of the area of construction informatics has revealed a lack of collaborative platforms that can assist, coordinate, train and provide feedback to the project participants during the construction phase (Assaad et al., 2022). In the context of renovation projects, the situation is even more challenging and these tools are usually tailored to new-build projects rather than to renovation (Amorocho & Hartmann, 2021; Doukari et al., 2022). When compared to new-build, renovation projects present additional challenges that include disruption to and by occupants, greater time and cost overruns, increased health and safety hazards, and often inferior quality (Doukari et al., 2024). Although supportive software tools have been developed and used, the lack of interoperability between them can result in inefficient management of information exchange and financial losses (Araszkiewicz, 2017). Furthermore, even when they exist, these tools are usually isolated and cannot communicate with each other as they use proprietary file formats that cannot be directly processed outside these tools. Such specific software present significant obstacles to collaboration and interoperability because data represented needs to be converted into other supportable file formats, which usually leads to information loss, misunderstanding, and additional works and delays.

This points out a clear research gap which is the necessity to investigate how building renovation can move beyond its high dependency on fragmented and isolated eco-system of tools and non-standardised file formats, to smoothly adopt an extensible, interoperable, and integrated service-oriented system which is capable of connecting designers, logistic planners, onsite workers, and project owner through an all-in-one platform. Previous studies have not fully exploited advanced technologies, such as web-services and distributed systems, to develop a coordination and collaboration platform that is extensible as well as able to benefit and integrate the current isolated software, and so overcome the complex nature of planning and delivering retrofitting works.

The contribution of this paper is twofold: (i) design, implement and test the RRM platform as an open distributed system that connects and integrates seven web-services deployed across three EU countries: France, Greece, and the UK; and (ii) implement a practical Lean-based multi-level planning approach, through the LPS, into the RRM to overcome the gap that usually exists between long-term and short-term project schedules, and enable the delivery of retrofitting works on time, on budget, and with agreed quality.

In essence, the RRM platform aims at improving renovation project performance by accelerating delivery and increasing building retrofit productivity. It does so by: (i) enhancing collaboration between stakeholders through user-friendly interfaces that facilitate the engagement of the professionals involved; (ii) centralising and securing project data, thereby streamline existing retrofitting processes to accelerate the delivery of renovation works; and (iii) improving interoperability between previously fragmented software tools, leading to project cost reduction.

3. RESEARCH METHODOLOGY

The RRM framework is part of the large European ‘RINNO’ research project to optimise and accelerate building renovation in Europe; the objective of this part of the project being to develop an automated process to enhance coordination, collaboration, monitoring, and training in renovation projects through an integrated web-based platform. The nature of the project and the multiplicity of research teams involved prompted the adoption of a Design Science Research (DSR) methodology which was based on the following five-stage process proposed in (Peffers et al., 2007). Subsequent sections of this paper correspond to each DSR stage (with a brief explanation and the section title) as follows:

- Stage 1 – *Problem identification and motivation* : collaborative meetings and workshops with partners to understand the problems (Section 4: ‘Problem identification and definition of objectives’).
- Stage 2 – *Definition of objectives*: collaborative definition of design requirements and high level functionalities and services to solve the problem (Section 4: ‘Problem identification and definition of objectives’).
- Stage 3 – *Design and development*: concurrent design, construction, and integration of RRM platform services and components in a functional version (Section 5: ‘Design and development of the RRM platform’).
- Stage 4 – *Demonstration and evaluation*: workshop evaluation and week-long testing of the resulting integrated system including collection of feedback (Section 6: ‘Demonstration and evaluation of the RRM platform’).
- Stage 5 – *Communication*: highlighting key results, contribution, limitations, and opportunities for future studies (Section 7: ‘Conclusion and perspectives’).

4. PROBLEM IDENTIFICATION AND DEFINITION OF OBJECTIVES

Discussions during the formulation of the RINNO research proposal confirmed the problems associated with the planning and control of retrofit projects. Post-award, in the first 6 months of the project, detailed consideration was given to this in workshops forming part of the work package: *Elicitation of Stakeholder Requirements & Market Needs*. The RRM platform was targeted at facilitating streamlined, collaborative, multi-level planning, onsite execution, and control of the retrofitting process, and set of high-level ‘core requirements’ (C1 - C6) was defined for the platform. These are shown in Table 1. A definition is provided alongside each, together with an anticipated *Technology enabler,* such as Open Application Programming Interfaces (Open API) (Rauf et al., 2019).

Table 1: Core requirements of the RRM platform.

		Definition	**Technology enabler**
Core requirements	**C1:** Extensibility	Easily extended without significant modifications to its core architecture.	SOC + Open API
	C2: Portability	Easily adapted or run on different hardware platforms or operating systems.	SOC + Open API
	C3: Maintainability	Effectively and efficiently maintained and updated over its lifecycle.	Distributed System
	C4: Scalability	Ability to handle increasing workloads, users, or data without a significant decrease in performance.	Distributed System
	C5: Interoperability	Seamless communication and data exchange with different software systems, applications, or components, including heterogeneous or diverse computing environments.	Open API + JSON format
	C6: 'Streamlinability'	Streamlined flow of retrofitting works with collaborative and multi-level planning.	LPS (Lean)

From these high-level requirements, specific functional requirements for the RRM platform were derived (Table 2). Alongside each of the seven requirements (P1 - P7) is shown the *Service type* (function descriptor) and *Service origin* (i.e., whether a service was novel, existing within partners' resources, or available from an external third-party).

Table 2: Functional requirements of the RRM platform.

		Service type	**Service origin**
Functional requirements of the complete RRM platform	**P1:** Provide single-system view	RRM engine	New service
	P2: Provide role-based access	Authentication	New service
	P3: Provide offsite/onsite recommendations	Offsite/Onsite	Adapt existing tool (Attouri et al., 2022)
	P4: Provide an optimised project schedule	Logistics	New service
	P5: Provide scenario-based training & support	AR/VR Environment	New service
	P6: Provide relevant project KPIs regularly	Monitoring: project 'Cockpit'	New service
	P7: Enable communication, coordination, and collaboration between project teams	Slack platform	Integrate third-party service (Slack, 2023)

Further workshops were held to elicit requirements of the new services (i.e., those not currently available). In the case of the *Monitoring component* (P6 in Table 2) for example, workshops were held with onsite construction workers, project and site managers and engineers to identify the most relevant information needed for regular reporting. For two days, fourteen participants from a large French construction company contributed to 'user stories' of needs and requirements in terms of onsite information and progress notification. This input was categorised into different dimensions (safety, quality, cost, scheduling, environmental, and services & benefits) to facilitate identification of KPIs and their monitoring.

Digital mock-ups of the KPIs were then developed for validation by site managers and workers as well as in workshops with construction company teams. Participant feedback was used in producing the finished component (see Section 5.5). As shown above, the requirement for the single-system view (P1) entailed the development of an *RRM engine*, designed to offer access to the entire RRM platform and whose functional requirements were elicited (Table 3).

Table 3: Components and detailed functionalities of the RRM engine only (requirement P1 in Table 2).

	Component	**Detailed functionalities**
Components and detailed functionalities of the RRM engine	Authentication	**F1:** Integrate the remote Authentication service. **F2:** Connect to the Slack service, send notifications, and enable coordination among project stakeholders *[This is required for all the RRM engine's components].*
	Offsite/Onsite	**F3:** Enable collecting users' needs and requirements regarding offsite/onsite choice. **F4:** Send data to and get recommendations from the remote service.
	Optimisation	**F5:** Enable collecting data related to construction materials, equipment, workers, zones, activities, and constraints. **F6:** Send data to and get optimised schedule from the Logistics service.
	Planning	**F7:** Display and enable validating the optimised schedule calculated. **F8:** Send the optimised schedule to both the AR/VR Environment and Cockpit services.
	Training & Support	**F9:** Load & display relevant training & support contents from AR/VR Environment service.
	Monitoring	**F10:** Connect to the Cockpit service & collect safety, quality, cost, schedule, & waste KPIs. **F11:** Store and display KPI values in the BIM model.

5. DESIGN AND DEVELOPMENT OF THE RRM PLATFORM

RRM is designed as an integrated platform that enables the orchestration and monitoring of information flows across all stages of the building renovation works. Its architecture, illustrated in Figure 1, shows seven retrofitting services enabling: (i) role-based Authentication; (ii) Offsite/Onsite recommendations; (iii) process optimisation and planning through the Logistics service; (iv) training and support via the AR/VR Environment service; (v) process monitoring using the Cockpit service; (vi) collaboration and communication between the project participants by integrating the Slack platform as a third-party service (Slack, 2023) which is a free real-time messaging service; and finally (vii) the RRM engine which implements a set of components including API to enable interconnection and data exchange with the remote web-services.

The RRM services were designed and developed collaboratively with RINNO partners and deployed as a distributed system on servers across different EU countries. The RRM platform functionalities, described in Section 4 (and Tables 1-3) enable sequenced and coordinated communication and information exchange between the project participants using the RRM services. The platform development was geared towards a Lean-based multi-level planning approach that involves producing long-term ('Baseline'), medium-term ('Look-ahead') and, ultimately, short-term, constraint-free ('Commitment') schedules. The process starts by recommending an offsite or onsite strategy for the work and ends by notifying stakeholders and displaying valuable information through several Key Performance Indicator (KPI) dimensions.

The first level consists of the retrofitting 'Scenario' which represents a project-level ('Baseline') plan as received and parsed from the Planning & Design phase. The second, 'Look-ahead' level, represents further enrichment of the renovation activities with assigned spaces, material types and logistics as well as the number and types of workers required to execute the tasks. The last level, 'Commitment' planning, identifies retrofitting work quantities that are manageable at crew level, validated and monitored at a weekly basis by the Cockpit service. The main advantage of adopting Lean methodology is the ability to consider the needs and constraints of each project actor by promoting and encouraging collaboration before tasks are executed. Furthermore, this integrated architecture enables the connection with downstream management systems, based on commitment plans that are executed on a weekly and daily basis, as well as with upstream management systems and higher-level planning. This should ensure a better consistency, quality, and transparency of the whole retrofitting process.

The RRM engine, which provides the main gate to the RRM platform, is implemented using React (React, 2022), a free and open-source JavaScript library, to develop the front-end, and C# programming language for the back-end. A free beta version of the RRM platform can be tested at (Doukari, 2023).

It is important to note that in the remainder of this paper, and as illustrated in Figure 1, the term ‘component’ is exclusively used to describe the inherent components of the RRM engine, while the term ‘service’ is reserved for those automatic processes, tools and platforms that are remote yet connected via API to the RRM engine. Only the development of the RRM engine and its components will be detailed in this article: the presentation, description, and testing of the RRM remote services are outside its scope.

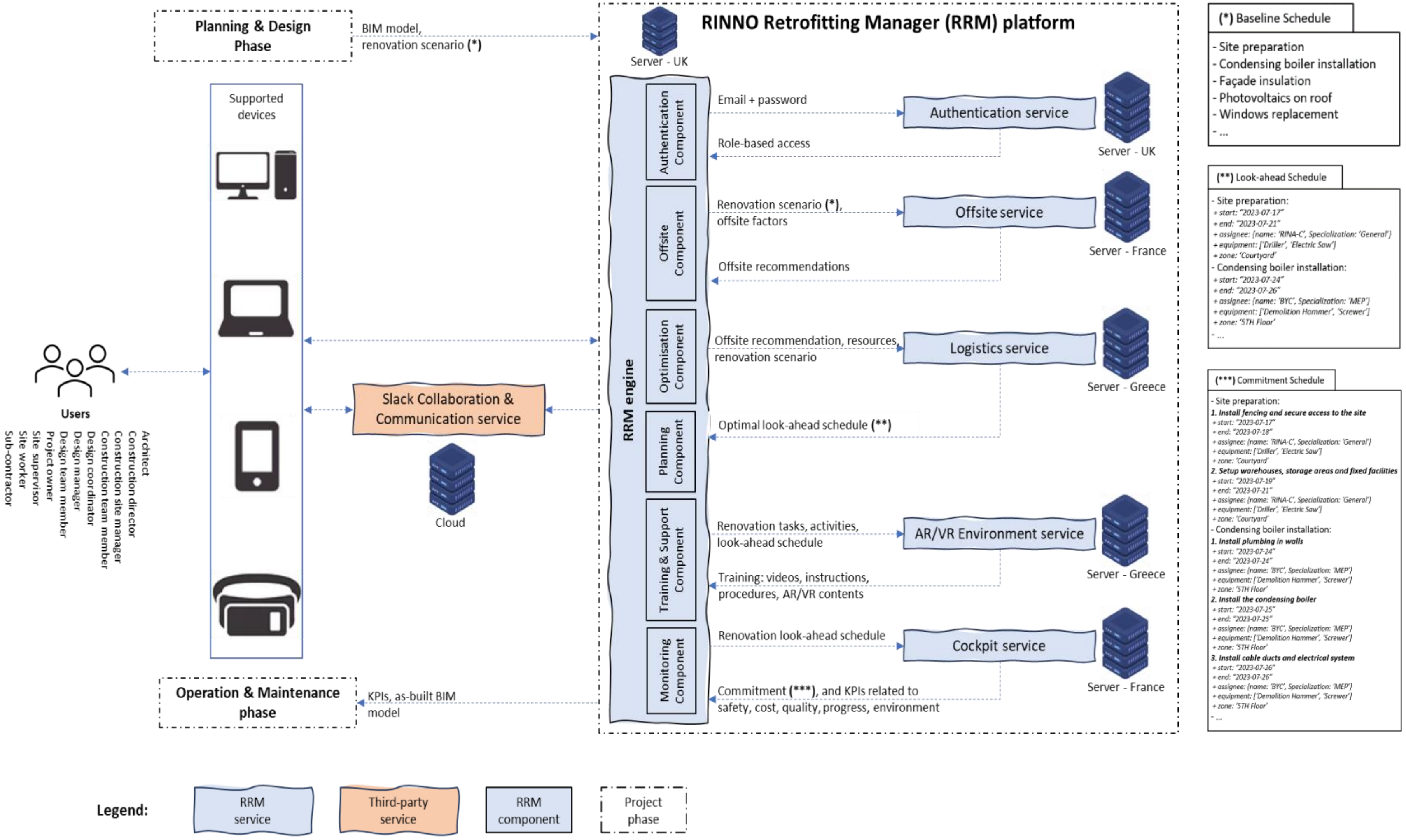
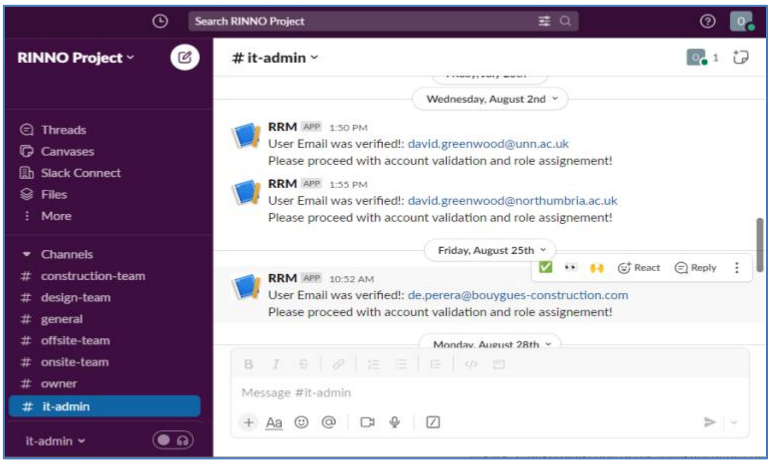


Figure 1: System architecture of the RINNO Retrofitting Manager (RRM).

5.1 Authentication component

To make data accessible to all project stakeholders while avoiding information losses and accidental data removal, the RRM platform integrates an *Authentication component* which provides role-based authorisation for access to the RRM platform, and for input and retrieval of data relevant to each stakeholder. The role-based connection allocates responsibility for data protection compliance and ensures that the designated stakeholder has the required right to view and update project data. For instance, the construction director's access and rights on the RRM platform are not the same as those of the project owner or site workers. The *Authentication component* is based on password verification. To simplify access to the RRM and its functionalities, the *Authentication component* adopts open industry standards, such as OAuth 2.0, OIDC, and SAML, so that the user can log into the RRM with different credentials, such as social media, Gmail, and corporate accounts.



RRM APP 1:50 PM
User Email was verified!: david.greenwood@unn.ac.uk
Please proceed with account validation and role assignement!

RRM APP 1:55 PM
User Email was verified!: david.greenwood@northumbria.ac.uk
Please proceed with account validation and role assignement!

RRM APP 10:52 AM
User Email was verified!: de.perera@bouygues-construction.com
Please proceed with account validation and role assignement!

Figure 2: Interconnection of the Authentication component with the Slack platform.

Table 4: The RRM platform user roles.

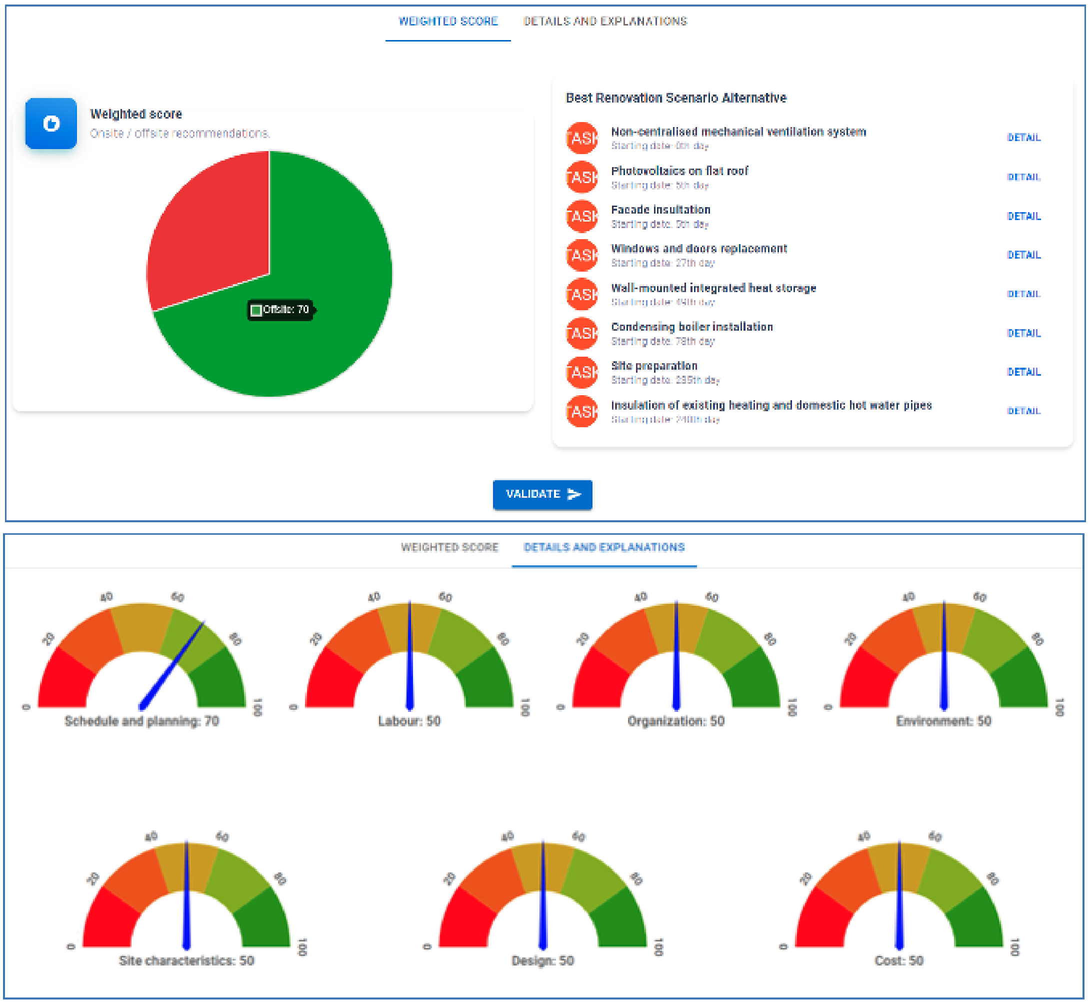
	User role										
Service	Architect	Construction director	Construction site manager	Construction team member	Design coordinator	Design manager	Design team member	Project owner	Site supervisor	Site worker	Sub-contractor
Authentication	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Offsite/Onsite	✓	✓			✓	✓	✓	✓			
Logistics		✓				✓					
AR/VR Environment		✓	✓	✓	✓	✓			✓	✓	✓
Cockpit		✓	✓	✓		✓			✓		
Slack platform	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
RRM engine	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

To access and use the RRM platform, a project participant signs up through the *Authentication component* by submitting their email and password. A verification email is automatically sent to check the correctness of the information provided. The new account however will be pending, and access will not be granted until the RRM platform administrator validates the account and assigns a relevant role to the new user. Once this is done, the new user can sign in to the RRM platform and use its services with respect to the role assigned to them. The RRM platform recognises 11 user roles and profiles with different access rights that have been identified through workshops with the RINNO industrial partners (Table 4).

Furthermore, as illustrated in Figure 2, the *Authentication component* is interconnected to the *Slack platform* [49] to enable instant notifications to be sent to the RRM administrator to validate account creation requests and authorize access.

5.2 Offsite/Onsite component

To recommend the best retrofitting strategy and enable deciding between onsite- and offsite-based renovation, the RRM platform implements the *Offsite/Onsite component*. It consists of an adapted version of an existing decision-making tool that had been developed for the construction of new buildings (Attouri et al., 2022). Through a set of factors, constraints and needs entered by the user (Figure 3), the RRM platform queries the *Offsite/Onsite service* to run the decision-making process and then proposes the optimum renovation strategy to be adopted (Figure 4). The decision criteria were based on seven primary factors (labour, design, site characteristics, organisation, environment, and cost) from which seventy-three secondary factors were derived. The decision-making process for selecting the appropriate mode of renovation (onsite or offsite) is based on the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method for solving multi-criteria problems (Doukari et al., 2023). The result is then sent to the *Optimisation component* to be integrated and treated as an optional or mandatory project constraint for optimising the retrofitting process and generating the optimal look-ahead renovation schedule.



Best Renovation Scenario Alternative

Non-centralised mechanical ventilation system
Starting date: 0th day
DETAIL

Photovoltaics on flat roof
Starting date: 5th day
DETAIL

Facade insultation
Starting date: 5th day
DETAIL

Windows and doors replacement
Starting date: 27th day
DETAIL

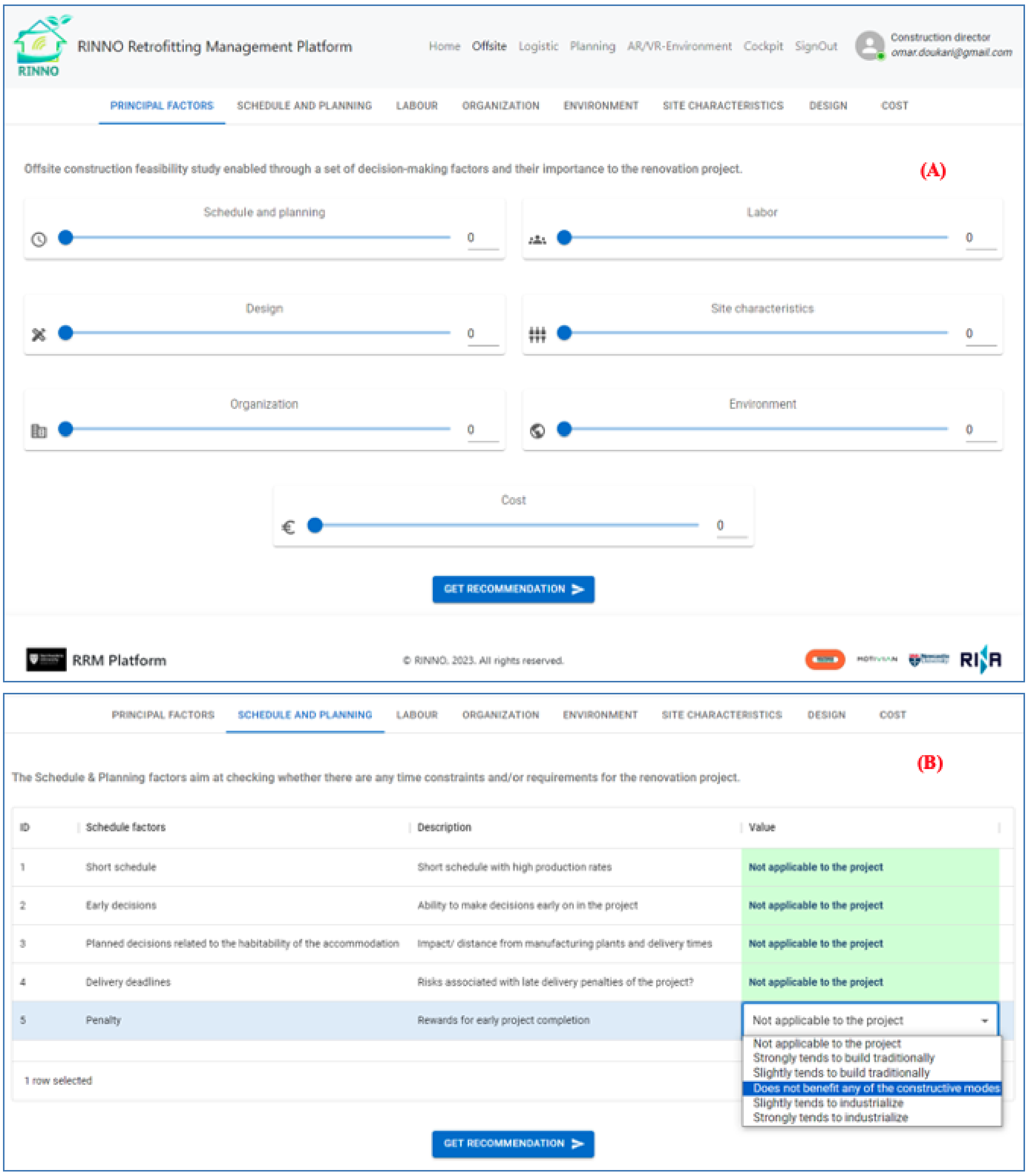
Wall-mounted integrated heat storage
Starting date: 49th day
DETAIL

Condensing boiler installation
Starting date: 78th day
DETAIL

Site preparation
Starting date: 235th day
DETAIL

Insulation of existing heating and domestic hot water pipes
Starting date: 240th day
DETAIL

Figure 4: Offsite recommendation results displayed on the RRM platform.



Offsite construction feasibility study enabled through a set of decision-making factors and their importance to the renovation project.

The Schedule & Planning factors aim at checking whether there are any time constraints and/or requirements for the renovation project.

ID	Schedule factors	Description	Value
1	Short schedule	Short schedule with high production rates	Not applicable to the project
2	Early decisions	Ability to make decisions early on in the project	Not applicable to the project
3	Planned decisions related to the habitability of the accommodation	Impact/ distance from manufacturing plants and delivery times	Not applicable to the project
4	Delivery deadlines	Risks associated with late delivery penalties of the project?	Not applicable to the project
5	Penalty	Rewards for early project completion	Not applicable to the project

Figure 3: Offsite component GUIs to collect (A) primary and (B) secondary factors.

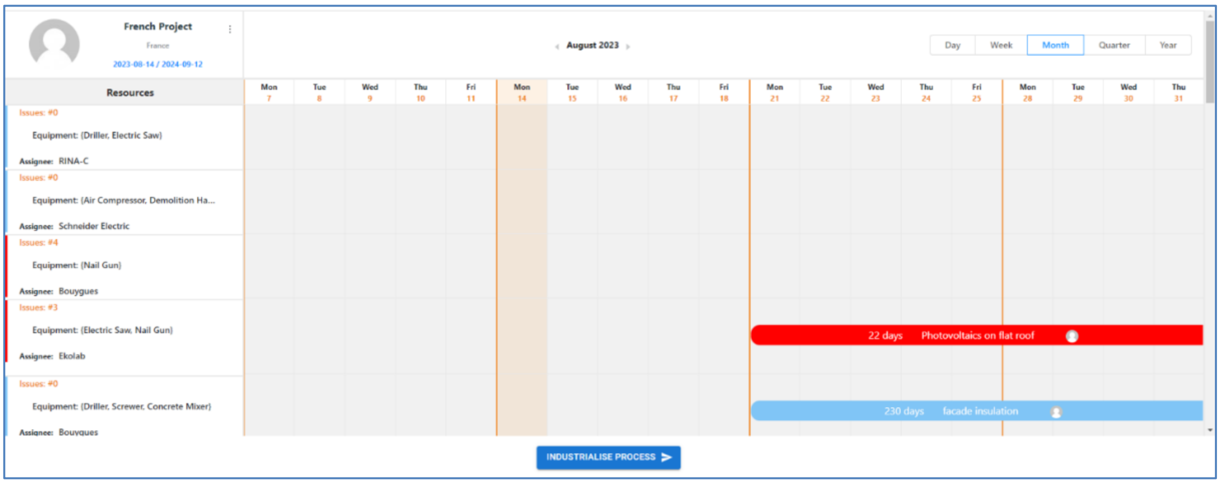
5.3 Optimisation and Planning components

Retrofitting process optimisation depends on analysis and concurrent satisfaction of different project objectives and parameters, such as duration, cost, resource, and space. In the construction industry, four classes of optimisation have been identified to solve the Resource-Constrained Project Scheduling Problem (RCPSP) (Liu & Wang, 2008), namely: (i) mathematical models (Pierott et al., 2021); (ii) heuristics (Averbakh & Pereira, 2021); (iii) evolutionary algorithms (Jaśkowski & Sobotka, 2006); and (iv) hybrid approaches (Rogalska et al., 2008). The optimisation method adopted by the RRM platform is based on the bio-inspired Particle Swarm Optimisation (PSO) algorithm (Sahib & Hussein, 2019). This algorithm integrates very few hyperparameters to search and identify an optimal solution while only the objective function is required, which makes it easy to implement and use.

The *Optimisation component* ensures the gathering of all project information that is required to optimise onsite organisation and sequence of works. This information includes data relating to materials, equipment, workers, zones, activities, and project constraints; such constraints include duration, cost, and the recommended renovation strategy (i.e., onsite or offsite approach) taken from the output of the *Offsite/Onsite component* (Figure 5).

Information related to materials, equipment and workers is automatically extracted from the RRM platform database and reflects the state of these resources and their availability. However, the information related to renovation zones, activities and constraints is extracted from the *Renovation Scenario* identified during the Planning & Design phase.

The RRM platform implements the twenty standard renovation activities (Doukari et al., 2023) proposed and adopted by the RINNO Planning & Design (RPD) toolbox (Sougkakis et al., 2023). The *Optimisation component* calculates the optimal retrofitting schedule by sending required data to the PSO algorithm implemented through the *Logistics service*. To clearly visualise the optimised schedule calculated by the PSO algorithm, the *Planning component* is implemented (Figure 6). Four different scales of planning (daily, weekly, monthly, and yearly) are developed and enabled by the *Planning component*. By hovering over the scheduled tasks, more details can be shown in pop-up windows, such as the project actor in charge of the task. The issues encountered are displayed along with some related details, such as number of occurrences, equipment in question and assignees to resolve the issue. As a complete planning management tool, the *Planning component* can be used to check, validate and if necessary, amend the look-ahead renovation schedule before being sent for execution to the *Cockpit service*. Moreover, it plays the role of interface between the RRM platform and both the *AR/VR Environment* and the *Cockpit service*. Once validated by the user, the retrofitting look-ahead schedule is sent to the *AR/VR Environment service* to identify task execution requirements and extract relevant individualised training and support procedures for the workforce. The relationship with the *Cockpit service* helps further detail and break-down the retrofitting look-ahead schedule into commitment schedules to be executed on a weekly and daily basis, facilitating the monitoring of retrofitting works using KPIs in the *Monitoring component*.



French Project
France
2023-08-14 / 2024-09-12

Issues: #0
Equipment: (Driller, Electric Saw)
Assignee: RINA-C

Issues: #0
Equipment: (Air Compressor, Demolition Ha...
Assignee: Schneider Electric

Issues: #4
Equipment: (Nail Gun)
Assignee: Bouygues

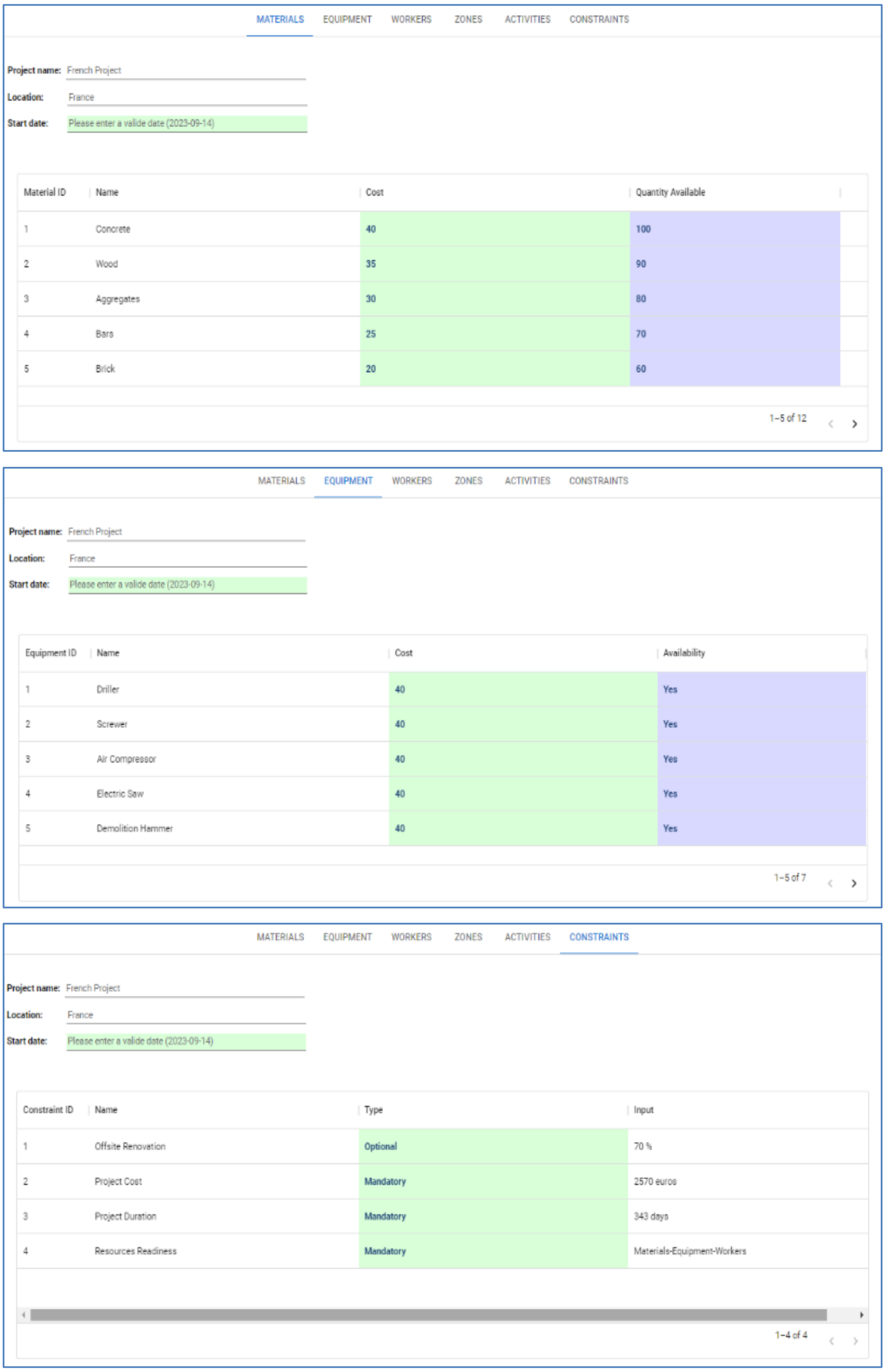
Issues: #3
Equipment: (Electric Saw, Nail Gun)
Assignee: Ekolab

Issues: #0
Equipment: (Driller, Screwer, Concrete Mixer)
Assignee: Bouygues

22 days Photovoltaics on flat roof

230 days facade insulation

Figure 6: Optimised schedule displayed on the Planning component.



Project name: French Project
Location: France
Start date: Please enter a valide date (2023-09-14)

Material ID	Name	Cost	Quantity Available
1	Concrete	40	100
2	Wood	35	90
3	Aggregates	30	80
4	Bars	25	70
5	Brick	20	60

1–5 of 12

Project name: French Project
Location: France
Start date: Please enter a valide date (2023-09-14)

Equipment ID	Name	Cost	Availability
1	Driller	40	Yes
2	Screwer	40	Yes
3	Air Compressor	40	Yes
4	Electric Saw	40	Yes
5	Demolition Hammer	40	Yes

1–5 of 7

Project name: French Project
Location: France
Start date: Please enter a valide date (2023-09-14)

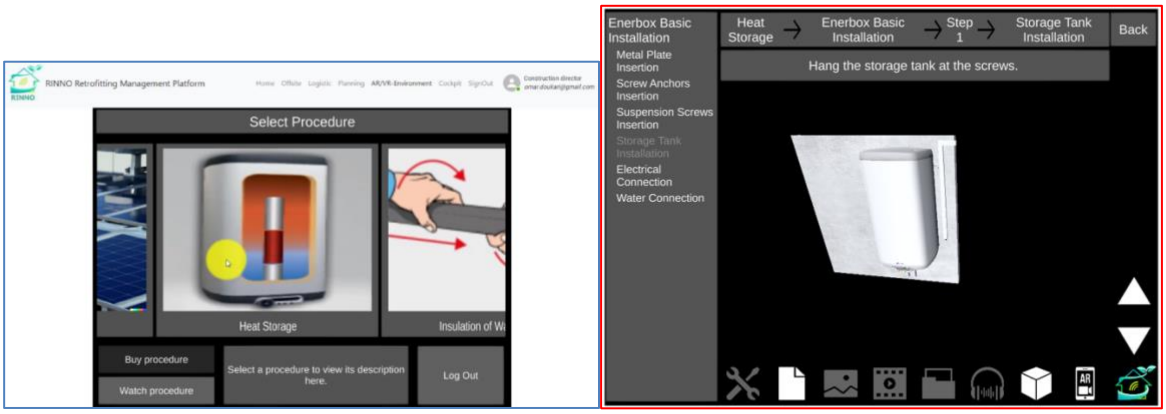
Constraint ID	Name	Type	Input
1	Offsite Renovation	Optional	70 %
2	Project Cost	Mandatory	2570 euros
3	Project Duration	Mandatory	343 days
4	Resources Readiness	Mandatory	Materials-Equipment-Workers

1–4 of 4

Figure 5: Optimisation component GUI to collect project data relating to (A) materials, (B) equipment, and (C) constraints.

5.4 Training & Support component

Since visual, virtual, and augmented representations are important for effective communication, training, and assistance in achieving retrofitting tasks and plans, the *Training & Support component* is developed to be an integral part of the RRM platform. It aims at providing multi-format contents to train and assist the workforce while they are conducting retrofitting tasks, including AR, VR, textual instructions and procedures, images, and interactive 3D videos and digital models. This support can be accessed before carrying out the planned works and delivered offsite as a set of role-based training programmes, or onsite through AR/VR-based instructions and interactive videos to assist in executing the planed retrofitting works. The *Training & Support component* is implemented in such a way to facilitate interaction with the *AR/VR Environment service* and grant a friendly and easy access to its content for project participants. Individual training contents are created and mapped to the twenty renovation activities already identified. This enables a scenario-dependant training and support contents selection which complements the role-based authentication functionality to implement a fully adaptive training and support environment. An example of the output is shown in Figure 7.



Select a procedure to view its description here.

Hang the storage tank at the screws.

Figure 7: Training & Support component: (A) main interface with all contents retrieved, and (B) 'Heat Storage' procedure selected.

5.5 Monitoring component

The *Monitoring component* enables monitoring of the retrofitting progress and the provision of feedback to 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. The elicitation of requirements and their development into appropriate KPIs was described earlier in Section 4. The results are shown in Table 5. Development of the *Monitoring component* was completed by integrating the BIM model received from the Planning & Design phase (Figure 8) and providing a set of friendly Graphical User Interfaces (GUIs) using React, CSS and HTML technologies (Figure 9). Particularly, Forge API and MUI library are used to ensure simplicity, clarity, and responsiveness of the UI components, 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.

Table 5: The RRM platform KPIs.

Dimension	Description	Calculation	Representation
Quality	1- Nr of quality incidents 2- Monitoring the quality controls 3- Nr of customer complaints 4- Identification/alerts on recurring quality issues	1- Nr of opened quality incident forms 2- Quality controls to be done in the next 10 days 3- Nr 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 & closing issues	7- Line chart 8- Pie chart 9- Line chart
Safety	10- Identification/alerts on recurring safety issues 11- Nr of safety incidents 12- Monitoring safety incidents control	10- The 5 most recurrent safety issues 11- Nr of safety issues 12- Stakeholders involved in safety issues	10- List 11- Line chart 12- List
Environment	13- Monitoring waste	13- Nr of recorded waste containers	13- Line chart

Figure 9: The RRM platform KPIs' dashboard for (A) Quality (B) Cost (C) Scheduling (D) Safety (E) Environment.

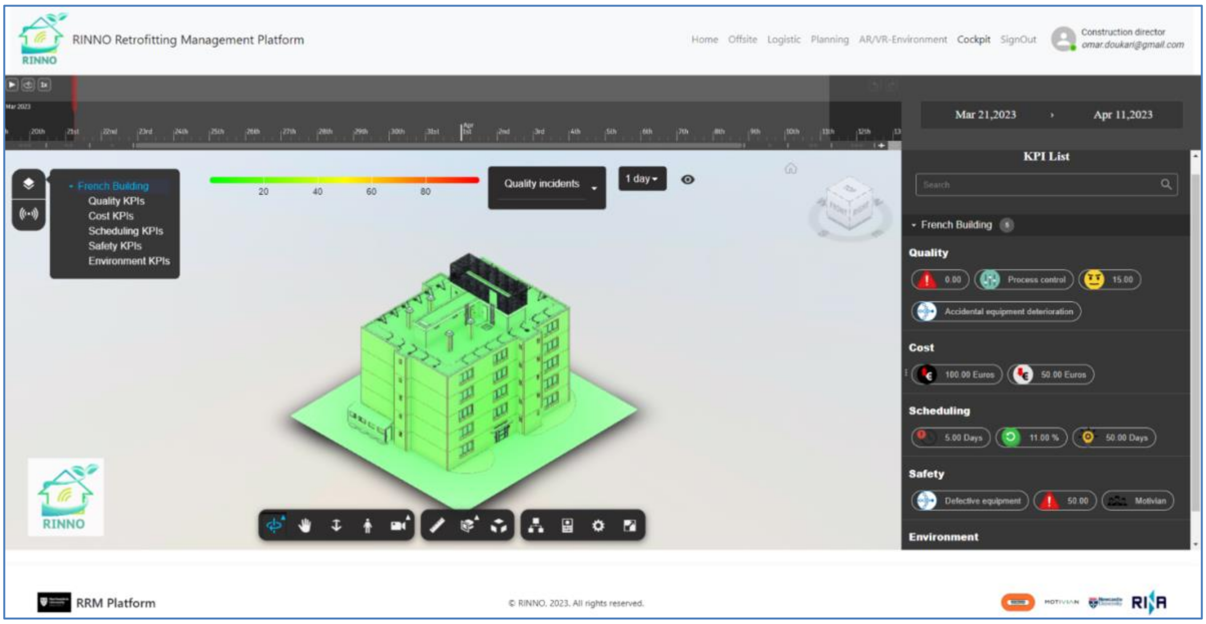
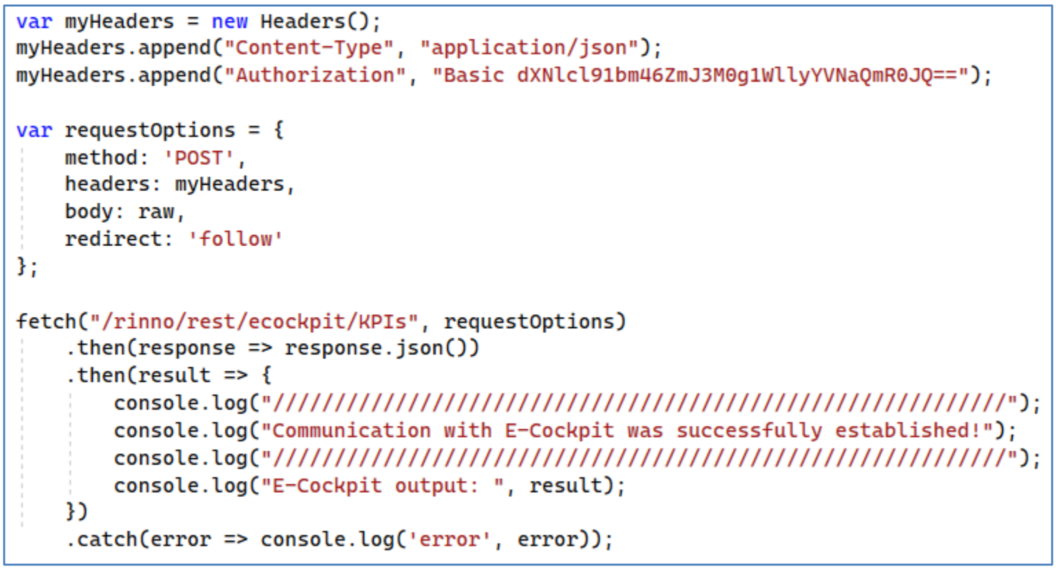


Figure 8: The Monitoring component integrating the French BIM model.

5.6 Integration

The RRM engine integrates all six components, namely: *Authentication*, *Offsite/Onsite*, *Optimisation*, *Planning*, *Training & Support*, and *Monitoring components*, through friendly, responsive, and color-coded GUIs (Doukari, 2023). It also enables linking these local components to six remote services in order to process input data and coordinate and streamline the execution of onsite retrofitting processes. The integration and interconnection of the RRM components and services particularly allows managing GET and POST requests (Figure 10) as well as regular data retrieval through a loose coupling using REST API. Information exchange between the RRM components and remote services is enabled using JSON format, which is language agnostic, human- and machine-readable.

To do so, JSON templates were created to get and store information into the RRM platform database. For instance, the following schema, in Figure 11, shows how quality KPIs data are structured so as to be received and parsed by the *Monitoring component*.



```
var myHeaders = new Headers();
myHeaders.append("Content-Type", "application/json");
myHeaders.append("Authorization", "Basic dXNlcl91bm46ZmJ3M0g1WllyYVNaQmR0JQ==");

var requestOptions = {
    method: 'POST',
    headers: myHeaders,
    body: raw,
    redirect: 'follow'
};

fetch("/rinno/rest/ecockpit/KPIs", requestOptions)
    .then(response => response.json())
    .then(result => {
        console.log("//////////////////////////////////////////////////////////////////");
        console.log("Communication with E-Cockpit was successfully established!");
        console.log("//////////////////////////////////////////////////////////////////");
        console.log("E-Cockpit output: ", result);
    })
    .catch(error => console.log('error', error));
```

Figure 10: POST request enabling communication and data exchange with the Cockpit service.

```
{
  "projectId": "project_id_integer",
  "projectName": "project_name_string",
  "qualityKPIInfo": [
    {
      "id": "KPI_id_integer",
      "name": "KPI_name_string",
      "value": [ "KPI_value1_integer", "…", "KPI_valueN_integer" ],
      "date": "KPI_measurement_date_string",
      "unit": "KPI_measurement_unit_string"
    },
    {
      "id": "KPI_id_integer",
      "name": "KPI_name_string",
      "value": [ "KPI_value1_string", "…", "KPI_valueN_string" ],
      "date": "KPI_measurement_date_string",
      "unit": "KPI_measurement_unit_string"
    },
    {
      "id": "KPI_id_integer",
      "name": "KPI_name_string",
      "value": [ "KPI_value1_integer", "…", "KPI_valueN_integer" ],
      "date": "KPI_measurement_date_string",
      "unit": "KPI_measurement_unit_string"
    },
    {
      "id": "KPI_id_integer",
      "name": "KPI_name_string",
      "value": [ "KPI_value1_string", "…", "KPI_value5_string" ],
      "date": "KPI_measurement_date_string",
      "unit": "KPI_measurement_unit_string"
    }]
}
```

Figure 11: JSON schema of the RRM quality KPIs.

6. TESTING AND EVALUATION OF THE RRM PLATFORM

To evaluate the RRM platform and showcase its benefits, a 2-step process was followed (Figure 12). First, the RRM was tested and demonstrated on a real case study using the French demonstration site and a renovation scenario generated by the RPD toolbox (Sougkakis et al., 2023). The objective was to verify that the RRM platform complies with the requirements, achieves its goals, and connects the different retrofitting modules without bugs and gaps. Second, consultations with third-party construction companies were organised and feedback collected on whether the product developed meet the requirements and end-users needs and expectations.

6.1 RRM testing

The RRM platform requirements and functionalities identified in Tables 1-3 were tested using the BIM model of the French demonstration site as well as a renovation scenario defined by the RPD toolbox. Since the main objective of the RRM is to integrate and interconnect a set of retrofitting components and services, particular attention was paid to these components, the communication between them, and inputs and outputs of each of them as to whether they complied with the design requirements. To do so, 'React Developer Tools' (*React Developer Tools*, 2023) which is a Chrome DevTools extension for the open-source React JavaScript library was installed. This helps inspect React components and identify potential performance problems. The RRM platform including all its services and components was shown to be error-free and working correctly; mainly because all the bugs and errors were fixed during the platform's development.

Figure 13 illustrates a successful connection and communication with the *Cockpit service*; no execution errors were reported on the React Console tab, and the different KPI categories are collected, stored, and then displayed using the BIM model of the French demonstration site and the *Monitoring component*. A few execution errors, such as the "*RuntimeError: memory access out of bounds*", appeared while testing the *Training & Support component*. After investigations, the errors were corrected by enabling automatic reloading of the training contents when procedures are being utilised more than once.

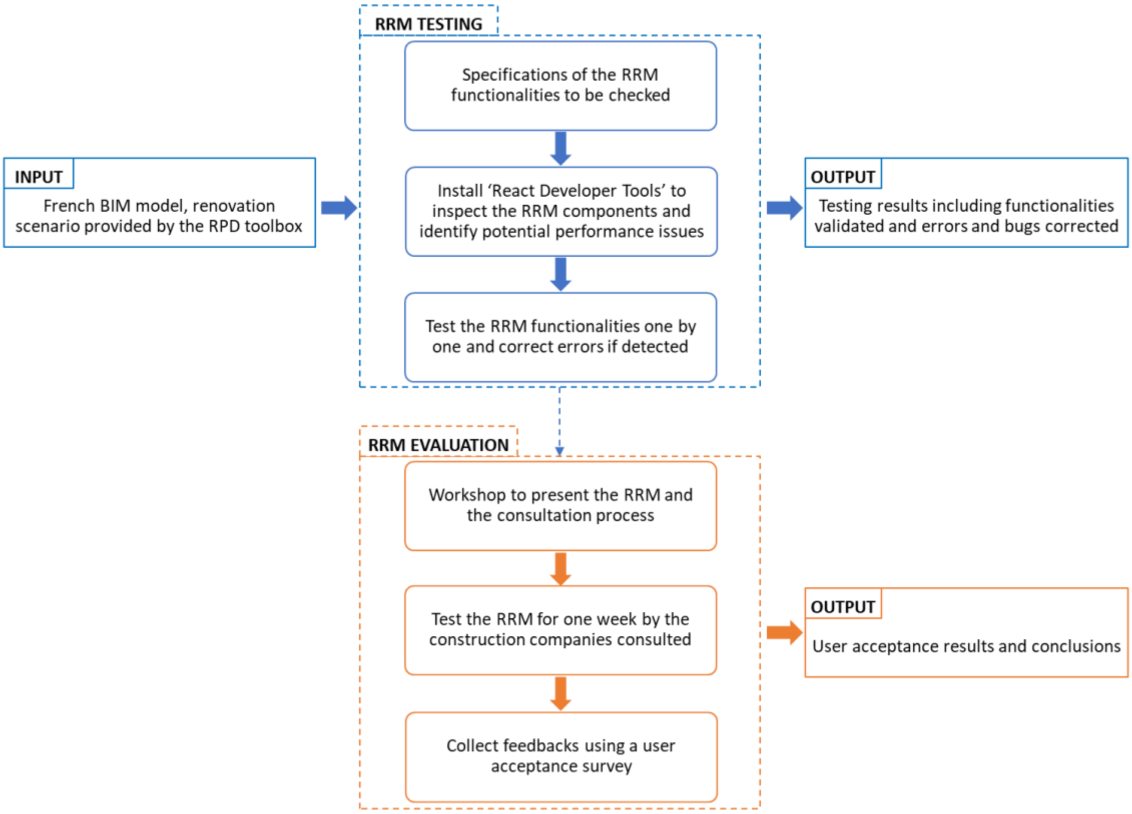
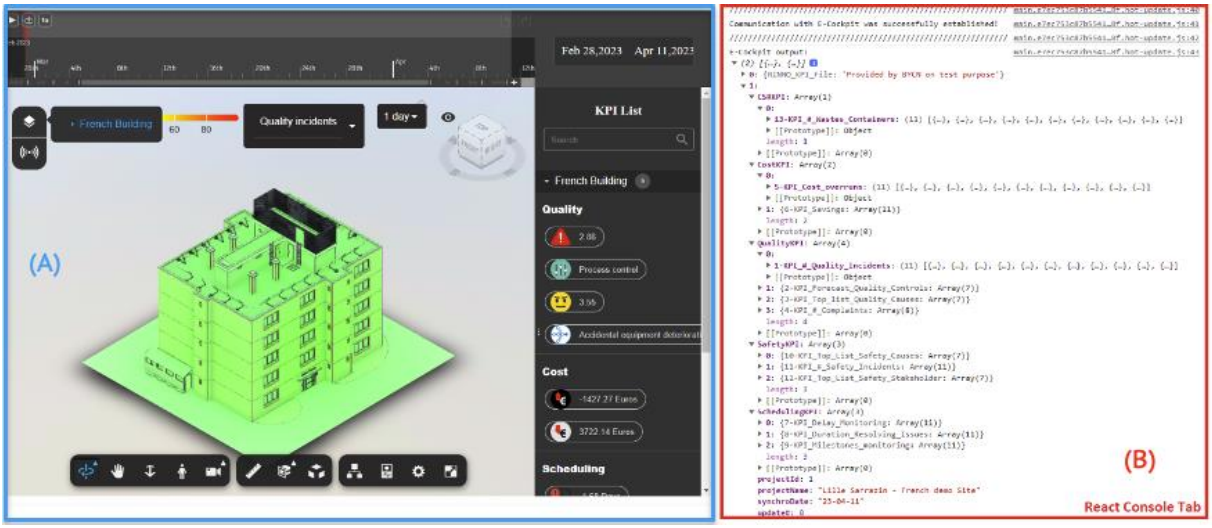


Figure 12: RRM testing and evaluation process.



```
/////////////////////////////////////////////////////////////
Communication with E-Cockpit was successfully established!
/////////////////////////////////////////////////////////////
e-cockpit output:
▼ (2) [{…}, {…}]
  ▶ 0: {RINNO_KPI_File: 'Provided by BYCN on test purpose'}
  ▼ 1:
    ▼ CSRKPI: Array(1)
      ▼ 0:
        ▶ 13-KPI_#_Wastes_Containers: (11) [{…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}]
        ▶ [[Prototype]]: Object
        length: 1
      ▶ [[Prototype]]: Array(0)
    ▼ CostKPI: Array(2)
      ▼ 0:
        ▶ 5-KPI_Cost_overruns: (11) [{…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}]
        ▶ [[Prototype]]: Object
      ▶ 1: {6-KPI_Savings: Array(11)}
        length: 2
      ▶ [[Prototype]]: Array(0)
    ▼ QualityKPI: Array(4)
      ▼ 0:
        ▶ 1-KPI_#_Quality_Incidents: (11) [{…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}, {…}]
        ▶ [[Prototype]]: Object
      ▶ 1: {2-KPI_Forecast_Quality_Controls: Array(7)}
      ▶ 2: {3-KPI_Top_list_Quality_Causes: Array(7)}
      ▶ 3: {4-KPI_#_Complaints: Array(8)}
        length: 4
      ▶ [[Prototype]]: Array(0)
    ▼ SafetyKPI: Array(3)
      ▶ 0: {10-KPI_Top_List_Safety_Causes: Array(7)}
      ▶ 1: {11-KPI_#_Safety_Incidents: Array(11)}
      ▶ 2: {12-KPI_Top_List_Safety_Stakeholder: Array(7)}
        length: 3
      ▶ [[Prototype]]: Array(0)
    ▼ SchedulingKPI: Array(3)
      ▶ 0: {7-KPI_Delay_Monitoring: Array(11)}
      ▶ 1: {8-KPI_Duration_Resolving_Issues: Array(11)}
      ▶ 2: {9-KPI_Milestones_monitoring: Array(11)}
        length: 3
      ▶ [[Prototype]]: Array(0)
    projectId: 1
    projectName: "Lille Sarrazin - French demo Site"
    synchroDate: "23-04-11"
    updated: 0
```

Figure 13: Successful loading of KPIs by (A) the Monitoring component, and (B) inspection using React Console tab.

6.2 RRM evaluation

The aim of the RRM evaluation is to ensure that the platform will work in the real world to meet the construction industry needs and requirements. To do so, a 3-step process is implemented. First, a workshop session was organised to present the software developed and explain the process of the consultations to 29 representatives of construction companies and other project organisations. The workshop lasted 2 hours and included sharing documentations and user guides about how to exploit and use the different functionalities provided by the RRM platform. The RRM platform was then made available for one week (4 - 10 September 2023) to allow the workshop participants to use the platform and assess its performance so as to alleviate the problem of changes over time in the participants' expectations and ensure accurate evaluation. Indeed, research in information technology usage suggest that users' pre-usage perceptions are often non-viable if they have never been exposed to technology (Bhattacherjee & Premkumar, 2004). Finally, based on a set of acceptance criteria inspired by the Unified Theory of Acceptance and Use of Technology (UTAUT) model (Marikyan, D. & Papagiannidis, S., 2023), a questionnaire was distributed to the users (Table 6), and feedback based on their experiences using the RRM platform collected to conclude the user acceptance testing. The UTAUT model has been used widely to examine technology acceptance and use in different domains, such as green building technology (Joyram et al., 2022), mobile devices for language learning (Hoi, 2020), Enterprise Resource Planning (ERP) software (Chauhan & Jaiswal, 2016), and healthcare informatics (Ward, 2013). The questionnaire addressed the platform's performance, ease of use, recommendation, and ease of implementation and deployment, which correspond to the 4 key constructs of the original UTAUT model (performance and effort expectancies, social influence, and facilitating conditions). In addition, moderating variables (age, experience, gender) were collected to better understand the feedback and identify more suitable corrective actions if needed. Some research suggests that moderating variables of the UTAUT model can be ignored as their effect seems to be closely dependent on the specific context considered (Dwivedi et al., 2019). On the other hand, variables such as voluntariness of use, culture, ethnicity, and religion, which are proposed in some studies to extend the UTAUT model, were not considered because of the organisational context of the consultations. After the workshop session and a week of testing the RRM, 26 participants (~ 90%) completed the survey which is based on a 5-point Likert scale from 'strongly disagree' (1) to 'strongly agree' (5).

The results (Figure 14) show good acceptance and use of the RRM platform by the participants whose age, experience, and gender are sufficiently varied to be representative (Table 6).

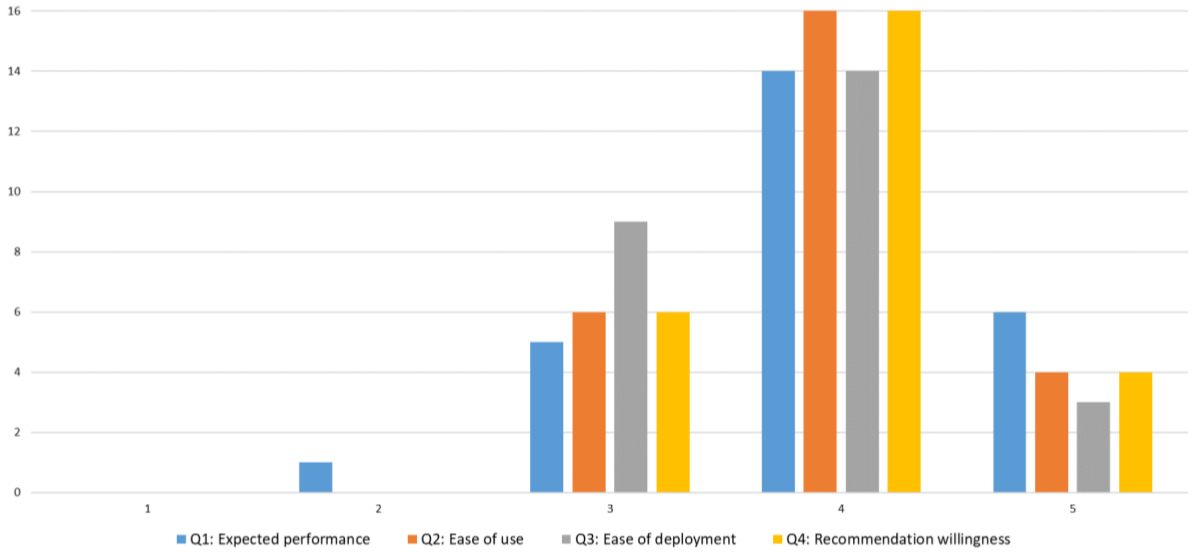


Figure 14: The RRM consultation results.

For instance, 20 out of 26 participants (more than 76%) confirmed that the RRM would improve the management of a renovation project (Q1), whereas 6 participants (23%) agreed that the RRM requires to be further tested on a real project and compared with a traditional renovation approach so that its functionalities and performance can be entirely demonstrated. This issue will be addressed in the coming months when the RINNO Suite, including the RRM platform, will be demonstrated, evaluated and its potential replicability analysed on 4 real-world renovation projects. Regarding the ease of use of the RRM platform (Q2), no problem was reported and the RRM was considered easy to use by most respondents. However, some proposed further automation to monitor the RRM process and execute its services without user intervention. This could be implemented for the *Monitoring component* such that the BIM model and project KPIs can be displayed as soon as the schedule is validated by the user. However, as for the *Offsite/Onsite*, *Optimisation and Planning components*, it would not be recommended to automatically trigger their execution as they require input from the user before being launched and executed. The consultation results regarding the RRM's ease of deployment and adoption by a construction company (Q3) show that the web-based platform would be easy to deploy within the participating companies as it only requires a computer and Internet network. Nevertheless, some feedback highlighted potential barriers to successful adoption, such as reluctance of project actors towards change, the financial aspects, and the supervised training of the workforce that would be needed. Finally, most participants would be willing to recommend the RRM platform to other users (Q4).

Table 6: Participant information.

Participant	Class	No.
Company	Architecture/design	2
	Construction management	3
	Engineering consulting	8
	General contractor	6
	R&D and training	1
	Real estate developer, social housing	5
	Renovation company	1
	Specialty contractor	2
	Transportation group	1

Participant	Class	No.
Age (years)	<25	3
	25-30	18
	30-35	1
	35-40	3
	>40	1
Experience (years)	<2	7
	2-5	12
	5-10	5
	>10	2
Gender	Female (including transgender women)	7
	Male (including transgender men)	15
	Prefer not to say	4

7. CONCLUSION & PERSPECTIVES

This paper presents the design and development of the RRM platform as part of the RINNO research project. The RRM platform addresses the critical problem of the lack and fragmentation of retrofitting tools and processes. It is implemented as a distributed system of web-services to streamline the processes, enhance accessibility and enable better interoperability between software tools and file formats while managing retrofitting works. The RRM introduces a 'Common Process Environment' concept where all retrofitting processes and tools required are integrated in all-in-one platform. Although, compared to single-purpose software, integrated solutions are usually less flexible, less customisable, and implement more complex user interfaces which may lead to longer adoption times as they cover several processes and functionalities, the RRM platform overcomes all these drawbacks through 'SOC and Open API' for implementing a loose coupling approach, 'distributed systems' to enable maintainability, and a 'role-based access' to facilitate interaction with the system, increase usability, and accelerate its adoption.

The RRM engine provides a coherent 'single-system view' to the platform where interoperability between the required renovation tools is internally managed through JSON-based data exchange, and there is no need to transform, import or export different file formats and deal with the issues related to data losses or formats that cannot be processed. JSON data format presents various merits, such as: (i) generating compact data models; (ii) ensuring high scalability; (iii) easy to parse for computers; (iv) incorporating a text-based format that is independent of the language used; which make it the most suitable human- as well as machine-readable format (Gerhart et al., 2015; Nurseitov et al., 2009). Research has shown that JSON is a more relevant choice over existing data formats, such as eXtensible Markup Language (XML), for web-based data exchange (Peng et al., 2011). With BIM data is being gradually unlocked through Construction Digital Twin (CDT), AI, and web technologies, JSON format can be used to improve interoperability of web-based BIM applications, since building data and related processes can be modelled as JSON specification using ifcJSON schema (Afsari et al., 2017). Future works will consider implementing the open ifcJSON schema so as to enable automating BIM data exchange with the RPD toolbox and remote services instead of using a proprietary BIM format ('rvt'- Autodesk Revit - file format in the current version) that is only used to visualise the project KPIs within the *Monitoring Component*.

Furthermore, based on a practical Lean methodology, the RRM platform ensures project actor needs are considered at the earliest stage of retrofitting and promotes and encourages collaboration before the onsite execution of tasks begins. The multi-level planning approach implemented through the LPS enables the project participants to overcome the gap that usually exists between long-term and short-term project schedules, and so help better streamline the retrofitting process and accelerate the delivery of renovation works. The RRM platform involves managing Baseline schedule (i.e., a project-level plan that is received from the Planning & Design phase), Look-ahead schedule (i.e., medium-term plan enriched with assigned spaces, materials, workers, etc.), and constraint-free Commitment schedules (i.e., work plans that are monitored at a weekly basis by the *Cockpit service*). The multi-level approach ensures the RRM platform can connect downstream management systems, based on commitment plans, with upstream management systems and higher-level planning. This will provide more consistency, and better quality and transparency to the planning and delivery of retrofitting works.

Moving into the era of the smart city, it becomes important to be able to benefit and rely on the existing web-services and distributed systems. This is why the RRM platform is designed and developed as an open distributed system that can integrate third-party web-services, such as the Slack platform, as well as offering its own services as third-party components to be easily integrated into other web-based applications. This is enabled by the Open API implemented that play a key role to make the RRM platform extensible and its web-services portable. On the other hand, the developed platform could be categorised as a free collaborative software, accessible online at (Doukari, 2023), which will reduce the financial costs of managing a renovation project. As such, web-services may become a more attractive building block for developing and sharing open and cost-effective digital resources for many construction companies. However, security in such systems poses real challenges that need to be considered and mitigated as early as possible in the design process (Luntovskyy & Spillner, 2017).

To test and prove the acceptance and use of the RRM platform by end-users, a workshop was organised with 29 third-party construction companies. The feedback shows good acceptance and use of the RRM with respect to the 4 key constructs of the original UTAUT model: performance expectancy, effort expectancy, social influence and facilitating conditions. In addition, the one-week testing demonstrates a good scalability of the RRM platform as many users are able to easily sign up and simultaneously use the RRM services without any noticeable loss of performance although dispersed in different geographic locations in Europe. However, following the consultation results, further testing of the RRM platform on real-world projects is important in order to confirm the platform's performance and superiority over the conventional approach of managing renovation works. To do this, as part of the RINNO project, 4 demonstration sites have been selected (in France, Denmark, Greece, and Poland) with retrofitting works scheduled over the coming few months and where the RRM will be tested as part of the RINNO Suite [64]. During these live demonstration projects, training sessions, materials, and user-hotline support will be provided to the stakeholders. Their experiences and feedback will be captured, formalised, and reported to prepare for future large-scale deployment.

Unlike parallel computing where all services share a unique memory to store data and communicate with one another (Walker, 2003), the RRM services have their own independent memory and communicate through API using JSON format. This provides a large memory space to store as much project data as needed and manage simultaneous requests from different processes and services. Ultimately, based on similarities between renovation projects, this data can be leveraged to better inform the RRM decision-making processes by implementing (or adapting an existing service such as the LinCTool (Eken et al., 2020)) and integrating a high level AI-based web-service for lessons-learned management. This web-service will learn from previous projects and transfer knowledge and lessons to the RRM services for better executing and managing retrofitting works.

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DATA AVAILABILITY STATEMENT

All data, models and code generated or used during the study appear in the submitted article.

COMPETING INTERESTS STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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