EVALUATION OF BUILDING RENOVATION STRATEGIES ACROSS THREE DEMONSTRATION SITES: A PRINCIPAL COMPONENT ANALYSIS BASED MULTIVARIATE SENSITIVITY ANALYSIS

Omar Doukari[1], David Greenwood[1], Rahim Aguejdad[2], Mohamad Kassem[3]
[1]Northumbria University, Newcastle, United Kingdom
[2]CNRS, Montpellier, France
[3]Newcastle University, Newcastle, United Kingdom

Abstract

Buildings are responsible for some of the largest environmental impacts, such as global energy consumption, waste production, and raw material depletion. Inefficient buildings negatively impact both humans and the environment. To enhance the living comfort and indoor climate, building renovation must be performed on a massive scale. However, due to the lack of optimised tools and methods for the planning and execution of renovation works, retrofitting projects present real challenges for the project stakeholders. This paper describes the development of an automated process for the assessment and simulation of renovation scenarios in terms of duration, cost and disruptive potential using Building Information Modelling (BIM). This process was then demonstrated, and its behaviour analysed through a sensitivity analysis using: (i) three European case studies; multi-residence apartment buildings comprising different construction components and systems, located in Greece, France and Denmark, respectively; and (ii) six different renovation strategies.

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 the most considerable environmental impacts with 40% of global energy consumption, 33 % of waste production, and 50 % of raw material depletion (Passoni et al., 2021). To achieve climate change targets (UN, 2021), instead of focusing on superficial, light and minimally disruptive refurbishment measures (e.g. boiler replacements), the built environment must opt for more holistic, innovative and disruptive policies and changes (Killip et al., 2020; Topouzi, 2016). 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 there are just a few examples (Radian, 2009) of deep renovation projects in both the social and private housing markets.

Renovation presents many challenges for the project actors as well as for the building occupants. This is mainly due to a lack of optimised tools and methods for the planning and execution of renovation works (Gholami et al., 2013) and high level of interaction and interference with occupants during the retrofitting phase (Fawcett and Palmer, 2004; Grath et al., 2013). Occupant disruption is one of the main challenges in renovation projects (Designing Buildings, 2022; Fawcett, 2011; Trowers & Hamlins, 2022). Although disruption seems inevitable during the period of implementing a renovation initiative, project participants should ensure managing and minimising its impact on occupants. Early-stage simulations, especially BIM-based methods, are known to be useful tools to identify optimised renovation strategies and enable better management of the retrofitting process (Chaves et al., 2017; Kemmer and Koskela, 2012; Volk et al., 2014).

The contribution of this paper is twofold. First, it presents an automated process for the assessment and simulation of renovation scenarios in terms of duration, cost and disruptive potential using BIM. Second, it demonstrates its applicability and analyses its behaviour and concepts using three demonstration sites located in three different European countries, and six different renovation scenarios. This study was conducted as part of a large European research project - the RINNO project (Doukari et al., 2021) - that involves nineteen 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 the paper is structured as follows. Section 2 provides detailed descriptions of the automated process developed. Section 3 presents the research method and data used to demonstrate and study the sensitivity and behaviour of the process proposed as well as the concepts implemented. Results are presented and discussed in Section 4, and conclusions and future works are finally outlined in Section 5.

Automated Techno-Economic Assessment process

The automated Techno-Economic Assessment (TEA) process was developed to enable project managers to efficiently evaluate and simulate renovation scenarios in order to select the optimum one with minimum disruption that could be caused to occupants (Doukari et al., 2023). Furthermore, it evaluates additional renovation project parameters, such as project duration, cost and workers needed during the renovation works. The tool that was developed enables the optimisation of existing renovation collaboration workflows using BIM standards through

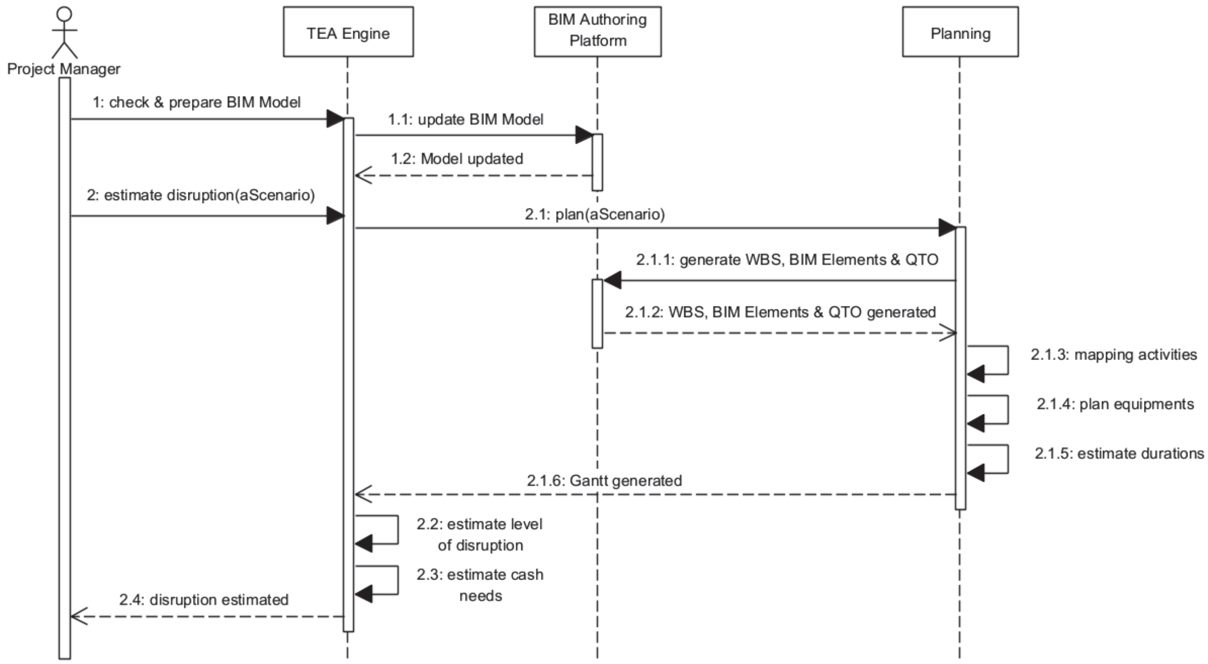

Figure 1: Automated Techno-Economic Assessment (TEA) process - UML sequence diagram

making direct link with occupants in the design process by calculating a set of Key Performance Indicators (KPIs) relating to project cost, duration, resources required and disruptive potential.

As illustrated in Figure 1, the TEA process is based on six main steps that can be detailed as follows:

Step 1 – BIM data preparation

The first step in using the TEA tool consists in uploading the BIM model within the BIM authoring platform (here Autodesk Revit) to enable data quality control and inputting basic renovation project information, such as project start date, owner, address, description and project name. 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; i.e., a BIM element must belong to only one level. For instance, A 'Wall' object should not be linked to more than two levels.

If any of the previous rules are not respected, the BIM model should be corrected and updated accordingly before it can be used as input for further processing with the TEA process.

Step 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 Table 1, the TEA process provides a dataset of renovation activities to enable users to create their own scenarios and simulate them automatically. It consists of selecting a subset of the eighteen activities identified and validated by the RINNO project partners during nine fortnightly workshops. The TEA process does not only automate the techno-economic assessment and simulation processes (that include disruption, resources, project duration and cost) but also provides useful tools, such as the scenarios definition component, required to enable design process optimisation.

Step 3 – Activity constraints definition

The third step consists in defining 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 provided already includes predefined constraints as recommended by the RINNO project partners to better organise and manage a renovation project. The first part of the template allows users to define which precedence rules should be applied while proceeding with the renovation of spaces in accordance with a project's work breakdown structure (WBS). The second part of the template allows the TEA users to indicate their own order of execution between renovation activities. This order is expressed in numbers and in the structure of the WBS. Externalising the definition of renovation constraints through an Excel file and making it independent from the TEA code ensures better flexibility, maintainability, and adaptability of the TEA tool and provides more freedom and possibilities to non-specialised users (Doukari et al., 2022) while defining and evaluating the constraints and strategies of different renovation scenarios.

Table 1: Renovation activities

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

Step 4 – Renovation schedule generation

Once the first three steps are completed, namely: data preparation, renovation scenario identification and activity constraints definition, the disruption estimation process can be launched. First, a renovation schedule is automatically generated by solving a Resource Constrained Project Scheduling Problem (RCPSP) (Hartmann, 1997) which is an NP-hard (Nondeterministic Polynomial) problem (Blazewicz et al., 1983). To solve a RCPSP problem, 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 problem and the number of renovation activities and constraints considered in this study, an 'exact method' was implemented for the TEA process. For large and complex 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 these solutions are approximate and not guaranteed to be optimal.

The schedule generated corresponds to the renovation scenario identified by the user and allows them to simulate all renovation activities selected while complying with the set of activity constraints defined. Each activity scheduled is assigned a relevant number of workers required for its completion. In addition, a set of project KPIs, such as 'average daily workers' and 'overall project workers' are calculated for possible comparison against any such constraints.

Table 2: Disruption levels, intensities, flags, and impacts

Level	**Values**	**Flag**	**Communication**
No impact	[0, 1]	(green)	Be aware!
Low impact	]1, 2]	(yellow)	Be aware!
Medium impact	]2, 3]	(orange)	Be prepared!
High impact	]3, 4]	(red)	Take action!

Step 5 – Disruption simulation

The fifth step estimates the different types of disruption using the schedule generated in Step 4. To do so, the TEA process's database is queried, and corresponding disruption values are estimated and assigned accordingly. This database includes data related to renovation activities, their sub-activities and procedures, duration, cost, equipment and disruptive potential that was gathered, structured and validated during workshops with the help of the industry-based partners of the RINNO project. Table 2 shows the four types of disruption that are considered by the TEA process, namely: (i) disruption of 'Utilities', such as gas, electricity and water interruptions; (ii) disruption of 'Traffic', such as access to the building or flat being blocked or restricted; (iii) 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 (iv) disruption of 'Internal Environment' when retrofitting works cause pollutions, such as noise, dust, daylight reduction, vibration, odour and demolition debris.

At the end of this step, disruption KPIs are calculated and reported for the four types of disruption in order to allow further renovation scenario evaluation and optimisation.

Step 6 – Weekly cash needs estimation

The TEA process allows users to automatically estimate project cash needs on a weekly basis and per WBS item. This cost includes the activity, labour and equipment costs. This step is enabled by the average value costs that were captured and populated by the TEA database.

Sensitivity Analysis of the TEA process

To demonstrate the applicability of the TEA process and analyse its sensitivity regarding data processed and building parameters, the methodology illustrated in Figure 2 was implemented. First, three case studies from different European countries were selected, and then several renovation scenarios were identified, simulated and compared using the TEA process and the KPIs calculated. This process is detailed in the following sections.

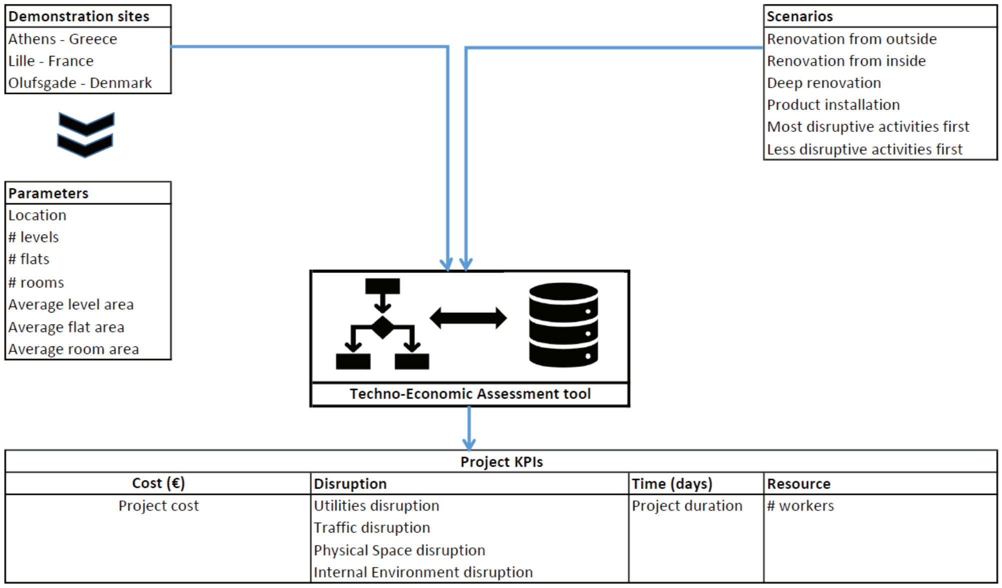

Figure 2: Sensitivity analysis of the TEA process

BIM 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, arranging a total of more than 3000 m^2 of floor area, 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 3). Table 3 outlines the main properties of each demonstration site.

Renovation scenarios

Table 4 presents the renovation scenarios identified and simulated using the TEA process. They are six different scenarios defined through the renovation activities implemented by the TEA process. The first scenario (i.e., 'renovation from outside') included renovation activities that are carried out from outside the building, whereas scenario S2 was dedicated to renovation from the inside. Scenario S3 represented a deep renovation scenario which included all activities that are compatible and can be carried out at once. For example, activity 'A' is compatible and can be conducted along with any other renovation activities, whereas activity 'B' is not compatible with activities 'C', 'D', 'E' and 'R' (Table 1). If 'B' is planned to be conducted none of activities 'C', 'D', 'E' and 'R' can be performed. Scenario S4 only includes activities relating to product installations, such as photovoltaic system installation. However, scenarios S5 and S6 were defined as two variants of S3 to test two different heuristics, respectively executing most disruptive renovation activities as early as possible in the renovation process (i.e., the Whiteman et al., heuristic (Whiteman and Irvvig, 1988)) and the opposite process which consisted in executing less disruptive activities first.

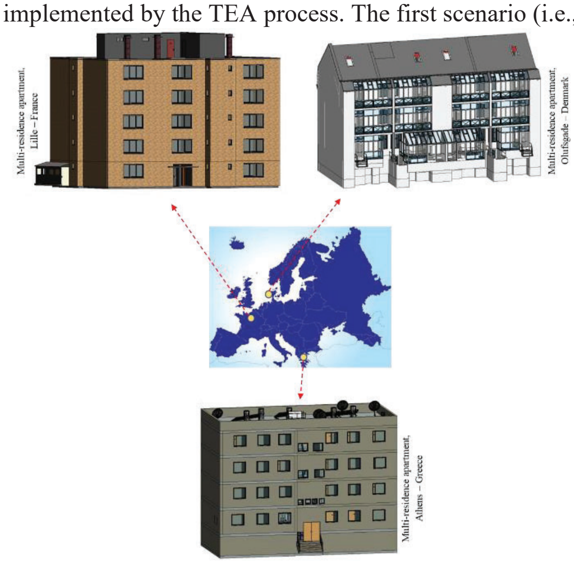

Figure 3: BIM models of the three demonstration sites

Table 3: Properties of the demonstration sites

		Demonstration sites		
Properties/Parameters	Location	Athens – Greece	Lille – France	Olufsgade – Denmark
	# levels	5	5	5
	# flats	9	29	18
	# rooms	52	58	58
	Average level area (m^2)	177,3	292,2	188,1
	Average flat area (m^2)	88,7	48,7	95
	Average room area (m^2)	17	24,3	16,2
	Basement?	Yes	No	Yes

Table 4: Renovation scenarios simulated

		Renovation activities																	
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Renovation scenarios	S1 - Renovation from outside	X	X				X					X							
	S2 - Renovation from inside	X							X									X	X
	S3 - Deep renovation	X	X				X	X	X	X		X	X	X	X	X		X	
	S4 - Product installation	X		X				X		X			X	X	X	X			
	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*																	

Results & discussion

Table 5 summarizes the simulation results which are also illustrated in figures 4 and 5. The findings indicate that 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 (Figure 4). For example, a deep renovation (S3) of the French building needs 814 days, 2200 workers and costs 904796 euros, whereas a renovation from outside (S1) involves 336 days, 770 workers and 229466 euros.

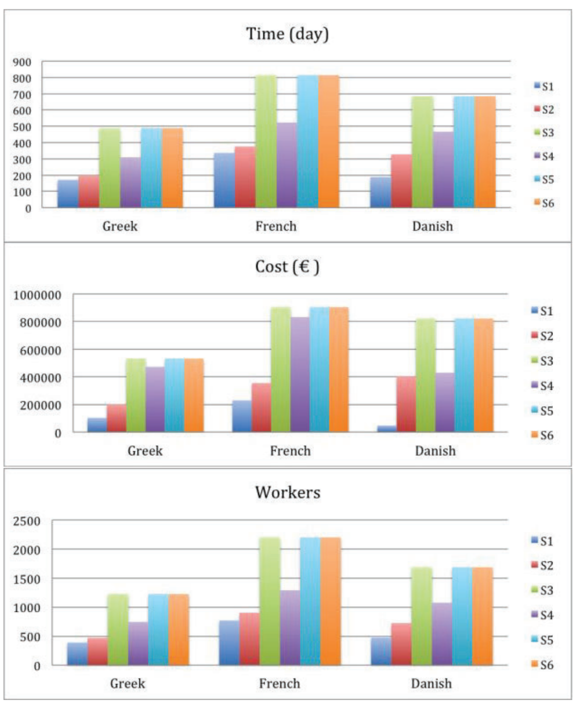

Figure 4: Simulated time, cost and workers

Figure 4 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 explains why these scenarios require more workers, time and budget than the other ones, regardless of the study site.

The simulation results also indicate that the first scenario S1 needs fewer workers, time and cost than S2 and S4, respectively. Actually, these findings are intuitive and confirm that renovation from outside (S1) is a lower-cost alternative to renovation from inside (S2) and product installation (S4), respectively. Moreover, results reveal that the renovation process in the French case study costs almost the same price for the four scenarios S3, S4, S5 and S6 even though S4 requires less time and workers (Figure 4). This can be explained by the fact that product installation activities usually cost more than traditional renovation activities.

Figure 5 provides a visual illustration of the four types of disruption that are implemented by the TEA process. 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 simulation results indicate that all the other scenarios present a similar and 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 exhibit similar behaviour of the three demonstration buildings in terms of disruption of traffic, physical space and internal environment (Figure 5). For the three demonstration sites, the simulation results highlight that the second 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. Additionally, 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 interrupted or impacted when the retrofitting works consist of deep renovation (S3, S5 and S6) or product installations (S4).

The results also show that the renovation activities from outside the building (S1) cause the highest degree of

Table 5: Simulation results

Renovation scenarios	Time (day)	Cost (€)	Workers	Disruption: Utilities	Disruption: Traffic	Disruption: Physical Space	Disruption: Internal Environment
Greek Project KPIs							
S1	171	102569,1	389,2999	0,029239766	0,087719299	0,020467836	2,005850554
S2	198	198960,1	470,1009	0	0,540404022	0	1,294445634
S3	489	531361,4	1223,901	0,034764845	0,030674847	0,838035762	1,3298558
S4	310	472221,5	745,0008	0,038709689	0,048387095	1,310643435	1,332902908
S5	489	531361,4	1223,901	0,034764845	0,030674847	0,838035762	1,3298558
S6	489	531361,4	1223,901	0,034764845	0,030674847	0,838035762	1,3298558
French Project KPIs							
S1	336	229466,2	769,6998	0,056547619	0,044642858	0,039583325	2,096427679
S2	376	354742,6	903,7032	0	0,555851042	0	1,297339201
S3	814	904795,8	2200,192	0,055896789	0,018427519	0,84692961	1,402454734
S4	523	832694,7	1288,6	0,050669242	0,028680688	1,2927351	1,37935102
S5	814	904795,8	2200,192	0,055896789	0,018427519	0,84692961	1,402454734
S6	814	904795,8	2200,192	0,055896789	0,018427519	0,84692961	1,402454734
Danish Project KPIs							
S1	188	47000	473,5	0,047872342	0,079787232	0,033510633	2,528727055
S2	328	402149,3	724,1023	0	0,484756112	0	1,368900895
S3	685	821710,5	1685,7	0,049489111	0,02189781	0,799707651	1,487441421
S4	467	430063,3	1075,299	0,053319145	0,032119915	1,159528255	1,441755056
S5	685	821710,5	1685,7	0,049489111	0,02189781	0,799707651	1,487441421
S6	685	821710,5	1685,7	0,049489111	0,02189781	0,799707651	1,487441421

disruption of internal environment (2≤disruption≤2.5) for the three buildings (Figure 5). Indeed, 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≤disruption≤1.5) for the three buildings.

Furthermore, the three scenarios S3, S5 and S6 show similar behaviour for the six 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. As suggested by Whiteman et al., (Whiteman and Irvvig, 1988) and in order to reduce disruption levels and make renovation works more acceptable by occupants, S5 consists in executing most disruptive renovation activities as early as possible in the renovation process, while S6 consists in simulating the opposite process and so executing less disruptive activities first. The outputs of the TEA tool do not show any difference between the outputs of these three renovation scenarios. Three hypotheses can be put forward for this. 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 or not modelled appropriately, which raises the problem of the definition of these scenarios and how they are taken into account by the TEA simulation tool.

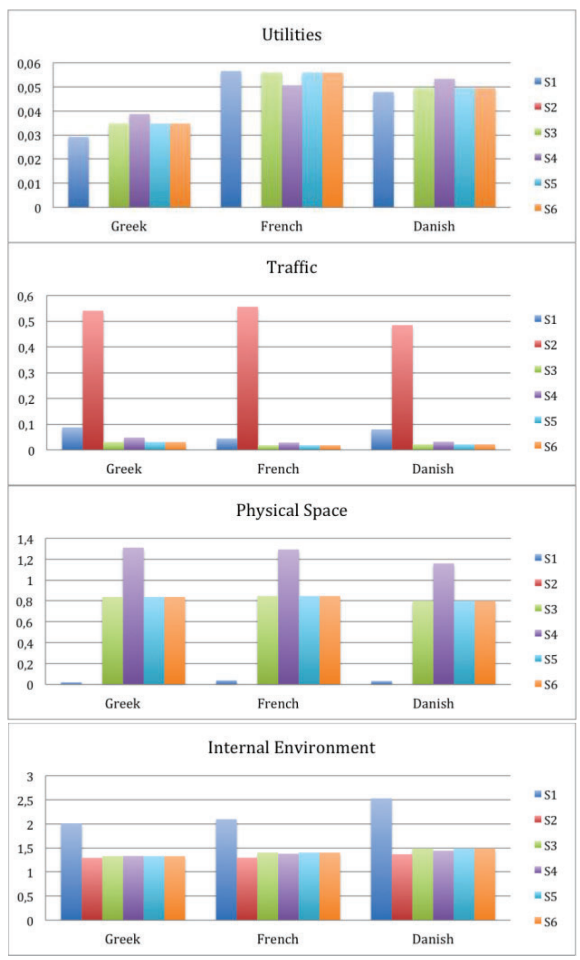

Figure 5: Simulated disruption on utilities, physical space, traffic and internal environment

Moreover, two Principal Component Analyses (PCA) (Doukari et al., 2016; Jolliffe and Cadima, 2016) were performed (figures 6 and 7). The first PCA was carried out to establish a typology of the six renovation scenarios according to the seven selected variables calculated using the TEA tool. The results, which provide a synthetic visualization of the distribution of the six scenarios, permit to evaluate the relevance of the scenarios definition.

The PCA plot (Figure 6) 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 has large negative association with traffic. For instance, in the Greek demonstration case, the first axis is correlated with the three variables cost (98%), time (95%), workers (94%), physical space (87%) and utilities (76%), while it is negatively correlated with the traffic variable (-74%). Furthermore, 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 6 shows that four groups of scenarios can be distinguished: S1, S2, S4, and S3-S5-S6. The first scenario S1 is characterised by high values disruption of internal environment and utilities and low values of traffic, physical space, cost, time and workers. S2 is more characterised by high values of traffic and low values of utilities, cost, time, workers and physical space. Scenarios S3, S5 and S6 exhibit similar characteristics since S5 and S6 are two variants of S3.

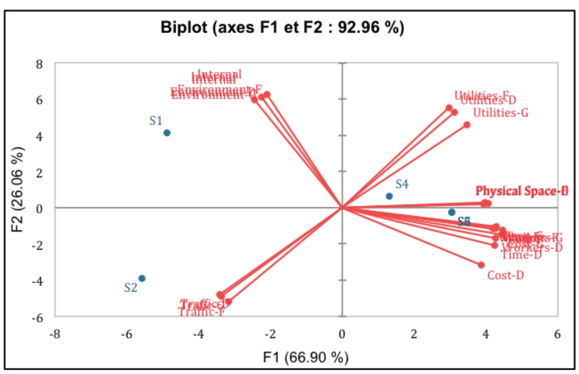

Figure 6: Distribution of the renovation scenarios based on the calculated variables

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 7 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 7). The Greek case study stands out clearly from the French and Danish buildings. In fact, 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).

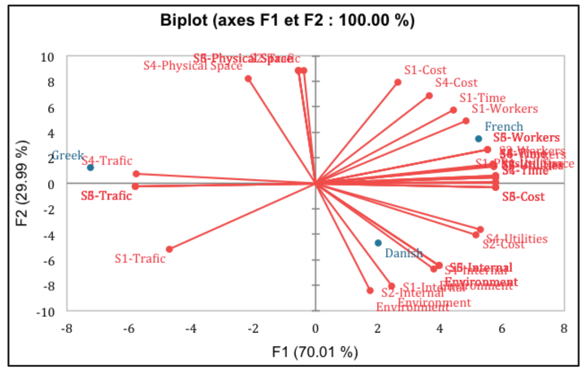

Figure 7: Distribution of the three buildings according to the simulation outputs

Conclusion & perspectives

This paper describes an automated process that is proposed for the assessment and simulation of renovation strategies in terms of duration, cost and disruptive potential using BIM. The TEA process developed was then thoroughly demonstrated, and its behaviour analysed through a sensitivity analysis using the PCA method. The experimentations explored six different renovation scenarios applied to three European demonstration sites; multi-residence apartment buildings comprising different construction components and systems, located in Greece, France and Denmark. This research demonstrated the ability of the TEA tool in simulating and assessing different renovation strategies in terms of duration, cost and disruptive potential. The methodology of this study can be utilised by decision and policy makers to better evaluate renovation scenarios and plan appropriate strategies.

Acknowledgments

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