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A BIM based tool for evaluating building renovation strategies: the case of three demonstration sites in different European countries

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Abstract

Purpose – Buildings are among the biggest contributors to environmental impacts. To achieve energy-saving and decarbonisation objectives while also improving living conditions, it is imperative to undertake large-scale renovations of existing buildings, which constitute the greater part of building stock and have relatively low energy efficiency. However, building renovation projects poses significant challenges owing to the absence of optimised tools and methods for planning and executing renovation works, coupled with the need for a high degree of interaction with occupants.

Design/methodology/approach – This paper describes the development of an automated process, based on building information modelling (BIM) and the principal component analysis method, for overcoming building renovation challenges. The process involves the assessment and simulation of renovation scenarios in terms of duration, cost, effort needed and disruptive potential. The proposed process was tested in three case studies; multi-residence apartment buildings comprising different construction components and systems, located in Greece, France and Denmark, on which six different renovation strategies were evaluated using sensitivity analysis.

Findings – The developed tool was successfully able to model and simulate the six renovation scenarios across the three demonstration sites. The ability to simulate various renovation scenarios for a given project can help to strategise renovation interventions based on selected key performance indicators as well as their correlation at two different levels: the building level and the renovated surface area level.

Originality/value – The objectives of this paper are twofold: firstly, to present an automated process, using BIM, for evaluating and comparing renovation scenarios in terms of duration, cost, workers needed and disruptive potential; next, to show the subsequent testing of the process and the analysis of its applicability and behaviour when applied on three live demonstration sites located in three different European countries (France, Greece and Denmark), involving six renovation scenarios.

Keywords Building renovation, Sensitivity analysis, Techno-economic assessment, Principal component analysis, Process automation, BIM, Occupant disruption, Scenario simulation, Demonstration site

Paper type Research paper

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1. Introduction

The construction industry's demand for natural resources accelerates climate change, and inefficient buildings negatively impact both humans and their environment (UN, 2021). For instance, buildings in Europe are responsible for some of the greatest environmental impacts (around 50% consumption of raw materials, 40% of energy and 33% production of waste) with the existing building stock, because of its overwhelming proportion and its inferior energy efficiency, warranting the greatest concern and remedial action (Passoni *et al.*, 2021).

Superficial and minimally disruptive refurbishment measures are insufficient for achieving climate change targets (UN, 2021); instead, this requires more wholescale, innovative and disruptive interventions (Killip *et al.*, 2020; Topouzi, 2016). While there is a significant concern about the rate and volume of renovation projects needed to meet the 2030 and 2050 European energy-saving and decarbonisation goals (Pohoryles *et al.*, 2020), there are at present just a few examples of deep renovation projects in social and private housing (Radian, 2009).

Renovation projects present many challenges: these include a lack of optimised tools and methods for their planning and execution (Gholami *et al.*, 2013) and high level of interaction and interference with occupants (Egbu, 1994; Fawcett and Palmer, 2004; Grath *et al.*, 2013). Disruption (including disturbance *by* or *to* occupants) is a particular challenge (Designing Buildings, 2022; Fawcett, 2011; Trowers and Hamlins, 2022), which, despite its likelihood, should be managed and mitigated. Early-stage simulations, especially building information modelling (BIM)-based methods, have been shown to be useful in identifying optimised renovation strategies and enabling better management of the retrofitting process and its challenges (Chaves *et al.*, 2017; Kemmer and Koskela, 2012; Volk *et al.*, 2014).

The contribution of this paper is twofold. Firstly, it presents an automated process, based on BIM, for the assessment and simulation of renovation scenarios in terms of duration, effort, cost and disruptive potential. Secondly, it analyses the application of the automated process to three demonstration sites located in three different European countries, on which six different renovation strategies were evaluated using sensitivity analysis. This study was conducted as part of a large European research project – the RINNO project (Doukari *et al.*, 2021) – that aims to accelerate building renovation in Europe.

The contents of the remainder of the paper are as follows. Section 2 presents state-of-the-art approaches to building renovation methods, tools and technologies, and how these have been proposed for overcoming challenges, including that of occupant disruption. The underlying research methodology and data collection relating to the featured work are described in Section 3, which then presents the automated techno-economic assessment (TEA) process developed; the three demonstration sites; and the six renovation scenarios considered. Results of the assessment process are presented and discussed in Section 4, and a general discussion, conclusions and future works are outlined in Sections 5 and 6.

2. Building renovation: state-of-the-art

2.1 Incorporating advanced technologies

The growing application of advanced technologies and tools in the architecture, engineering and construction industry offers real potential for addressing current renovation project issues. Several integrated systems based on parallel technological advancement in hardware, software and cloud computing platforms have been developed to improve executing building renovation processes (Altohami *et al.*, 2021). By integrating BIM and Internet of Things devices through service-oriented architecture, it has become possible to collect and share the geometric, semantic and real-time performance data related to buildings, thereby enabling large-scale technological innovations and value-added services for supporting sensing, diagnosis, planning and completion of retrofitting works (Altohami *et al.*, 2021).

An integrated system of both BIM and blockchain technology was proposed in the study of Nawari and Ravindran (2019) to improve and streamline the reconstruction and retrofitting process of buildings in post-disaster recovery by reducing the time and resources usually required for rebuilding. Koh (2020) explored building contextual information, proposed metadata models and methods to better characterise the smart building concept and developed several efficient applications, such as an energy assessment and visualisation dashboard to visualise the timeseries data of energy usage for a particular area in a building. To address the huge amount of data generated during the operation and maintenance phase of buildings and help discovering and providing useful knowledge and rules to inform renovation and repairs activities, Peng *et al.* (2017) proposed a hybrid approach based on BIM and using three combined data mining techniques, namely, cluster analysis, outlier detection and a cluster-based algorithm on temporal complexities to identify logic relationships between records. Aiming to improve building energy retrofitting, Desogus *et al.* (2017) used the concept of "cognitive building" to enable linking real-time data taken from sensors to BIM models and then retrieve useful information based on users' behaviour and feedbacks to adapt its utilisation and optimise energy consumption and user's comfort.

In the context of historic building restoration and rehabilitation, Solla *et al.* (2020) developed an integrated approach using BIM and several non-destructive testing tools and techniques, including light detection and ranging, ground-penetrating radar (GPR), infrared thermographic, anomaly identification based on RGB imaging and unmanned aircraft system. The approach was then tested and demonstrated on the Monastery of Batalha in Portugal. Maierhofer (2003) investigated GPR technologies, usually used for geophysical surveys and based on the propagation of short electromagnetic impulses, to regularly inspect, assess and monitor the quality of building concrete structures and demonstrated their usefulness. Amano *et al.* (2018) proposed a hybrid approach that enables coupling (i) laser scanning techniques to create the 3D point cloud model including geometrical and spatial information, with (ii) hyperspectral imaging technologies providing high-resolution images of spectral and spatial information of scenes. The integration of 3D point cloud data into hyperspectral images enabled semantic model enrichment by identifying some semantic information, such as surface materials, and so generating the BIM model dedicated to facilitating refurbishment works from the 3D representation.

Based on experts' input and knowledge from renovation engineering documents, Amorocho and Hartmann (2021) developed the Reno-Inst ontology for installation of regularly-used renovation products, such as windows, HVAC items and insulation panels. The Reno-Inst ontology was implemented using the Protégé platform (Stanford University, 2022), evaluated and validated in terms of content and applicability with experts and through a real renovation case study.

Dalla Mora *et al.* (2018) developed an easy-to-use open source worksheet-based tool to evaluate and compare different packages of renovation measures to identify the optimal renovation strategy in terms of cost-effective energy and carbon emissions. The proposed tool is based on a life cycle approach that integrates several parameters (e.g. energy consumption, carbon emissions and costs) with emphasis on the overall benefits of a renovation project, such as building quality and comfort improvements, to support decision makers in building renovation optimisation. Other building optimisation tools that have been adapted to renovation projects and tested and compared in the literature include MATLAB toolbox (2022), Generic Optimization Program (2022), Building Energy Optimization ToolMATLAB (2022), GENE_ARCH (Caldas, 2006), MCDM-23 (Wright *et al.*, 2002), MOBO (Matti Palonen, 2014), NECADA (Fonseca Casas and Fonseca Casas, 2015) and ThermalOpt (Welle *et al.*, 2011).

2.2 Decision-making tools

To define clear performance objectives for a renovation project, reliable assessment methods are required to support related decision processes. These methods can be divided into three classes (Menna *et al.*, 2022): firstly, sustainable protocols, such as BREEAM Projects (2022), DGNB System (2022) and LEED v4 (2022), that offer energy and environmental-related targets during the decision process; then, depending on the target of the assessment, component assessment methods (Giresini *et al.*, 2020) and global assessment methods (Caruso *et al.*, 2020). The building envelope is the most investigated component in the literature due to its role and location as a separating element between the internal and external environment (Ascione *et al.*, 2021). For instance, in Bui *et al.*'s (2020) study, a computational optimisation approach was proposed to evaluate the performance of responsive envelope systems that can dynamically adapt their structural and thermal functions, and in Cascone *et al.* (2018) a multi-objective optimisation analysis was developed for phase-change materials in building envelope components.

Passoni *et al.* (2021) introduced the sustainable building renovation framework to minimise building life cycle impacts. Based on several methods, including multi-criteria decision-making, they created a multidisciplinary performance-based design approach, with expanded life cycle analyses, that combines the three pillars of sustainability: environmental, economic and social. They identified two main approaches of existing sustainable building renovation. The first category consists of techniques and solutions that have been developed to improve building sustainability and overcome renovation barriers, such as techniques avoiding the relocation of occupants and so minimise hazard and disruption by enabling installing, implanting and assembling renovation products only from outside of the building (Margani *et al.*, 2020). The second category consists of decision-making approaches that evaluate and select the most optimised renovation strategies in terms of cost, and environmental and social impacts, such as LCA approach (ISO 14040, 2006) which is developed to evaluate and quantify the environmental impacts of a building during all its life cycle.

2.3 The problem of occupant disruption

The challenge of disruption in renovation projects has already been highlighted, as has the characteristic and problematic role of occupants, as either a disruptive factor themselves, or as the objects of disruption. This requires planners and managers of retrofitting projects to adapt their sequencing, safety plans and logistics (Kelsey, 2003; Salvalai *et al.*, 2017) to minimise the time and cost of disruption, ideally after appraising different scenarios (Tokede, 2016). These include trade-offs between "one-off" and "over-time" interventions, such as strategies that advance the timing of more disruptive activities (Whiteman and Irvvig, 1988), requiring tenants to vacate the building for a fixed period (Fawcett, 2014), prioritising retrofit objectives (e.g. improved energy efficiency and seismic safety) (Moschella *et al.*, 2018) and the importance of early and effective communication with residents (Vainio, 2011). In each case, a categorisation of different disruptions is useful. These can range from a simple low (exterior) or high (indoor) disruptive activities (Vadodaria *et al.*, 2010), a three-level ("low", "medium" and "high") classification (Tokede, 2016) or more detailed differentiation of the effects of groups of activities (creating problems with utilities, traffic, space, access, pollution, etc.) (Chaves *et al.*, 2017).

2.4 Research gaps and contribution

Automated processes and digital tools for evaluating and comparing renovation project strategies are lacking, especially in terms of occupant disruption. New building projects, on the other hand, have benefited from the availability of several such design, planning and management tools. Where these tools have been adapted to the context of building renovation work (as in Amorocho and Hartmann, 2021), they have performed less efficiently and effectively than in their original context (Singh *et al.*, 2014). Existing research in adapting such tools for renovation work also lack sufficient testing in real-world case studies; and their performance with specific inputs, context and constraints has rarely been examined. The present study derives from an EC-funded project called RINNO (Doukari *et al.*, 2021; Lynn *et al.*, 2021) and aims to overcome these gaps and contribute to the wider EU target of accelerating the rate of building renovation in Europe. The objectives here are twofold: firstly, to present an automated process, using BIM, for evaluating and comparing renovation scenarios in terms of duration, cost, workers needed and disruptive potential; next, to show the subsequent testing of the process and the analysis of its applicability and behaviour when applied on three live demonstration sites located in three different European countries, involving six renovation scenarios. The principal component analysis (PCA) method was selected to perform a sensitivity analysis (Doukari *et al.*, 2016; Jolliffe and Cadima, 2016) that enables an improved understanding of costs, duration, workers needed and disruption generated in building renovation projects at two different levels: the building level and renovated surface area.

3. Materials and methods

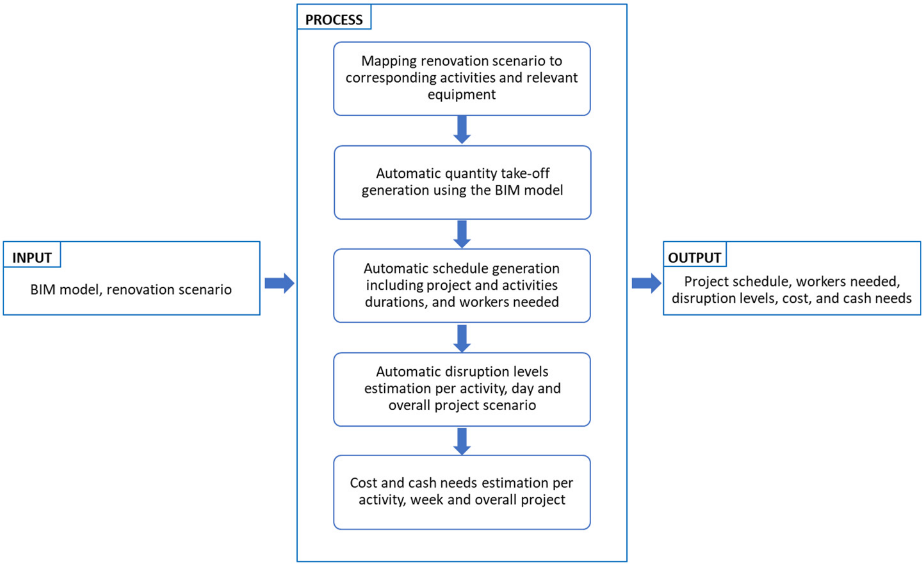
3.1 Techno-economic assessment process

The automated TEA process was developed to enable project managers to efficiently simulate and evaluate various renovation scenarios and, as illustrated in Figure 1, select the best in terms of least disruption to occupants, together with additional renovation project parameters, such as project duration, cost and effort needed for the renovation works. The tool is designed to improve existing collaboration workflows in renovation projects using BIM. It considers occupants in the earliest stages of the design process by calculating a set of key performance indicators (KPIs) relating to project cost, duration, resources required and disruptive potential. The TEA process is based on six main steps that can be detailed as follows:

3.1.1 Building information modelling data preparation. As illustrated in Figure 1, the TEA process requires a BIM model as input. This latter is used to provide the type and quantities of the building elements to be renovated, such as floors, facades, windows/doors, roof and equipment. To enable correct data extraction and data quality control, the BIM model needs to be checked, and its data prepared within the BIM authoring platform (here, Autodesk Revit). Although there is no requirement for the implementation of any specific classification systems, this step ensures that the BIM model complies with some basic modelling rules such as:

- BIM objects should be modelled and named using elemental objects provided by the English version of the BIM authoring platform.
- The BIM model should be created with respect to a level-based modelling approach. This means that a BIM element should belong to only one level. For example, a “Wall” object should not pass through many BIM levels and must be bounded by only two levels.

3.1.2 Renovation scenario identification. The second step consists in defining a renovation scenario that will be simulated to estimate disruptions caused to occupants. As illustrated in Table 1, the TEA process provides a common list of typical activities involved in renovation projects of residential buildings. The renovation activities were identified and characterised through workshops with the RINNO project’s industrial partners from 10 different EU



Source: Authors' own creation

Figure 1.
Automated techno-economic assessment (TEA): input, process and output

Table 1.
Renovation activities

ID	Activity	ID	Activity
A	Site preparation	J	Solar collectors on roof
B	Façade insultation	K	Wall-mounted/integrated heat storage
C	Façade insulation with plug-and-play system	L	Condensing boiler installation
D	Façade insulation with photovoltaic integrated plug-and-play system	M	Mini split installation
E	Façade insulation with cavity insulated	N	Radiant floor installation
F	Roof insulation	O	Decentralised mechanical ventilation system
G	Photovoltaics on roof	P	Centralised mechanical ventilation system
H	Windows and doors replacement	Q	Insulation of existing heating and domestic hot water pipes
I	Windows replacement with photovoltaic	R	Insulation from the inside

Source: Authors' own creation

countries so as to be usable and adapted to any EU contexts (Doukari *et al.*, 2023). This list enables users to create their own renovation scenarios for residential buildings and simulate them automatically. The TEA process automates the techno-economic assessment and simulation processes (that include disruption, resources, project duration and cost) and provides useful components such as the scenario definition component that can be used to optimise the renovation strategy of residential buildings.

3.1.3 Activity constraints definition. The third step is the definition of the renovation constraints that must be satisfied during simulation. The TEA process provides an Excel template in which users can define renovation activities, constraints and rules. The Excel template is pre-populated with predefined constraints (determined by RINNO's industry partners) to better organise and manage a renovation project. This includes precedence rules for activity sequencing in accordance with a project's work breakdown structure (WBS). Externalising the definition of renovation constraints through an Excel file that is independent from the TEA code ensures better flexibility, maintainability and adaptability of the TEA tool.

3.1.4 Renovation schedule generation. Once the first three steps are completed, the disruption estimation process can be launched, and a renovation schedule is automatically generated while sets of project KPIs, such as "average daily workers" and "overall project workers" are calculated. Here, a resource-constrained project scheduling problem (RCPSP) (Hartmann, 1997) is encountered. To solve this type of non-deterministic polynomial-hard problem (Blazewicz *et al.*, 1983), three classes of algorithms exist, namely:

1. "exact" mathematical methods;
2. heuristics; and
3. meta-heuristics (Habibi *et al.*, 2018).

Due to the nature of the problem and the number of renovation activities and constraints considered in this study, an "exact method" was implemented for the TEA process. However, for large and complex RCPSP instances where this class of algorithm can be very slow, the heuristic and meta-heuristic methods are usually recommended though their solutions are approximate and not guaranteed to be optimal.

3.1.5 Disruption simulation. This step estimates the different types of disruption using the schedule generated at the previous step. To do so, the TEA process's database is queried, and the corresponding disruption values are estimated and assigned accordingly. This database was gathered, structured and validated in workshops with RINNO's industry partners and includes data related to renovation activities, their sub-activities and procedures, duration, cost, equipment and disruptive potential. The TEA process enables contemplating four types of disruption, namely:

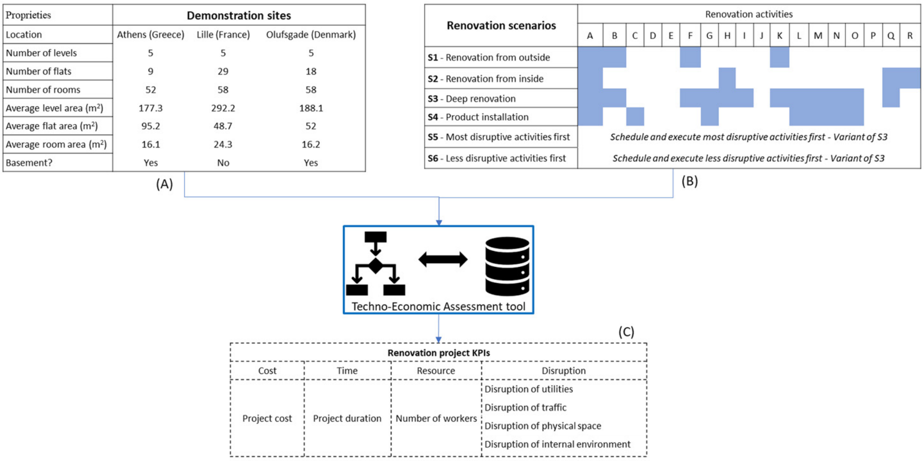
1. disruption of "Utilities", such as gas, electricity and water interruptions;
2. disruption of "Traffic", such as access to the building or flat being blocked or restricted;
3. disruption of "Physical Space" when occupants have to vacate part of or the entire building, or where their daily activities and comfort are interrupted or impacted by the retrofitting works; and
4. disruption of "Internal Environment" when retrofitting works cause pollutions, such as noise, dust, daylight reduction, vibration, odour and demolition debris.

Following this step, KPIs are calculated for the four types of disruption and reported to allow further evaluation and optimisation of renovation scenarios.

3.1.6 Weekly cash needs estimation. The TEA process allows users to automatically estimate project cash needs on a weekly basis and per WBS item, using the aforementioned TEA database-based co-created with RINNO's industry partners.

3.2 Sensitivity analysis of the techno-economic assessment process

To test the TEA process and verify its sensitivity to the involved data and building parameters, the methodology illustrated in Figure 2 was implemented. Three case studies from different European countries, which involved six renovation scenarios, were selected. The six renovation scenarios were simulated and compared using the TEA process, and



Proprieties	Demonstration sites		
Location	Athens (Greece)	Lille (France)	Olufsgade (Denmark)
Number of levels	5	5	5
Number of flats	9	29	18
Number of rooms	52	58	58
Average level area (m²)	177.3	292.2	188.1
Average flat area (m²)	95.2	48.7	52
Average room area (m²)	16.1	24.3	16.2
Basement?	Yes	No	Yes

(A)

Renovation scenarios	Renovation activities																	
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
S1 - Renovation from outside	🟦	🟦				🟦					🟦							
S2 - Renovation from inside	🟦							🟦									🟦	🟦
S3 - Deep renovation	🟦	🟦				🟦	🟦	🟦	🟦		🟦	🟦	🟦	🟦			🟦	
S4 - Product installation	🟦		🟦				🟦					🟦	🟦	🟦				
S5 - Most disruptive activities first	*Schedule and execute most disruptive activities first - Variant of S3*																	
S6 - Less disruptive activities first	*Schedule and execute less disruptive activities first - Variant of S3*																	

(B)

Renovation project KPIs			
Cost	Time	Resource	Disruption
Project cost	Project duration	Number of workers	Disruption of utilities Disruption of traffic Disruption of physical space Disruption of internal environment

Figure 2.
Sensitivity analysis of the TEA process

Note: (A) Demonstration sites, (B) renovation scenarios; (C) project KPIs
Source: Authors' own creation

their KPIs were calculated. A sensitivity analysis was then conducted using the PCA approach (Doukari *et al.*, 2016; Jolliffe and Cadima, 2016). PCA is considered as one of the most frequently and widely used multivariate data analysis methods in many research fields. PCA consists in projecting observations from a p-dimensional space with p variables to a k-dimensional space. PCA aims to conserve the maximum amount of the total variance of the data set. The initial dimensions are transformed into new dimensions or components also called "Axes" or "Factors". The information associated with the first two or three factorial axes should represent a sufficient percentage of the total variability of the initial information which makes the visual interpretation much easier. An optimal visualisation of the variables and data is then provided based on "biplots" representation.

The BIM data used along with the renovation scenarios identified and simulated are detailed in the following subsections.

3.2.1 Building information modelling data: three demonstration sites. The RINNO project (Doukari *et al.*, 2021) provides a relevant application context with three demonstration sites located in Greece, France and Denmark, accounting for a total floor area just over 3,000 m^2, and representing three multi-residence apartments that had been built using different construction components and equipment, and equipped with different systems and building amenities. Figure 2(A) outlines the main characteristics and properties of each demonstration site.

3.2.2 Renovation scenarios. Figure 2(B) presents the renovation scenarios identified and simulated using the TEA process. Scenario S1 includes renovation activities that are carried out from outside the building, whereas Scenario S2 is dedicated to renovation from the inside. Scenario S3 represents a deep renovation scenario which includes all activities that are compatible and can be concurrent within the same renovation initiative. For example, referring to the earlier Table 1, activity "A" is compatible and can be concurrent with any other renovation activities, whereas activity "B" is not compatible with activities "C", "D", "E" and "R". If "B" is conducted, none of activities "C", "D", "E" and "R" can be performed. Scenario S4 only includes activities relating to product installation, such as photovoltaic system installation. However, Scenarios S5 and S6 were defined as two variants of S3 to test two different heuristics, namely, executing most disruptive renovation activities as early as possible in the renovation process [i.e. the Whiteman *et al.*, heuristic (1988)] and its opposite process (i.e. executing less disruptive activities first).

3.2.3 Project key performance indicators. Figure 2(C) illustrates the project KPIs developed and used to enable renovation scenarios comparison and selection, and Table 2 provides the corresponding formulas implemented and calculated.

4. Results

4.1 Global analysis at the building level

Table 3 summarises the simulation results. The findings indicate that the renovation of the multi-residence apartment building in the French context yields the highest score of duration, cost and number of workers needed, followed by the Danish and Greek demonstration sites.

For instance, a deep renovation (S3) of the French building needs 814 days, 2,200 man-days and costs 904,796 euros, whereas a renovation from outside (S1) involves 336 days, 770 man-days and 229,466 euros. Table 3 shows that duration, cost and the number of workers involved in S3, S5 and S6 renovation activities are the same for each demonstration site. These results are consistent with the nature of the renovation activities that are associated with each scenario. In fact, Scenario S3 and its two variants refer to a deep renovation which

Project KPIs	Calculation formulas
Project cost	$\sum_{x=1}^{x=Duration_{Project}} \sum_{i=1}^{i=n} Average\ \ activity\ \ cost(a_{ix}) + Average\ \ equipment\ \ cost(a_{ix})$ where a_{ix} are activities scheduled for day x.
Project duration	$EndDate_{Project} - StartDate_{Project}$
Number of workers	$\sum_{x=1}^{x=Duration_{Project}} \sum_{i=1}^{i=n} Workforce(a_{ix})$
Disruption of utilities	$\dfrac{\sum_{x=1}^{x=Duration_{Project}} \underset{i=1}{\overset{i=n}{MAX}} \left(Disruption_{Utilities}(a_{ix})\right)}{Duration_{Project}}$
Disruption of traffic	$\dfrac{\sum_{x=1}^{x=Duration_{Project}} \underset{i=1}{\overset{i=n}{MAX}} \left(Disruption_{Traffic}(a_{ix})\right)}{Duration_{Project}}$
Disruption of physical space	$\dfrac{\sum_{x=1}^{x=Duration_{Project}} \underset{i=1}{\overset{i=n}{MAX}} \left(Disruption_{Physical\ \ Space}(a_{ix})\right)}{Duration_{Project}}$
Disruption of internal environment	$\dfrac{\sum_{x=1}^{x=Duration_{Project}} \underset{i=1}{\overset{i=n}{MAX}} \left(Disruption_{Internal\ \ Environment}(a_{ix})\right)}{Duration_{Project}}$

Source: Authors' own creation

Table 2.
Renovation project KPIs

Table 3.
Simulation results

					Greek project KPIs		
				Disruption			
Renovation scenarios	Time (day)	Cost (€)	Workers (man-day)	Utilities	Traffic	Physical space	Internal environment
S1	171	102,569.1	389.299	0.029	0.088	0.020	2.006
S2	198	198,960.1	470.101	0	0.540	0	1.294
S3	489	531,361.4	1,223.901	0.035	0.031	0.838	1.330
S4	310	472,221.5	745.001	0.039	0.048	1.311	1.333
S5	489	531,361.4	1,223.901	0.035	0.031	0.838	1.330
S6	489	531,361.4	1,223.901	0.035	0.031	0.838	1.330
				French project KPIs			
S1	336	229,466.2	769.699	0.056	0.045	0.039	2.096
S2	376	354,742.6	903.703	0	0.556	0	1.297
S3	814	904,795.8	2,200.192	0.056	0.018	0.847	1.402
S4	523	832,694.7	1,288.600	0.051	0.029	1.293	1.379
S5	814	904,795.8	2,200.192	0.056	0.018	0.847	1.402
S6	814	904,795.8	2,200.192	0.056	0.018	0.847	1.402
				Danish project KPIs			
S1	188	47,000	473.500	0.048	0.080	0.033	2.529
S2	328	402,149.3	724.102	0	0.485	0	1.369
S3	685	821,710.5	1,685.700	0.049	0.022	0.780	1.487
S4	467	430,063.3	1,075.299	0.053	0.032	1.159	1.442
S5	685	821,710.5	1,685.700	0.049	0.022	0.780	1.487
S6	685	821,710.5	1,685.700	0.049	0.022	0.780	1.487

Source: Authors' own creation

usually involved a higher level of resources (i.e. workers, duration and budget) compared to the other scenarios, regardless of the site location.

The simulation results also indicate that Scenario S1 (renovation from outside) required fewer workers, shorter duration and less cost than S2 (renovation from inside) and S4 (product installation). Moreover, the results reveal that the renovation process in the French case study involved nearly the same costs for four scenarios (S3, S4, S5 and S6) despite S4 requiring less time and fewer workers. This can be explained by the fact that product installation activities usually cost more than traditional renovation activities.

The disruption simulation results are also provided in Table 3. The second scenario (S2), which is dedicated to renovation from the inside, causes no disruption of utilities such as gas, electricity and water interruptions. Conversely, the results indicate that all the other scenarios present a similarly high level of disruption of utilities, especially for the French and Danish buildings. Gas, electricity and water interruptions are less significant in the Greek building compared to the French and Danish ones.

The results show similar behaviour of the three demonstration buildings in terms of disruption of traffic, physical space and internal environment (Table 3). For the three demonstration sites, the simulation results highlight that Scenario S2 leads to a high disruption of traffic compared to the other renovation scenarios that have very low impact. The access to the building or flat is substantially blocked or restricted when the renovation activities are performed from the inside. In addition, S2 has no disruption of physical space, whereas S1 causes very low level. Therefore, it can be assumed that daily activities and comfort of occupants are most impacted when the retrofitting works consist of deep renovation (S3, S5 and S6) or product installation (S4).

The results also show that renovation from outside the building (S1) causes the highest degree of disruption of internal environment ($2 \leq$ disruption ≤ 2.5) for the three buildings. Scenario S1 causes relatively more disruption of internal environment in the Danish case study (2.5) compared to the Greek and French ones (2). Renovation activities from outside result in more pollution such as noise, dust, daylight reduction, vibration, odour and demolition debris compared to other scenarios. However, these scenarios (S2, S3, S4, S5 and S6) account for the same disruptive potential of internal environment ($1.3 \leq$ disruption ≤ 1.5) for the three buildings.

Furthermore, Scenarios S3, S5 and S6 show similar behaviour for the seven variables and for the three demonstration sites. This result can be explained by the fact that Scenarios S5 and S6 are defined as two variants of S3. The outputs of the TEA model do not show any difference between the three renovation scenarios. Two hypotheses can be put forward. On the one hand, it can be assumed that the model, as defined based on the implemented approach and simulation rules, is not able to capture the differences that are supposed to exist between S3, S5 and S6. On the other hand, one of the possible explanations is that the differences between the three scenarios are insignificant, and the general applicability of the Whiteman *et al.*'s heuristic (1988) is questionable.

Moreover, two PCAs were performed (Figure 3). The first PCA [Figure 3(a)] was carried out to establish a typology of the six renovation scenarios according to the seven selected variables calculated. The results, which provide a synthetic visualisation of the distribution of the six scenarios, enable evaluating the relevance of the scenarios' definition.

The PCA plot [Figure 3(a)] visually shows the results for the first two components that explain 93% of the variation in the data. The first component sums up 67% of the variance explained. It has large positive associations with cost, duration, workers, physical space and utilities, while having large negative association with traffic. For instance, in the Greek demonstration case, the first axis is correlated with the five variables cost (98%), duration (95%), workers (94%), physical space (87%) and utilities (76%), while it is negatively correlated with the traffic variable (−74%). The second component explains 26% of the inertia. This axis is positively correlated with internal environment and utilities factors, while has negative correlation with disruption of traffic.

Figure 3(a) shows four groups of scenarios can be distinguished: S1, S2, S4 and S3-S5-S6. Scenario S1 is characterised by high disruption values of internal environment and utilities and low values of traffic, physical space, cost, duration and workers. S2 is more characterised by high traffic disruption values and low values of utilities disruption, cost, duration, workers and physical space. Scenarios S3, S5 and S6 exhibit similar characteristics because S5 and S6 are two variants of S3.

The second PCA was performed to establish a typology of the three demonstration buildings based on the seven variables derived from the TEA tool. The PCA plot in Figure 3(b) shows the results for the first two components that explain 100% of the variance in the data. The first component accounts for 70% of the variance explained, whereas the second component explains 30% of the inertia.

The three European projects are clearly differentiated from each other [Figure 3(b)]. The Greek case study stands out clearly from the French and Danish buildings. The Greek residential building is characterised by high values of disruption of traffic, especially for S1, S3, S4, S5 and S6. Conversely, the French building is characterised by high scores of duration, cost, workers and disruption of utilities and physical space (S1 and S2).

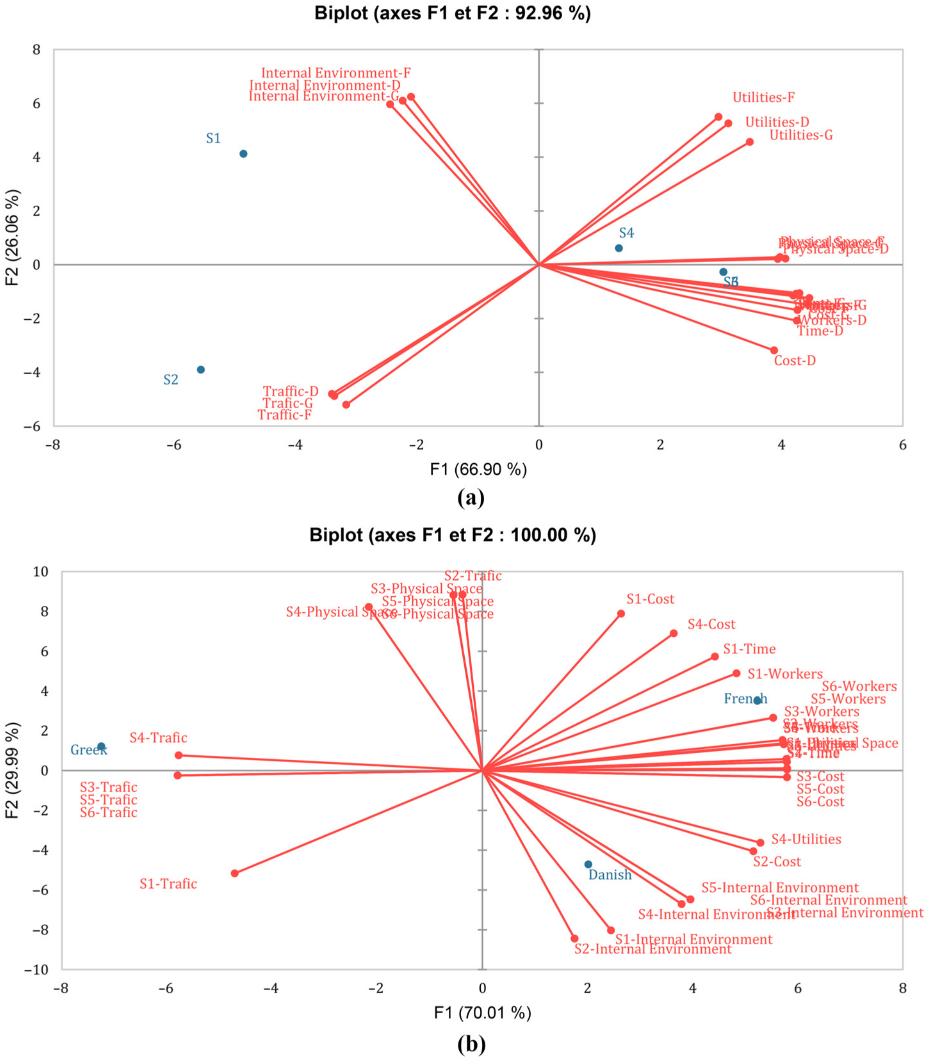


Figure 3.
PCA analyses based on the simulation outputs

Notes: (a) Distribution of the renovation scenarios; (b) distribution of the three demonstration sites
Source: Authors' own creation

4.2 Analysis based on renovated surface area

To complement the first analysis conducted at the building level, the model outputs are further analysed for the three demonstration sites according to the characteristics of the four main renovation scenarios (i.e. S1, S2, S3 and S4). The output variables such as cost, duration and number of workers are calculated and discussed per renovated square metre (m^2) so as to compare the three demonstration sites. In addition, a correlation analysis is carried out to identify and quantify behaviours between these variables. The total area of the Danish building is 940 m^2 compared to 1,461 m^2 and 886 m^2 for the French and Greek case studies, respectively.

The findings of this analysis reveal a large positive correlation between the three variables. For example, an increase in the duration leads to an increase in the number of involved workers and then the unit price. Spending more time on renovation site requires more workers and costs more. A high linear correlation scores point a strong linear relationship between the duration, workers involved and cost per renovated square metre. More specifically, duration and number of workers are highly related (99%). This perfect positive correlation between the duration and the number of needed workers indicates that these two variables move together by the same percentage and direction. A positive correlation exists between the number of involved workers, the duration and the renovation activities' associated price per renovated square metre.

Table 4 summarises the estimated cost, duration and number of workers involved per renovated square metre. The analysis is performed for the three demonstration sites according to S1, S2, S3 and S4 scenarios. Table 4 illustrates that the deep renovation scenario (S3) is clearly the most expensive one followed by S4, S2 and S1, respectively. For example, a deep renovation of the Danish, Greek and French demonstration buildings costs 874, 774 and 619 €/m^2, respectively. The product installation scenario (S4) in Denmark costs 457 €/m^2, while deep renovation scenario costs 874 €/m^2. The difference in price per square metre between S3 and S4 is more important for the Danish site compared to the French and Greek sites, which corresponds to a difference of 417 €/m^2. However, for the French and Greek buildings, the difference between the two scenarios S3 and S4 is 49 and 86 €/m^2, respectively. Furthermore, a product installation involving eight activities is more expensive than from the inside or the outside renovation scenarios. Scenario S4 costs the price of both S1 and S2 scenarios combined.

Moreover, a renovation project from the outside only is found to be the cheapest scenario. It costs 157, 159 and 50 €/m^2 for the French, Greek and Danish sites, respectively. Renovation from the outside in French and Greek, which involves only four renovation activities, is three times more expensive than in Denmark. In addition, renovation from the inside, which includes four renovation activities, is more expensive in Denmark (427.59 €/m^2) compared to France (243 €/m^2) and Greece (290 €/m^2).

The analysis shows that duration and number of workers variables follow the same trend as the cost variable for the selected scenarios. Scenario S3 requires more time and

Scenarios	Building	Total area (m^2)	Duration (day/m^2)	Cost (€/m^2)	Workers (man-day/m^2)
S1	Greek	686.5	0.25	149.41	0.57
	French	1,461	0.23	157.06	0.53
	Danish	940.5	0.20	49.97	0.50
S2	Greek	686.5	0.29	289.82	0.68
	French	1,461	0.26	242.81	0.62
	Danish	940.5	0.35	427.59	0.77
S3	Greek	686.5	0.71	774.02	1.78
	French	1,461	0.56	619.30	1.51
	Danish	940.5	0.73	873.70	1.79
S4	Greek	686.5	0.45	687.87	1.09
	French	1,461	0.36	569.95	0.88
	Danish	940.5	0.50	457.27	1.14

Source: Authors' own creation

Table 4.
Cost, duration and number of workers per square metre

workers followed by S4, S2 and S1, respectively. Table 4 points a trend between duration and workers variables per square metre. An increase in the duration leads to an increase in the number of workers per square metre. This finding is in accordance with the observed high intensity of correlation between these two factors which is almost perfect ($R = 99\%$).

The results also indicate that renovation from the outside according to S1 takes less time compared to S2, S4 and S3. In France, the duration is 0.23, 0.26, 0.36 and 0.56 day/m^2 for scenarios S1, S2, S4 and S3, respectively. Moreover, renovation in Denmark according to S2, S3 and S4 requires relatively more workers and duration and thus costs more compared to Greece and France. The duration per square metre raises an important issue in terms of price, number of needed workers but also in terms of the daily comfort of occupants; a renovation project that lasts over time can lead to longer disruption of utilities, traffic, physical space and internal environment.

These findings prove the ability of the TEA process outputs to simulate the four selected scenarios. The results reveal that deep renovation scenario (S3) is more expensive and requires more time and workers compared to product installation (S4), renovation from the inside (S2) and renovation from the outside (S1), respectively. These results are consistent with the numbers and types of renovation activities involved in each scenario. The deep renovation scenario includes 12 activities (A, B, F, G, H, I, K, L, M, N, O and Q) compared to product installation (A, C, G, I, L, M, N and O), renovation from the inside (A, H, Q and R) and renovation from the outside (A, B, F and K) scenarios which are associated with 8, 4 and 4 renovation activities, respectively. Scenario S3 includes all of the activities involved in S4 except the C activity (i.e. "Façade insulation with plug-and-play system"). It also includes the four activities involved in S1 and three from the four activities of S2.

5. Discussion

The work presented is new given the evidenced gap in the literature around BIM-based tools for automatic evaluation of renovation projects. The literature revealed that existing tools for renovation simulation are either missing or lacking the ability to automatically simulate renovation scenarios in BIM-based context while capturing the set of variables considered in this study. This is still a critical gap for both researchers and policy makers interested in increasing adoption rates as part of the endeavours to meet the EU net zero greenhouse gas emissions target by 2050. Given the identified gap and the significance of the challenge, the proposed approach and tool provides an important point of departure for researchers interested in building renovation to investigate approaches to automation and data-driven tools in this area. In particular, the proposed work advances the theoretical understanding in the building renovation domain by providing a new approach to modelling and simulating both the attributes of the building being renovated and the characteristics of the renovation intervention. At the most elementary level, the tool highlighted the importance of integrating various parameters, including disruption to building components and occupants, schedule and cost, in a single decision support tool when trying to achieve an optimal renovation intervention.

The proposed work has practical implications especially for construction stakeholders and technology developers. Enabling the quantification and analysis of renovation disruption causes, including noise, dust, vibration, odour and demolition debris, will certainly help improving occupants and workers' health, comfort, safety and security conditions while planning and executing retrofitting activities. Similarly, understanding the complex interrelationships between various parameters, such as cost, schedule, resources and disruptive potential through their modelling and simulation in the proposed tool, is a new ability that the building renovation industry requires to improve predictability of outcomes and de-risk the sector for incumbents and new entrants. The tool can be used by architects designing the renovation solution to make design choices and product specifications that prioritise certain indicators at building level (e.g. minimise disruption to occupants) or at area unit (cost/m^2, day/m^2, etc.). The tool can also bridge the communication gap between designers and contractors and with tenants by providing a rationale for the selected renovation intervention, thus overcoming tenants' concerns and resistance, and increasing their acceptance and so the rate of renovation which can lead to generating a significant number of new jobs in the EU. Owners of large estate portfolios, both in the private and the public sector (such as social housing landlords), can tailor the application of this to improve their renovation interventions based on their own priorities (e.g. economic, environmental and social). The methodology can also be extended to accommodate further variables such as environmental waste generated which is considered a top priority as part of growing discussion about circular economy in the built environment, as well as variables such as climate data, façade orientation, materials and different building codes.

The ability of successfully maintaining and deploying the tool relies on the availability of historical knowledge bases and databases which are generally lacking within the building renovation sector and within the construction industry in general. Hence, a secondary contribution of the work is to highlight the importance of developing such knowledge bases especially by large estate owner and contractor organisations.

For technology developers, the proposed work provides insights about the technology gap in this significant building renovation domain, given the EU target to increase renovation rates, and uncovers an initial approach to the development of such technologies and their data input, processes and output. Based on the initial approach proposed in this research, technology developers can further explore the development of more advanced decision support tools through their ability to embed the proposed approach with industry standard construction planning and simulation tools.

The proposed approach in this paper is deterministic relying on the assumption that all input values, parameters and variables are precisely known or can be precisely measured. While this may be considered a limitation as the solution requires the availability of knowledge bases to effectively operate, a potential future development is to develop artificial intelligence (AI) approaches for the same building renovation challenge proposed in this paper and compare the performance of the AI approach with the current BIM-based deterministic approach. This is a likely scenario, as data-centric approaches are increasingly being adopted in construction, by both practitioners and academicians, throughout the entire life cycle of a construction project.

6. Conclusion

This paper describes an automated process for the assessment and simulation of renovation strategies in terms of duration, cost, workers needed and disruptive potential using BIM. The proposed TEA process and tool were explained and tested to perform a detailed analysis of six renovation scenarios across three multi-residence apartment buildings in three EU countries (France, Greece and Denmark). The performance of the TEA tool was verified through a sensitivity analysis using the PCA method.

The TEA tool was able to simulate the six renovation scenarios (S1 – renovation from outside; S2 – renovation from inside; S3 – deep renovation; S4 – product installation; S5 – most disruptive activities first; S6 – less disruptive activities first). Despite the various nuances and in some cases the subtle differences between the renovation scenarios, the TEA tool successfully captures the impact on cost, duration, labour resources and disruption potential. Indeed, the subsequent sensitivity analyses performed using the PCA method, the analysis of renovation scenarios at building level and the analysis at renovated surface area level across the three demo sites reflected a coherent performance with the results obtained by the TEA tool.

One limitation of the proposed work is in the approach used to analyse the tool performances. It consisted of an internal evaluation comparing renovation case studies relatively to each other instead of comparing the results with those of their corresponding actual situations. However, the data used was real industry data which was provided for each demonstration site from the contractors involved in the RINNO project which is now an accepted practice in research, provided the limitations are clearly acknowledged. In future, the testing should be extended by comparing the simulated renovation solution to the actual renovation performed in the real world.

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