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A BIM-BASED TECHNO-ECONOMIC FRAMEWORK AND TOOL FOR EVALUATING AND COMPARING BUILDING RENOVATION STRATEGIES

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SUMMARY: *Building renovation presents real challenges for project participants which frequently generate high cost and schedule overruns. The disruption caused to occupants is one of the main challenges for the planning and management of renovation works. To better manage occupant interference and enable the acceleration of renovation works, this study aims to develop a novel framework for the assessment and optimisation of renovation strategies using BIM. The concept of disruption is formalised through a renovation ontology using the UML language. To enable process automation, the renovation ontology is then populated, and knowledge related to renovation tasks, constraints, duration, cost, equipment, and disruption are captured, structured and validated with industry partners. A digital tool and a set of Key Performance Indicators are also developed so as to facilitate the identification, assessment and optimisation of renovation scenarios in terms of cost, project duration and disruptive potential. Using a step-by-step process, detailed descriptions of the methodologies and workflows of the proposed framework are finally provided and demonstrated on a live case study located in Greece.*
The findings show no spatial correlation exist for the disruption concept and also confirm the disruptive nature of building floor renovation which can lead to a low rate of retrofitting them. Furthermore, the findings question the general applicability of the Whiteman et al.'s heuristic suggesting to prioritise the planning and execution of the most disruptive renovation activities as early as possible in the renovation process, and of the preference of Fawcett for a one-off renovation strategy recommending to conduct renovation works in one go as quickly as possible. Ultimately, the TEA framework will be further demonstrated and tested by end-users on three additional European case studies within the RINNO project which will particularly help validating the added value and benefits of the TEA framework from a user perspective.

KEYWORDS: *disruption simulation, techno-economic assessment, ontology, process automation, BIM, building renovation, process optimisation, occupant interference, renovation scenarios*

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1 INTRODUCTION

In Europe, buildings are responsible for the largest environmental impacts including almost 40% of energy consumption, 33 % of waste production, and 50 % of raw material depletion (Passoni et al., 2021). The building and construction sector's demand on natural resources accelerates climate change (UN, 2021). Inefficient buildings negatively impact both humans and the environment (UN, 2021). Although many research efforts have been investigating the construction process of new buildings and how to improve their performance, renovation of existing buildings seems to be a neglected area in the architecture, engineering, and construction (AEC) domain. To achieve climate change targets (UN, 2021), instead of focusing on superficial, light and minimally disruptive measures (e.g. boilers replacement), the built environment must opt for more holistic, innovative and disruptive policies and changes (Killip et al., 2020; Topouzi, 2016). The facts show 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% of the existing built environment is energy-intensive and inefficient (Energy Efficient Buildings, 2022), and up to 80% of them will still be in use by the year 2050 (Menna et al., 2022). While there is a significant concern about the rate and amount of renovation projects that need to be achieved to meet the European energy-saving and decarbonisation goals by 2030 and 2050 (Pohoryles et al., 2020), at present, except for some examples (Radian, 2009), there is only rare deep renovation projects that are carried out in both the social and private housing markets.

Building renovation presents real challenges for project participants, managers, policymakers and occupants. This is mainly due to (i) high uncertainty (Bozorgi et al., 2013; Singh et al., 2014); (ii) limited durations (Manuel, 2011); (iii) small quantities-based production; (iv) poor understanding of user requirements and the technologies to be installed (Gholami et al., 2013); (v) dearth of tools and approaches to evaluate renovation strategies (Gholami et al., 2013); (vi) low degree of anticipation and efficiency in the retrofitting phase (Amorocho et al., 2021), and (vii) high level of interaction and interference with occupants (Egbu, 1994; Fawcett et al., 2004; Grath et al., 2013), while planning and executing renovation works. Such challenges usually generate high increase in project costs and schedule overruns (Aldanondo et al., 2014; Singh et al., 2014). One of the main barriers of building renovation is the disruption caused to occupants (Designing Buildings, 2022; Fawcett, 2011; Trowers et al., 2022). Considering this constraint during the planning and execution of renovation works is particularly challenging because of the lack of normalised and improved workflows, and practical tools (Amorocho et al., 2021). Rodger et al., (2019) recommend integrating a larger view in terms of data and activities in the context of renovation projects in order to avoid potential impacts of interfering with occupants and their needs, otherwise the planning process will be prone to errors and multiple corrections. The research in (Vainio, 2011) suggests that interferences with occupants would be better managed through implementing a good communication plan where occupants are informed of the renovation works and issues to be faced in advance, so as they can explicitly understand the benefits of the renovation works and make appropriate decisions (Miller et al., 2011; Sunikka-Blank et al., 2012; Wallace, 1986). This, as highlighted in (Yee et al., 2013), will facilitate engaging occupants during the renovation project and incentivise and encourage them to effectively share the same spaces during the execution of renovation works. In contrast, unexpected works, changes and delays may cause occupants stress and dissatisfaction (Vadodaria et al., 2010).

Virtual design and construction (VDC) approaches (Dawood et al., 2008; Eastman et al., 2009; Han et al., 2000; Haymaker et al., 2004; Khanzode et al., 2008) have demonstrated the benefits of visualisation, simulation, and process automation to enable better control and transparency of project execution in the AEC domain. Early-stage simulation methods are particularly known to be useful tools to identify optimised renovation scenarios in terms of cost and time (Chaves et al., 2017; Kemmer et al., 2012; Volk et al., 2014). They also allow the reduction of renovation uncertainty, assessing the performance of different renovation approaches and strategies and assisting decision-making processes (Kamari et al., 2019, 2021; Sacks et al., 2009). For instance, Building Information Modelling (BIM) based simulations enable to share and clarify the perception of the renovation process by all stakeholders including building occupants. It allows better visualisation, communication and decision-making through 3D-based simulations of several renovation scenarios and strategies (Egbu, 1997; Papamichael, 1999; Sheth et al., 2010). Furthermore, BIM has the potential to reduce disruption to users (Chaves et al., 2017; Kemmer et al., 2012; Volk et al., 2014). Despites all these advantages and benefits, research works are still lacking on the use of BIM (Joblot et al., 2019) and simulations for refurbishment projects (Chaves et al., 2017; Kemmer et al., 2012; Volk et al., 2014).

To enable project managers to efficiently communicate with occupants, evaluate and simulate renovation scenarios, a Techno-Economic Assessment (TEA) framework is proposed in this paper. It demonstrates how using BIM, ontologies, digital tools, and Key Performance Indicators (KPI) enables representing and processing automatically building renovation knowledge to improve managing interferences with occupants. This research is conducted as part of a large European research project, which is the RINNO project (Doukari et al., 2021), that involves eighteen partners from ten different EU countries and aims to accelerate building renovation in Europe by developing a holistic multidisciplinary renovation platform through an operational interface with augmented intelligence. The remainder of this paper is structured as follows. Section 2 includes a review of related works on building renovation disruption. Section 3 describes the research methodology. Section 4 introduces the framework proposed, including a renovation ontology, the TEA tool and a set of KPIs to enable retrofitting strategies comparison and optimisation regarding their duration, cost, resources and disruption. Section 5 demonstrates the applicability of the proposed framework using a live case study, which is the RINNO's Greek multi-residence apartment building demonstration site, and evaluates three different renovation strategies in terms of project cost, duration, resources required and disruptive potential. Conclusions and future extensions of the proposed framework are finally outlined in Section 6.

2 RELATED WORKS

In construction, disruption usually refers to a disturbance of onsite productivity that impacts the overall efficiency of the project (Designing Buildings, 2022). It can be defined as a disturbance which interrupts, diminishes or alters the usual functioning of an activity, service or system, and its impacts over a period of implementing a renovation initiative. Disruptions and delays are two interrelated concepts. While disruptions can cause delays in the progress of construction works, delays similarly can generate disruptions and loss of productivity. Gleeson et al., (2011) have estimated two to twelve days the time of disruption to install individual retrofit technologies in a typical house building project. The cost of a renovation project should include the added cost caused by disruptions so as to enable the project manager to evaluate and compare the different retrofitting scenarios, and decide about the best retrofitting strategy to be implemented (Tokede, 2016). Based on fuzzy logic principals, Tokede (2016) suggested that disruption can increase costs by up to 12%.

Renovation projects typically disturb building occupants and vice-versa. While planning and executing retrofitting activities, project managers must take into account occupants' presence and schedules so they can adapt accordingly the construction site pathways, the material storage and the waste management plans. When occupants are present in the renovation site, their safety should be guaranteed and disruption, due to noise, dust, vibration, odour and/or demolition debris (Amorocho et al., 2021), should be reduced as much as possible (Salvalai et al., 2017). Kelsey (2003) highlighted the importance of considering the reduction of disruptions as one of the strategic objectives of renovation projects and one of the impactful factors to be managed. Several studies have proposed different strategies to manage and reduce the impact of disruptions. The first step to minimise this impact is through building trust and communication with occupants by explaining in advance the benefits of building renovation and its positive impacts to occupants so that they accept disruptions and be prepared before launching the renovation works (Trowers et al., 2022; Vainio, 2011). BIM-based simulations along with detailed planning for the retrofitting phase can help addressing this need (Chaves et al., 2017). Using 4D BIM simulations, Chaves et al., (2017) evaluated different renovation scenarios in order to improve building energy efficiency. The 4D BIM models created were simplified so that they do not contain unnecessary information and enable clear visualisations of retrofitting works. Whiteman et al., (1988) proposed estimating the disruption level of renovation activities so as to prioritise planning and executing the most disruptive tasks as early as possible in the renovation process. They suggest that such an approach could minimise occupants' dissatisfaction. Fawcett (2011, 2014) suggested that conducting renovation activities in one go according to one-off strategy would reduce the disruptions caused to occupants and make them more collaborative as they would have to leave and vacate the building once instead of many times as it is the case in over-time renovation strategy. Similarly, Moschella et al., (2018) pointed out the importance of developing integrated renovation processes where several retrofitting objectives, such as energy efficiency and seismic safety, are simultaneously considered so as to reduce additional costs and disruptions to occupants.

Moreover, to increase the acceptance of renovation by occupants, retrofitting practices and their impacts (e.g., comfort and disruption) must be clarified. A characterisation of different types of disruption is required to distinguish between tolerable and intolerable interferences with occupants while planning and managing retrofitting works. Several research have attempted to classify renovation activities according to the level of disturbance they might cause to occupants. Vadodaria et al., (2010) categorized two levels of disruption: 'Low' and 'High' disruptions. The former corresponds to retrofitting tasks that are carried out outside the building, and the latter corresponds to indoor tasks which are more disruptive to the daily life of occupants. By conducting a disruption analysis of technologies installation, Tokede also proposed a disruption classification of three levels, namely 'Low', 'Medium' and 'High' disruptions (Tokede, 2016). Chaves et al., (2017) identified six categories of disruption according to the impacts they have on occupants: (i) disruption of utilities, such as gas, electricity and water interruptions; (ii) disruption of traffic, such as access to the building or flat blocked or restricted; (iii) disruption of physical space when occupants have to vacate part or the whole building, or their daily activities and comfort are interrupted or impacted by the retrofitting works; and (iv) disruption of internal environment when retrofitting works cause pollutions, such as noise, dust, daylight reduction, vibration, odour and demolition debris; (v) disruption to the external environment, such as changing the yards; and (vi) disruption to parking spaces when parking facilities are reduced.

3 RESEARCH METHODS

The research methods used to achieve the objective of this study are illustrated in Fig. 1. A literature review was performed to understand the available approaches and frameworks relevant to the posed research aim and capture potential recommendations, requirements, and concepts the proposed approach should consider.

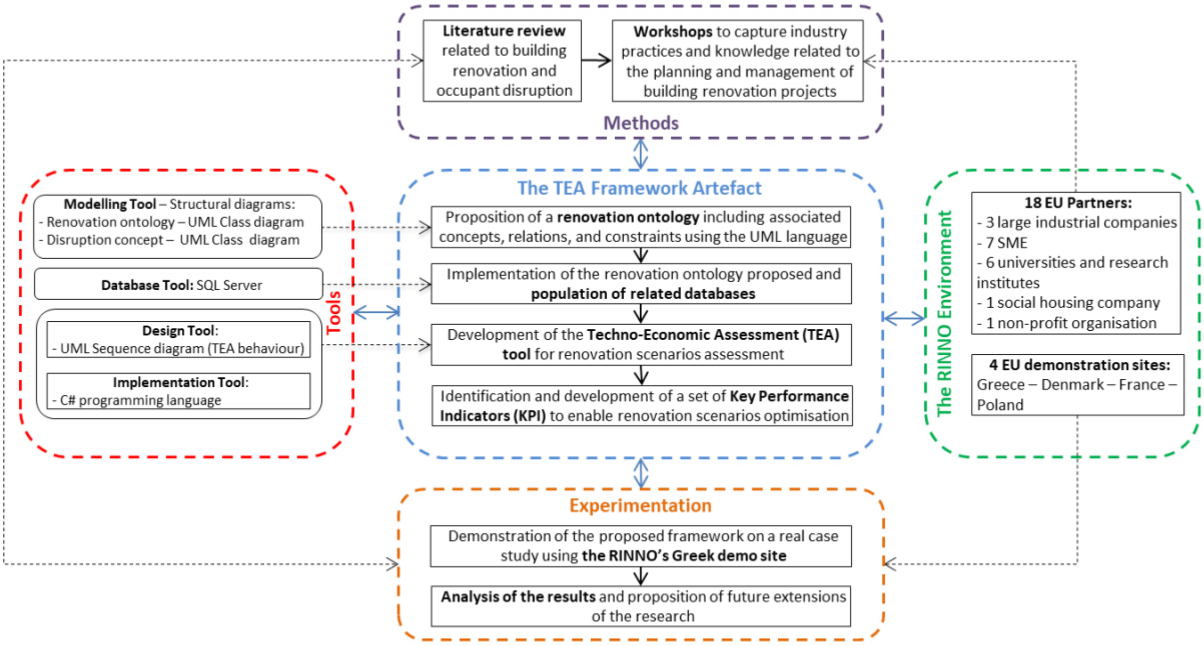


FIG. 1: Research methods, tools and environment

As presented in Section 2, the review was focused on research studies related to the concept of disruption, which was the main purpose of this study. To complement the literature's findings with industry perspectives, workshops were conducted with the RINNO project experts from key organisations and engineering consultancy companies in Europe. The RINNO project (Doukari et al., 2021) includes 18 partners (3 large industrial companies, 6 universities and research institutes, 7 SME, 1 social housing company, and 1 non-profit organisation) from 10 different EU countries. The workshops were organised remotely via Teams (due to the COVID-19 pandemic) lasting between 60 and 90 min each. A first version of a renovation database was prepared in advance by RINA-C, one of the RINNO partners, using Microsoft Excel, and then refined and completed throughout the workshops. The main objectives of the collaborative workshops were to understand building renovation processes, formalise related knowledge via a renovation ontology, and then populate it through a database. The Unified Modelling Language (UML) (Booch et al., 2005) was used to represent the renovation ontology including the disruption concept, its relations, and constraints. To enable process automation, tools development and provide a machine-readable representation of renovation knowledge, the ontology was populated using SQL Server. Knowledge related to renovation activities, their sequencing rules, constraints, duration, cost, equipment, and disruptive potential were captured and structured into several tables, each of which enabled implementing a concept from the ontology.

The research then demonstrated the applicability of the renovation ontology proposed by developing the TEA tool; a digital tool for renovation strategies assessment and simulation in terms of project's duration, cost, resources and disruptive potential. Finally, the proposed framework was applied on a live case study using the RINNO's Greek demonstration site, and three renovation scenarios were identified and assessed through a set of KPIs developed as part of the TEA framework.

4 THE TECHNO-ECONOMIC ASSESSMENT FRAMEWORK

Two main strategies to manage and reduce the impact of disruption during renovation projects have been proposed in literature. First, communication with occupants to explain the renovation process, build trust and minimise the impact of disruption (Trowers et al., 2022). Second, enabling renovation scenarios assessment, simulation and optimisation to maximise user comfort and minimise disruption (Tokede, 2016). The TEA framework was developed in order to implement these two strategies and enable project managers to efficiently communicate, evaluate, and simulate renovation scenarios to select the optimum one with minimum disruption that could be caused to occupants. In addition, the TEA framework permits the evaluation of renovation project parameters, such as project duration, cost and workers needed during the renovation works. Thus, it enables optimising existing renovation collaboration workflows through making direct link with occupants in the design process by providing a set of KPIs relating to project cost, duration, resources required and disruptive potential.

The TEA framework includes three main components, namely: (i) a renovation ontology and its database developed with the help of the RINNO project partners; (ii) the TEA tool along with a friendly GUI to enable automated renovation scenarios selection and evaluation; and (iii) the TEA KPIs to enable renovation strategies comparison and optimisation. These three components are detailed in the following sections.

4.1 Renovation ontology

Ontologies are useful AI tools in formalising specific domain knowledge including their concepts, relations, and constraints (Hartmann et al., 2020). They enable process automation and tools development as they provide a machine-readable representation of knowledge. To develop the TEA framework, a renovation ontology was proposed and validated with the RINNO partners. Fig. 2 introduces the RINNO renovation ontology via a UML class diagram illustrating the ontology concepts, their relations, and constraints as well as the attributes that define each concept to facilitate its implementation and population as a renovation database.

As presented in Fig. 2, a 'Built Asset' is composed of several 'Elements' (e.g., window, wall, HVAC) and many 'Areas' (e.g., room, corridor). An 'Element' could be manipulated while achieving a 'Renovation Scenario'. A 'Renovation Scenario' is an aggregation of 'WBS' (Work Breakdown Structure), takes place at one or many 'Areas', manipulates one or many 'Elements', and could involve the installation of many 'Innovative Products'. A 'WBS' is a combination of renovation activities that are carried out at the same spatial breakdown, and so can be defined as a work package or a macro renovation activity. Each renovation 'Activity' is timely constrained by activities that should begin and finish before it, whereas some others will be triggered and executed after its completion. It also requires a set of 'Material', 'Workforce' and 'Equipment' to be executed, and it may cause 'Disruption' to the building occupants and/or 'Hazard' to the 'Workforce'. The 'Hazard' concept is beyond the scope of this research and so will not be further discussed in this paper.

The workshops conducted with the RINNO partners enabled understanding the concept of disruption and its relationship with renovation works from the industry perspective. Only four types of disruption were validated and considered, namely disruption of Traffic, Utilities, Physical Space and Internal Environment. Fig. 3 illustrates the disruption concept as it was formalised and implemented within the TEA framework. As shown in Table 1, some levels of disruption, such as those with no impact or just waste of time disruptions, were considered as part of the normal operation of building, whereas some others could impact the entire renovation project and influence its benefits if they were not examined and treated in advance.

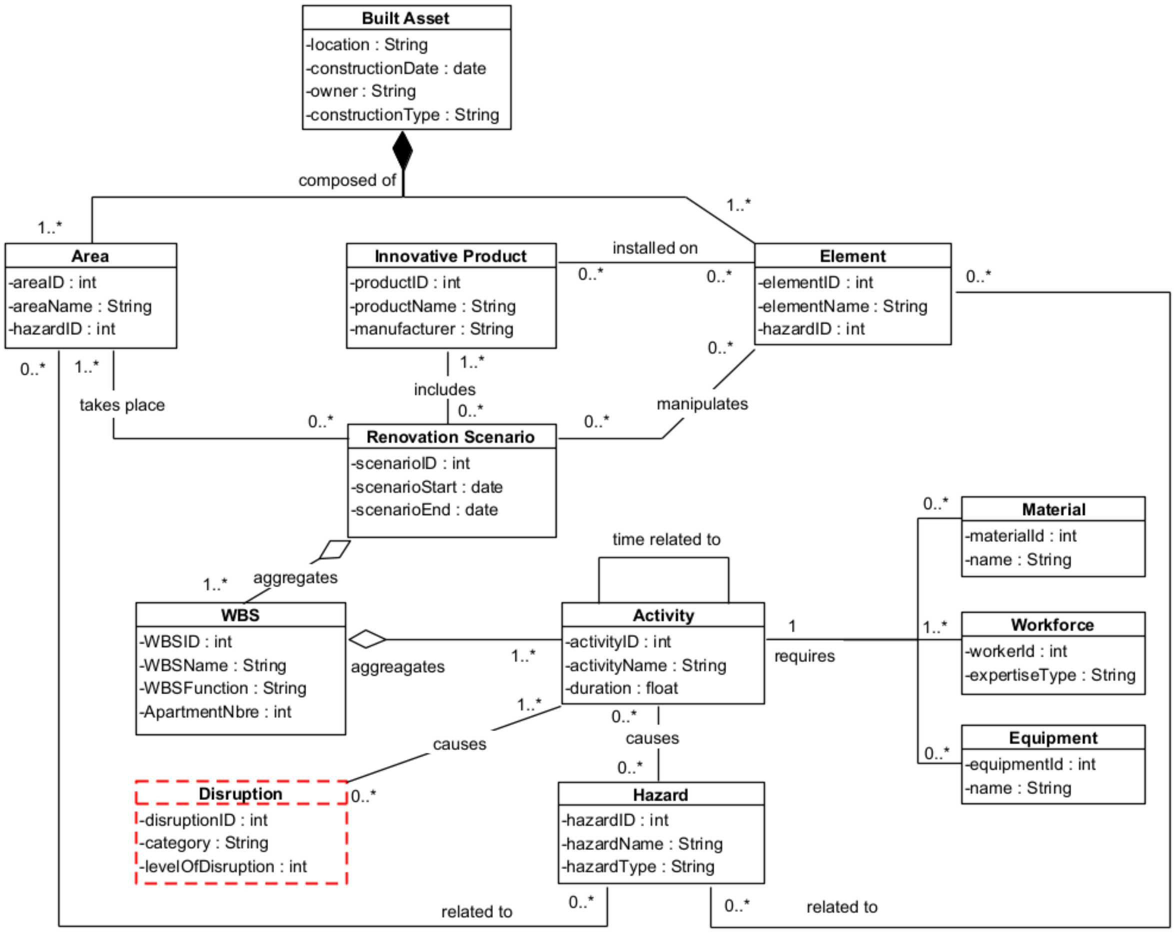


FIG. 2: Renovation ontology – UML class diagram

TABLE 1: TEA Framework – Disruption classification, levels & intensities, flags, and impacts

Level of disruption	Range of disruption values/intensities	Intensity flag	Communication
No impact / downtime	[0, 1]		Be aware!
Low impact	]1, 2]		Be aware!
Medium impact	]2, 3]		Be prepared!
High impact	]3, 4]		Take action!

The workshops allowed capturing data related to renovation activities, their sub-activities, sequencing rules, constraints, duration, cost, equipment and disruptive potential. Two existing levels of sequencing rules were identified between renovation activities, namely: (i) spatial rules, such as Courtyard related activities (e.g., site preparation) must begin first; and (ii) activity-based rules. The latter can be further detailed into three different classes of rules which are sequential (e.g., while renovating a roof, activity 'F' must be conducted before activity 'L'), simultaneous (e.g., activity 'G' can be performed while conducting activity 'H') and disjunctive rules (e.g., if activity 'B' is planned none of the following activities can be conducted 'C', 'D', 'E' and 'T'). Furthermore, the four disruption classes were characterised, and their levels and intensities with regards to renovation activities were quantified. Data was collected at the sub-activity level, and then average values for each parameter were calculated. Table 2 below presents an extract from the data collected and populated using SQL Server.

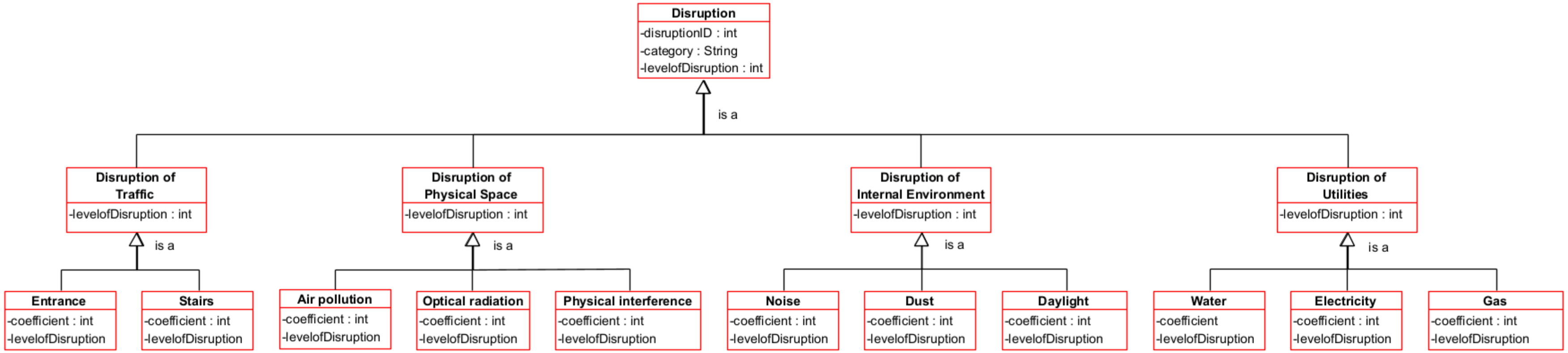


FIG. 3: The disruption concept – UML class diagram

TABLE 2: Renovation activities characterisation and relationships with disruption

Activity ID	Activity Name	Unit	Average duration (day/Unit)	Activity average cost (€/Unit)	Labour incidence (%)	Average workforce (#/day)	Average Disruption: Utilities	Average Disruption: Traffic	Average Disruption: Physical space	Average Disruption: Internal Environment
A	Site preparation	Activity	5	2000	15%	4	0	3	0	1.6
B	Façade insultation	m^2 facade	0.21	110	50%	2.5	0	0	0	2.6
C	Façade insulation with insufflated plug-and-play system	m^2 facade	0.2	400	20%	2.1	0	0	0	2
D	Façade insulation with PV integrated plug-and-play system	m^2 facade	0.22	500	20%	2.2	0	0	0	2
E	Façade insulation with cavity insufflation	m^2 facade	0.01	25	60%	3	0	0	2	3
F	Flat roof insulation	m^2 roof	0.3	120	60%	1.7	0	0	0	0.9
G	Sloped roof insulation	m^2 roof	0.2	130	60%	2.3	0	0	0	1.3
H	Photovoltaics on sloped roof	m^2 roof	0.15	300	25%	2.4	0.1	0	0	0.8
I	Photovoltaics on flat roof	m^2 roof	0.13	200	20%	2.3	0.1	0	0	0
J	Windows and/or doors replacement	Activity	0.6	1100	15%	1.7	0	0	0	1.3
K	Windows replacement with photovoltaic windows	Activity	0.9	1400	20%	1.8	0.1	0	1	1.3
L	Installation of solar collectors on flat roof	Activity	0.14	1000	10%	1.6	0.1	0	0	1.7
M	Wall-mounted/integrated heat storage	Activity	0.6	2500	10%	1.5	1	0	0.7	1.4
N	Condensing boiler installation	Activity	0.6	1500	14%	1.5	1	0	0.7	1.4
O	Mini split installation	Activity	0.6	750	13%	1.5	0	0	0.5	1.7
P	Radiant floor installation	m^2 floor	0.15	120	25%	2.4	0	0	2.4	0.5
Q	Non-centralised mechanical ventilation system	Activity	0.83	350	20%	1.6	0	0	1.8	1.7
R	Centralised mechanical ventilation system	m^2 floor	0.1	100	45%	2.4	0	0	2.7	2
S	Insulation of existing heating and domestic hot water pipes	m^2 floor	0.11	50	85%	2.7	0	0	2	0.6
T	Insulation from the inside	m^2 facade	0.11	80	55%	2.7	0	2	0	2.4

4.2 The TEA Tool

Fig. 4 illustrates a general overview of the automated process implemented through the TEA tool. It begins by importing a BIM model and then allowing users to define a renovation scenario to be simulated. Secondly, based on the renovation ontology and related database, the TEA tool maps the renovation scenario to corresponding activities and relevant equipment along with their details, such as unit prices, durations and number of workers needed. Thirdly, building elements and material quantities are generated from the BIM model and linked to the renovation activities which allows the generation of the renovation schedule corresponding to the scenario selected. Finally, using the database developed, the TEA tool estimates and simulates disruption levels, and cash needs according to different perspectives: daily, weekly, per activity and for the whole project duration.

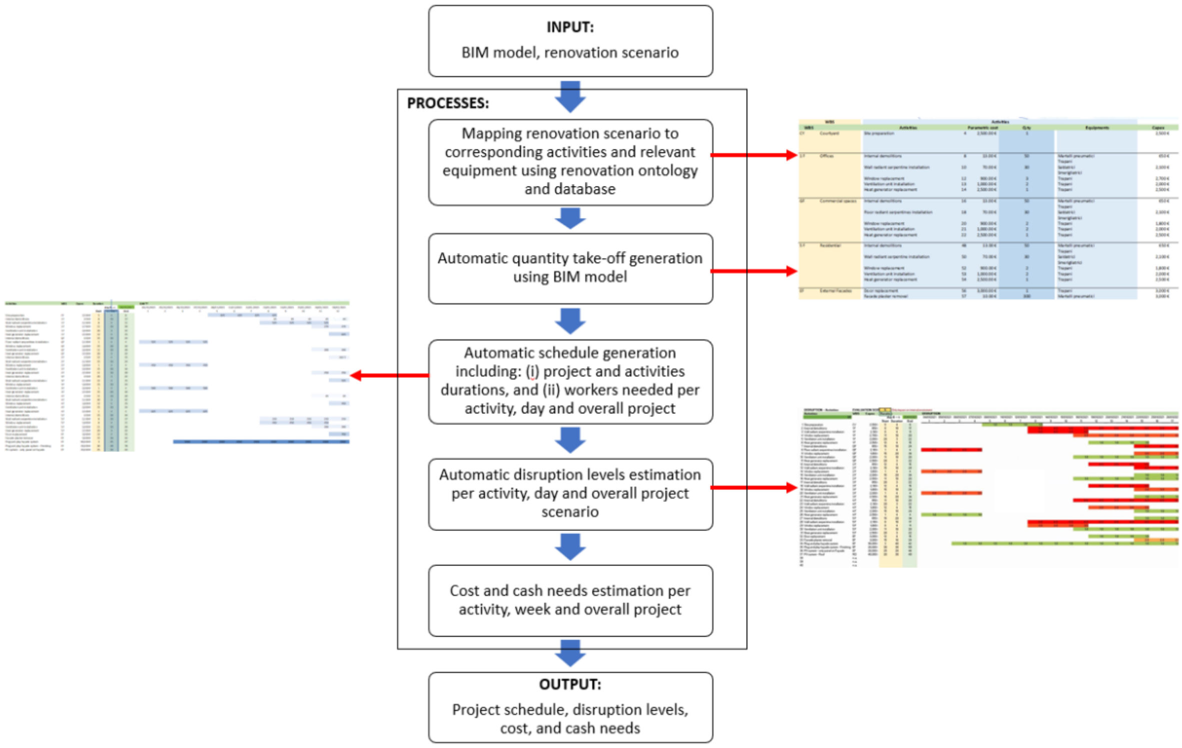


FIG. 4: TEA process overview

Fig. 5 shows a UML sequence diagram of the Disruption module and how disruptions are estimated using the TEA tool. This diagram represents high level interactions between the system users and the TEA tool to trigger the execution of the disruption estimation, and how this will be coordinated through sub-systems' interactions/messaging in a timed manner. The Disruption module sub-systems developed and used to enable disruption estimation are: (i) the TEA Engine; (ii) the BIM Authoring platform (Autodesk Revit) and related APIs; and (iii) the Planning component. As illustrated in Fig. 5, the project manager begins by preparing the BIM model and its data to be processed. They upload the BIM model, check the data, its quality (e.g., completeness of BIM elements/objects and parameters) and modelling rules (e.g., storey/level-based modelling), and complete, if needed, missing information. The project information, such as the project start date, owner, and address, should be indicated before estimating disruptions. To enable users to simulate several renovation strategies and scenarios in order to select the best one, the TEA tool provides a Graphical User Interface (GUI) to identify and generate renovation scenarios. This interface can be used to create and simulate disruption of any renovation scenarios. Once a renovation scenario is identified and the disruption process is launched, the TEA Engine creates the corresponding renovation schedule by interacting with the Planning component and using the renovation database populated. First, BIM elements, areas/WBS and quantities take-off concerned by the renovation scenario are generated through the BIM Authoring platform APIs. Second, activities are mapped, equipment assigned as well as other information (durations, workforce, costs, etc.) are queried and generated, using the renovation database, to be associated with corresponding BIM elements and information. Finally, a schedule is automatically generated. To estimate disruption caused to users according to the renovation scenario selected, the TEA Engine uses the schedule generated and queries the database to estimate corresponding disruption values for the four disruption categories: Traffic, Utilities, Physical Space, and Internal Environment.

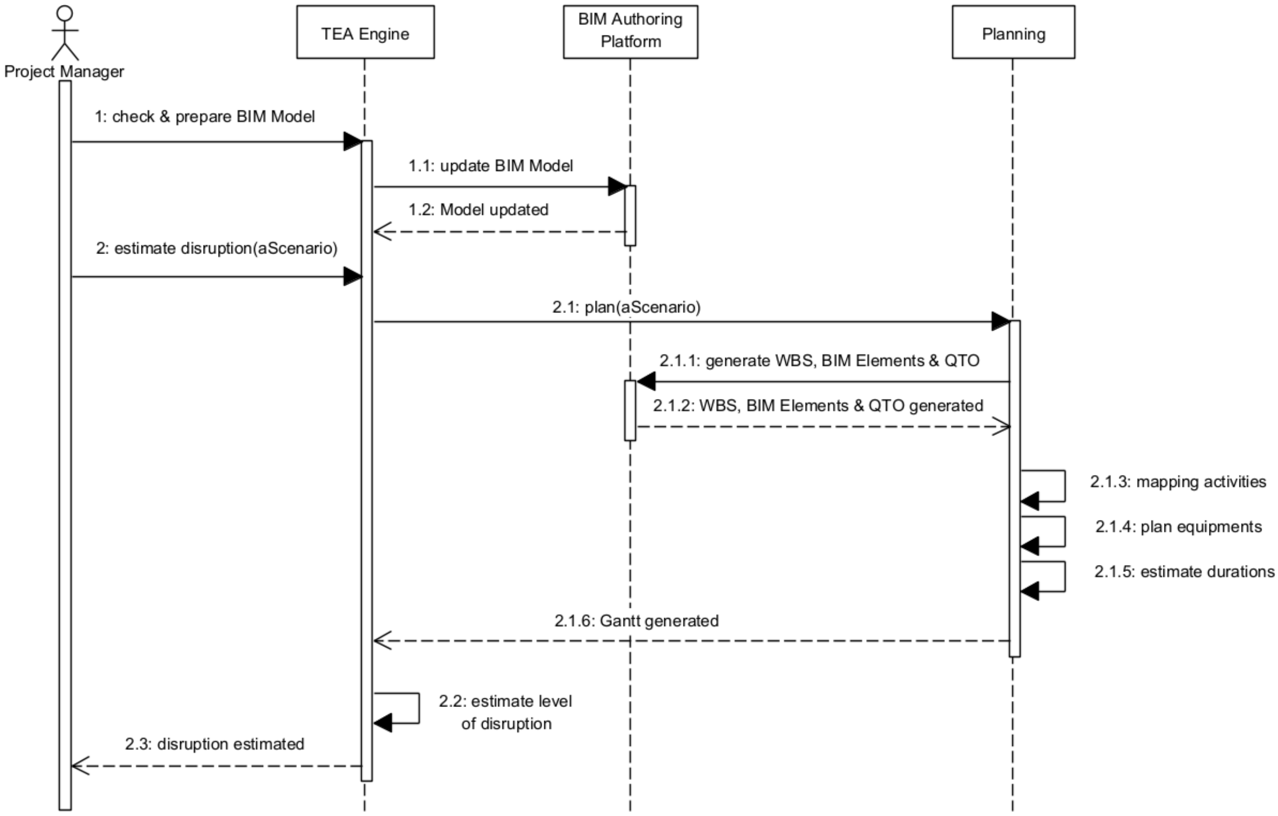


FIG. 5: Automated disruption estimation process - UML sequence diagram

4.3 The TEA KPIs

To enable design process optimisation and renovation strategies comparison and selection, a set of KPIs were developed. Table 3 illustrates the TEA KPIs provided and calculated within the TEA framework. They include KPIs related to the renovation project duration and cost as well as disruption caused to users while executing renovation works and average daily and overall project workers required.

5 CASE STUDY OF THE RINNO'S GREEK DEMONSTRATION SITE

This section provides detailed descriptions of the methodologies and workflows of the proposed framework demonstrated on a live case study which is the RINNO's Greek multi-residence apartment building demonstration site. Three renovation scenarios were selected and evaluated to test the applicability of the TEA framework.

5.1 BIM model preparation

As illustrated in Fig. 6, the first step consists in checking BIM data quality and inputting basic renovation project information, such as project start date, owner, address, description and project name. Although there is no specific geometric level of detail (LOD) required, basic data and BIM objects, such as walls, windows, doors, floors, stairs and roof, must be modelled and added to the BIM model. This step ensures BIM data completeness and that it complies with the following modelling rules:

- BIM objects should be modelled and named using elementary objects provided by the English version of the BIM authoring platform.

- The BIM model should be created with respect to a level or storey-based modelling approach. For instance, a ‘wall’ object should not be linked or connected to more than two levels as what it used to be the case with some inadequate modelling practices.

TABLE 3: The TEA framework KPIs

RINNO TEA KPIs			Formulas
Category	KPI	ID	
Cost	Project Cost	1	$\sum_{x=1}^{x=Duration_{Project}} \sum_{i=1}^{i=n} Average\ activity\ cost(a_{ix}) + Average\ equipment\ cost(a_{ix})$ where a_{ix} are activities scheduled for day x. Labour costs are included in the activity costs.
Duration	Project Duration	2	$EndDate_{Project} - StartDate_{Project}$
Resource	Average Daily Workers	3	$\frac{\sum_{x=1}^{x=Duration_{Project}} \sum_{i=1}^{i=n} Workforce(a_{ix})}{Duration_{Project}}$
	Project Workers	4	$\sum_{x=1}^{x=Duration_{Project}} \sum_{i=1}^{i=n} Workforce(a_{ix})$
Disruption	Average Project Utilities Disruption	5	$\frac{\sum_{x=1}^{x=Duration_{Project}} \underset{i=1}{\overset{i=n}{MAX}}\left(Disruption_{Utilities}(a_{ix})\right)}{Duration_{Project}}$
	Average Project Traffic Disruption	6	$\frac{\sum_{x=1}^{x=Duration_{Project}} \underset{i=1}{\overset{i=n}{MAX}}\left(Disruption_{Traffic}(a_{ix})\right)}{Duration_{Project}}$
	Average Project Physical Space Disruption	7	$\frac{\sum_{x=1}^{x=Duration_{Project}} \underset{i=1}{\overset{i=n}{MAX}}\left(Disruption_{Physical\ Space}(a_{ix})\right)}{Duration_{Project}}$
	Average Project Internal Environment Disruption	8	$\frac{\sum_{x=1}^{x=Duration_{Project}} \underset{i=1}{\overset{i=n}{MAX}}\left(Disruption_{Internal\ Environment}(a_{ix})\right)}{Duration_{Project}}$

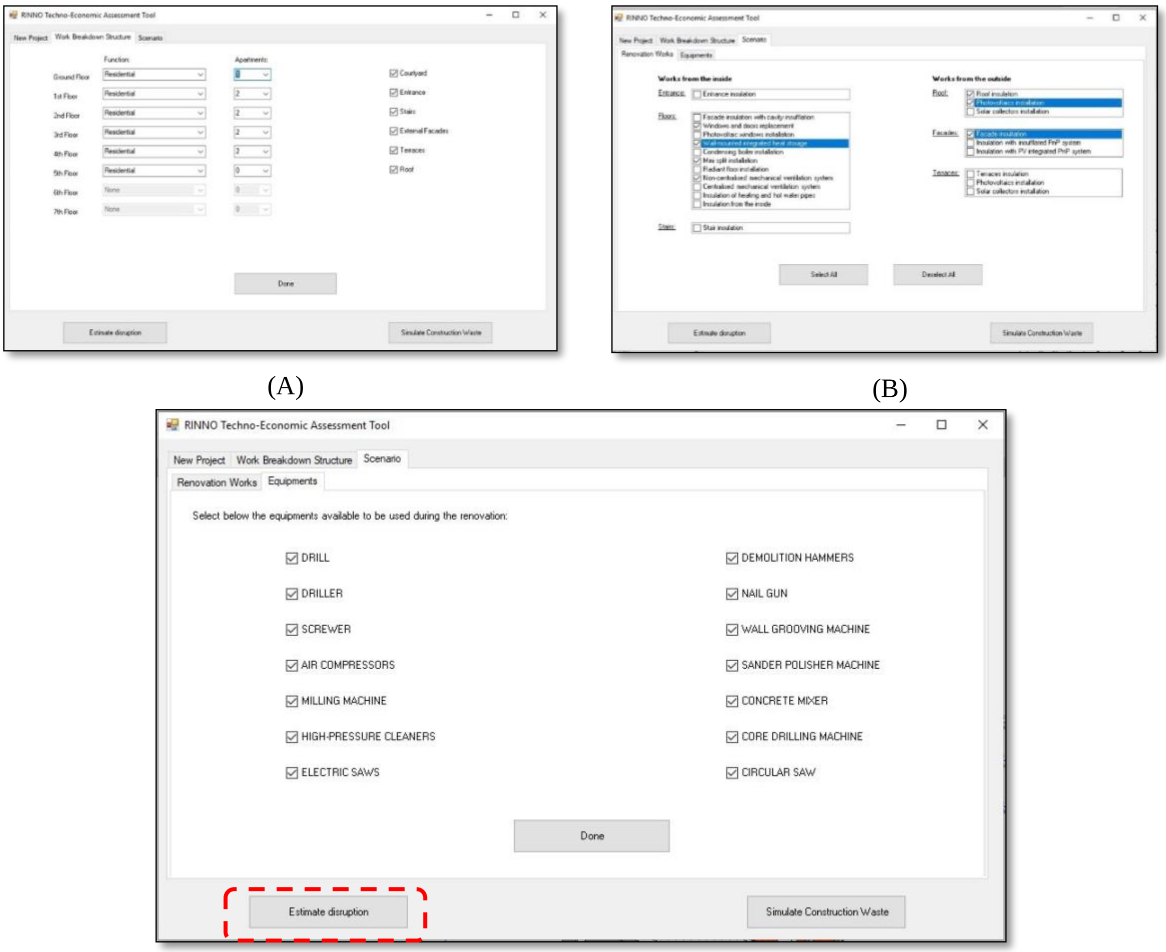
(A) (B)

FIG. 6: BIM model preparation: (A) front view, and (B) back view

5.2 Renovation scenario identification

The second step consists in defining a renovation scenario that will be simulated in order to estimate disruptions caused to users. As illustrated in Fig. 7[1], the TEA framework provides three different GUI to enable users to create their own scenarios and simulate them automatically. The first GUI (Fig. 7 – A) allows users to select the WBS that will be renovated as well as inputting data related to the number of apartments existing at each level as BIM models usually lack such data. The second GUI (Fig. 7 – B) enables users to refine their scenarios by selecting renovation activities to be performed for each WBS. It consists of selecting a subset of the twenty activities identified and validated with the RINNO partners. The third GUI provides a list of renovation equipment to be used to conduct the renovation activities selected. Through these three GUI, users are assisted in defining their own renovation scenarios in order to evaluate different renovation strategies and select the best one in terms of disruption, resources, project duration and cost.

In this paper, three renovation scenarios were randomly selected and processed using the TEA framework (Fig. 8). The three scenarios consisted of conducting the same set of renovation activities but related to different WBS, such that Scenario 1 was to renovate the building's 'Basement', Scenario 2 for the 'Ground Floor', and Scenario 3 was dedicated to the '1st Floor' renovation.



(A) (B)

(C)

FIG. 7: Renovation scenario identification: (A) WBS; (B) activity; and (C) equipment selection

[1] The 'Simulate Construction Waste' button illustrated in the TEA GUI corresponds to another RINNO tool which is the 'Waste Management' module. This latter is beyond the scope of this paper.

Scenario definition

	Scenario 1	Scenario 2	Scenario 3
WBS	Basement	Ground Floor	1st Floor
Activities	- Site preparation - Façade insulation with cavity insufflated - Windows and/or doors replacement - Condensing boiler installation - Radiant floor installation	- Site preparation - Façade insulation with cavity insufflated - Windows and/or doors replacement - Condensing boiler installation - Radiant floor installation	- Site preparation - Façade insulation with cavity insufflated - Windows and/or doors replacement - Condensing boiler installation - Radiant floor installation

TEA KPIs computation

KPIs*			
ID	Value	ID	Value
1	29497.03	5	0
2	33	6	0.5
3	2.5	7	1.7
4	84.1	8	0.9

KPIs			
ID	Value	ID	Value
1	53023.7	5	0
2	44	6	0.3
3	2.3	7	1.2
4	102.1	8	1

KPIs			
ID	Value	ID	Value
1	57383.56	5	0
2	46	6	0.3
3	2.3	7	1.2
4	105.5	8	1

*<u>**KPI descriptions:**</u> **1:** Cost (€) – **2:** Project Duration (*days*) – **3:** Average Daily Workers – **4:** Project Workers – **5:** Utilities Disruption – **6:** Traffic Disruption – **7:** Physical Space Disruption – **8:** Internal Environment Disruption

FIG. 8: TEA assessment of three (03) different renovation strategies for the Greek demonstration site

5.3 Results and discussion

Finally, the three renovation scenarios were evaluated according to their cost, duration, workers needed, and disruption caused using the TEA framework. The results illustrated in Fig. 8 showed different KPIs for the three scenarios even though the same renovation activities were considered. The first four KPIs (i.e., project cost, duration, average daily workers and project workers) are obviously different due to, as illustrated in Table 4, different building element quantities that belong to the Basement, Ground floor and 1st floor of the Greek building; thus, different renovation work quantities, costs and efforts required to retrofitting the three WBS. The fifth KPI (i.e., disruption of utilities) was (or converged to) zero for the three scenarios, since the 'Condensing boiler installation' activity, which is the only one here that could cause this kind of disruption, lasted one day to enable the installation of one boiler for Scenario 1 and two boilers for Scenarios 2 and 3. The quantity of boilers to be installed is dependent of the number of apartments existing in each level as per the conclusions of the workshops conducted. The sixth and eight KPIs showed 'No impact' levels of Traffic and Internal Environment disruptions, respectively. The corresponding values were approximately the same for the three scenarios. This is mainly due to 'Site preparation' and 'Windows and/or doors replacement' activities which are the principal causes for Traffic and Internal Environment disruptions. Their quantities were estimated to 5 and 1 days, respectively, for the three scenarios. The seventh KPI showed 'Low impact' levels of Physical Space disruption that could be caused to occupants. For instance, Scenario 1 disruption results showed that the 'Radiant floor installation' activity caused nearly an overall 'Medium impact' level of Physical Space disruption, including two thirds of Scenario 1 duration (i.e., 22 days) of 'Medium impact' level. This confirmed previous research works that had stated the disruptive nature of renovating building floors (Pelsmakers et al., 2017) which have so far led to a low rate of retrofitting this building component (Fawcett, 2011, 2014).

TABLE 4: BIM element quantities of the Greek demonstration site

		WBS		
		Basement	**Ground Floor**	**1st Floor**
BIM Elements	**Facades/Walls (m2)**	81.07	100.26	97.08
	Floor (m2)	180.68	175.7	176.1
	Boilers	1	2	2
	Doors	1	14	14
	Windows	6	12	16

Furthermore, the assessment results of the three scenarios confirmed that no correlation exist between the disruption concept, including its four types, and the WBS renovated whatever its high. Thus, there were no relevant relationship or association between disruption and the level in which renovation works were conducted, i.e., the disruption concept was not spatially dependent. As illustrated in Fig. 9, the four disruption categories' values were not linearly related to the WBS considered at different highs (Basement, Ground floor and 1st floor) with respect to the Ground reference.

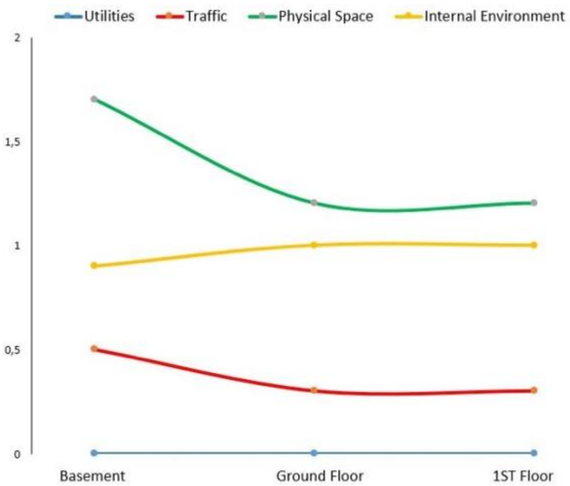


FIG. 9: Relationship between disruption and WBS

Moreover, in order to implement and demonstrate the validity of Whiteman et al.'s renovation strategy (Whiteman et al., 1988) proposing to prioritise the planning and execution of the most disruptive renovation activities as early as possible in the renovation process so as to reduce their disruption levels and impacts and make renovation works more acceptable by occupants, the three renovation scenarios were reassessed after ranking the renovation activities according to their unitary disruption values to enable scheduling more disruptive activities first before less disruptive ones. Results showed no significant change in the Utilities, Traffic, Physical Space and Internal Environment disruption values and levels, since the daily disruption values were still the same as well as the three scenario durations. However, the results also showed that increasing parallelism when planning and managing renovation activities would increase intensities and levels of disruption, especially Traffic and Physical Space ones, while shortening and optimising project durations, and vice versa. Fig. 10 illustrates a variant of Scenario 1 assessed using the TEA framework by implementing as much as possible parallel scheduling of the five renovation activities. Clearly, accelerating the retrofitting works and undertaking parallel activities in order to optimise renovation duration (i.e., 22 instead of 33 days, Figures 8 and 10) did not help in reducing the intensity and level of disruption that could be caused to occupants (i.e., Traffic: 0.7 instead of 0.5 ; Physical Space: 2.4 instead of 1.7). Consequently, Fawcett's one-off renovation strategy (Fawcett, 2011, 2014) which suggested to conduct renovation works in one go as quickly as possible rather than sequentially following an overtime strategy, would generate high intensities and levels of disruption, since most the activities will be undertaken concurrently. However, if the occupants were required to vacate the premisses, Fawcett's strategy could represent an efficient alternative and a good compromise to optimising both the renovation project duration and disruption, since these two project parameters were revealed to be negatively correlated.

KPIs			
ID	Value	ID	Value
1	29497.03	5	0
2	22	6	0.7
3	3.8	7	2.4
4	84.1	8	0.8

FIG. 10: Results of parallel planning of Scenario 1's activities

6 CONCLUSION, DISCUSSION AND PERSPECTIVES

Research has shown that a good communication with occupants to explain renovation works coupled with an efficient process for renovation strategies assessment and selection, contribute significantly to addressing the challenges and complexity of building renovation projects. This paper proposed the TEA framework to enable implementing these two strategies, and so allowing project managers to efficiently communicate with occupants using VDC tools, such as BIM and simulation, and evaluate renovation strategies to enable selecting and implementing the optimum one in terms of minimum disruption, cost, project duration, as well as number of workers required during the retrofitting phase. The TEA framework enables optimising existing BIM-based renovation collaboration workflows through making direct link with occupants in the design process by providing a set of KPIs relating to different project parameter classes including cost, duration, resources and disruption. The TEA framework consists of three main components, namely: (i) a renovation ontology and its database developed with the help of the RINNO project partners; (ii) the TEA tool along with a friendly GUI to enable automated renovation scenarios identification and evaluation; and (iii) the TEA KPIs to enable renovation strategies comparison and the design process optimisation. The TEA framework was demonstrated, following a step-by-step process, using a real case study which is the RINNO's multi-residence apartment building demonstration site located in Greece. Furthermore, the case study enabled: (i) discussing some characteristics of the disruption concept, such as potential correlations and relationships with other building components and project parameters; (ii) confirming the disruptive nature of renovating some building elements; (iii) demonstrating and examining the accuracy of the Fawcett's one-off renovation strategy and the Whiteman et al.'s heuristic.

Several workshops were organised with the RINNO project partners, including key organisations and companies working in the field of renovation, in order to formalise the concept of disruption and capture related knowledge and data. This first step enabled the development of a renovation ontology and populating its knowledge through a renovation database that was implemented using SQL Server. Using the Protégé platform (Stanford University, 2022), Amorocho et al., (2021) recently developed and implemented a renovation ontology dedicated to the installation of common renovation products, such as windows, HVAC components, and external thermal insulation panels. The renovation ontology proposed in this paper considers the general case of renovation projects and so proposes a holistic approach including all related activities: innovative products installation as well as general activities, such as 'Façade insulation with cavity insufflation'.

However, further research works are needed in order to extensively validate the content of the renovation knowledge and databases developed in terms of activities characterisation, equipment costs and relevancy. To do so, a large EU survey was launched, and data will be soon integrated. In addition, to ensure the TEA framework meets the practitioners' needs and prove its added value and benefits, the RINNO project provides a relevant application context with three other demonstration sites located in France, Denmark, and Poland, arranging a total of 3 386 m^2 of floor area. The TEA framework will be experimented by end users on the three additional demonstration sites that include both single-residence and multi-residence apartment buildings and integrate different construction systems and building amenities. Moreover, a Principal Component Analysis (PCA) (Jolliffe et al., 2016) would then be suitable to improve the disruption concept understanding and formalisation, and identify all its potential correlations with the renovation ontology concepts. A sensitivity analysis of the TEA tool will help exploring and validating its behaviour regarding the evaluation and the simulation of different renovation strategies and project parameters (Doukari et al., 2016).

To estimate disruption and evaluate a renovation strategy, the TEA framework calculates automatically a renovation schedule that complies with a set of activity constraints and rules using the Planning component; thus solving a Resource Constrained Project Scheduling Problem (RCPSP) (Hartmann, 1997) which is an NP-hard problem (Nondeterministic Polynomial) (Moradi et al., 2019). To do so, three classes of algorithms exist in the literature, namely: (i) exact methods; (ii) heuristics; and (iii) meta-heuristics (Habibi et al., 2018). Due to the nature of the RCPSP problem and the number of renovation activities and constraints considered in this framework, an exact method was implemented. For large instances of RCPSP however, this class of algorithms tend to be very slow, and heuristic and meta-heuristic methods are usually recommended to be used although approximate and non-optimal solutions can only be provided.

The TEA framework enables renovation scenarios identification and evaluation. However, the process of selecting the optimal solutions based on the TEA KPIs is still manual, and so error-prone and time-consuming. To better optimise this process and enable automatic renovation strategies optimisation, the RINNO Renovation Scenario Decision Support System (DSS) that will facilitate the selection of the optimum renovation scenario is being developed using a multi-criteria decision-making approach to allow analysing several alternatives involving various and often conflicting objectives and parameters (Mulliner et al., 2016).

Up-to-date and daily simulations and visualizations are very useful to keep occupants informed about project progress and the intensity and level of disruptions that could be caused. To be enabled, this functionality requires the integration of the time as a fourth dimension, which is known as 4D BIM (Doukari et al., 2022a), alongside linking real-time data taken from sensors to the BIM model (Doukari et al., 2022b). 4D BIM-based disruption simulations will enable linking the renovation activities and their sub-activities to corresponding 3D-BIM elements, and then to related disruption data. This would help occupants to be aware, be prepared, and take necessary actions when it is required according to the levels of disruption expected.

Ultimately, quality assurance (QA) and quality control (QC) of BIM data are crucial concepts and concurrent processes for data quality management (Doukari et al., 2022c). Research in this domain is still lacking and no existing comprehensive framework for semantic compliance checking has been proposed (Doukari et al., 2022d). The extension of the renovation ontology proposed in this paper so as to integrate QA-QC related knowledge and ensure accuracy for both syntactic and semantic BIM data will enable optimisation and automation of the TEA framework which is currently based on manual and unfortunately tedious BIM data checking and preparation.

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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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