Integration of control policies for comfort improvement in a large public building

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ABSTRACT

Some public buildings, which date back to the 1980-1990s, often miss to comply with comfort basic requirements. Also, their energy consumption is often above thresholds posed by regulations presently in force. Hence, low-cost technology improvements for renovation with high return on investment is a good opportunity in order to limit the required budget. To this purpose, the integration of advanced control policies may optimize energy use of buildings with minimum hardware enhancement.

In this paper, we evaluated the performances of an existing building that belongs to the campus of the Università Politecnica delle Marche (Ancona, Italy), and that is made of offices, teaching rooms, laboratories, a library and other public spaces. Thanks to an extensive monitoring of indoor comfort conditions, the main inefficiencies in terms of comfort were analyzed and a Dymola model of the actual building was worked out. Then, some energy improvement actions were assumed and tested by means of numerical simulation in the Dymola environment, and the benefits in terms of comfort and energy saving were estimated. Meanwhile, a BIM model of the building was built, regarding both the present status and each improved scenario, that allowed to perform a detailed cost estimation of each scenario. As a result, a cost-benefit analyses of each renovation scenario was performed and all the options were compared. The analyses showed that some renovation actions could be supported by energy savings with reasonable return on investment.

Keywords –

comfort improvement; control systems; energy analysis; cost-benefit analysis; BIM.

1 Introduction

Large buildings are the cause of a remarkable part of worldwide energy consumption, and keeping in mind that a huge part of large buildings is represented by public buildings, the development of customized refurbishment approaches is critical for the benefit of the whole society [1]. Evaluating refurbishment actions requires that an accurate model of the current and design scenarios of the building are setup. The development of the current scenario means setting the baseline, which must be validated against measured consumption data. Also, the collection of physical and geometrical data through on-site surveys may be necessary. What is more important, the simulation tool must be very flexible, in order to mirror both the current scenario and several possible design scenarios, in terms of performance and convenience; also, it must be supported by dynamic simulations [2]. The use of dynamic simulation tools will make the evaluation of the benefits deriving from customized – even if minor – renovation actions more accurate and reliable [3]. In this paper, a case study relative to the evaluation of the convenience of energy renovation actions applied to a large public building located in Italy is presented. Both energy analyses, indoor comfort assessment and cost analyses were performed in order to evaluate the best renovation actions. These analyses took advantage of BIM modelling for information generation and management about the current and future scenarios of the building undergoing renovation.

2 The case study

2.1 General description

Our case study is a building called "Eustachio", that hosts the rooms of the Faculty of Medicine and Surgery of the Università Politecnica delle Marche, located in

Ancona, Italy. Eustachio is made of two blocks, the northern and southern ones, which are connected by two transverse wings inside which the staircases and elevators are placed (Figure 1). For the purpose of this paper, only the southern block of the building was analysed, because users reported that the majority of drawbacks related to environmental discomfort in the summer season were experienced inside this block. The sourthern block of Eustachio accommodates lecture halls, educational laboratories and staff offices. Its southern façade is made of a curtain wall, that extends over the whole length and height of the building block.

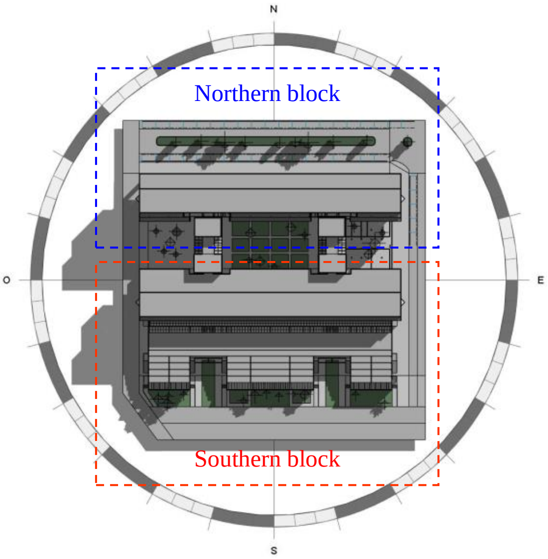

Figure 1. Plan and orientation of the University building considered as a case study.

According to what is depicted on Fig. 2, the air conditioning system of the southern block was split into several sections. The educational laboratories and staff offices are supplied with fresh or hot air (depending on the season) by three AHUs placed on the roof. The lecture halls are supplied by seventeen AHUs placed on the first level of the building. Furthermore, VAVs for local air-conditioning were installed inside every laboratory and fan coils are installed in the remaining rooms.

More specifically, fan coils are located above the entrance door of each room and staff office, which face the south orientation and whose external wall is made of a curtain wall. Instead, the VAVs were arranged in the corridors and in the educational laboratories, which face the internal courtyard of the building (they are north facing rooms). All the AHUs, fan coils and VAVs are served by a two pipe system working both in summer and winter, and connected to the central plant that includes four boilers placed in technical room at the basement level, and two chillers placed on the roof, i.e. on the fifth level.

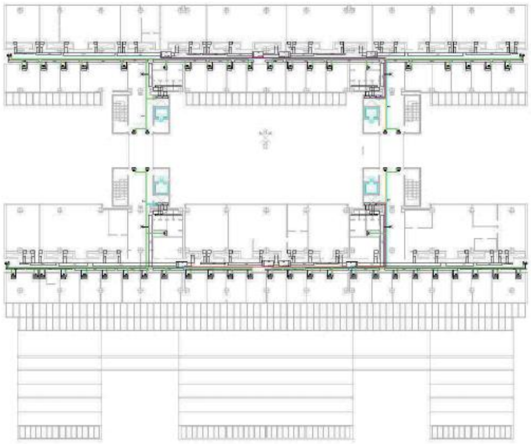

Figure 2. Plan of the fourth level

2.2 Breakdown of energy consumption

As a first step, energy consumption bills were examined and users were interviewed, who reported that the most relevant discomfort was experienced in summer, particularly from June to September. However, even spring and fall days - when a high level of irradiation occurs – can too often cause indoor overheating.

Table 1. Monthly consumption of electric energy.

	Electric energy (kWh)			
Month	**2011**	**2012**	**2013**	**2014**
Jan	150242	148034	153013	145977
Feb	151019	150231	148877	139205
Mar	165008	155370	158433	156506
Apr	133405	123241	131138	129658
May	136429	133284	135521	124810
Jun	236866	203897	186091	156443
Jul	242928	283445	259033	221287
Aug	191435	167258	196223	165546
Sep	228419	161058	203745	156150
Oct	150696	145358	151167	145758
Nov	145377	148630	156828	144243
Dec	132017	130551	137588	127120
TOT.	2063841	1950357	2017657	1812703

Table 2. Overall electric consumptions of the chiller in the summer season due to Eustachio.

Month	Jun	Jul	Aug	Sep	TOT
kWh	18392	37940	12894	15424	84652

The consumption of the chiller was estimated by analysing monthly electric bills charged by the utility company all over the past four years, which are detailed in Table 1. Keeping in mind that electric bills include every type of electric consumption, that is not limited to just cooling, and that the cooling system in the Eustachio building works from from June to September, the estimation of electric consumption caused by cooling was worked out as the difference between the average consumption from June to September and the average in the remaining months of the year. This approach was considered valid because the lighting system is always on, irrespective of the season (indeed, no dimming control system is installed).

Then, the monthly electric energy required by the chiller was averaged over the four years and the means listed in Table 2 were obtained. These figures were used to validate the numerical Dymola model reported in the next Section.

3 Simulation and assessments

The numerical simulation model that is described in this Section, was aimed first at the diagnosis of the main drwabacks of the building in terms of indoor summer comfort; secondly, at the assessment of low-cost energy enhancement actions, that can improve its behaviour. Hence, the whole model was developed by means of the Modelica-Dymola simulation tool (sub-Section 3.1). This model was validated with respect to the invoiced cooling consumption estimated as reported in sub-Section 2.2. Finally, the comfort improvement and energy savings than can derive from requalification strategies and control policies will be presented in sub-section 3.2.

3.1 The simulation model

The model that we want to showcase in this paper was developed by means of the Dymola™ development platform, which is based on the Modelica simulation language, whose reliability and benefits were demonstrated in previous papers [4] [5].

The whole building's model was developed thanks to the exploitation of two Dymola libraries: the first one is the Modelica Standard library and the second one is the Modelica "Buildings Library" v3.0 [6]. When necessary, those libraries were integrated with new components developed by the research team and customized for the Eustachio building.

The whole model is managed in Dymola as a layered representation of several connected sub-components. Figure 3 depicts a graphical schematic and logic representation of the top layer of the Dymola model for our case study. It is made up of five components that are integrated at the model's top layer, namely: the thermal zones of the building (A), the Air Handling Units sub-system (B), the model of the air duct and hydronic sub-system (C), the chiller (D) and lastly, the model of the fan coil, that was managed as an underlying layer (i.e. new class component). Due to length restrictions of this paper, not all the components will be described in detail, rather the methodology that was used to develop the class model of the fan coil will be reported in detail. The remaining sub-systems were developed similarly.

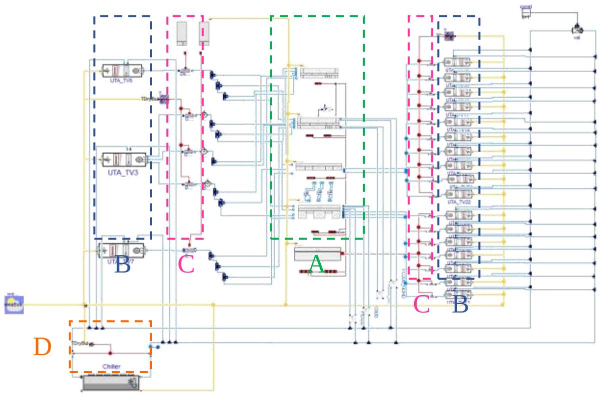

Figure 3. The sub-model of the cooling system.

The first phase related to the fan coil sub-model development was data collection. These data were taken from design drawings and technical reports provided by the office in charge of Eustahio's management, from surveys and from a measurement campaign carried out over two months by means of a Hobo™ sensor setup, including temperature and humidity tracking.

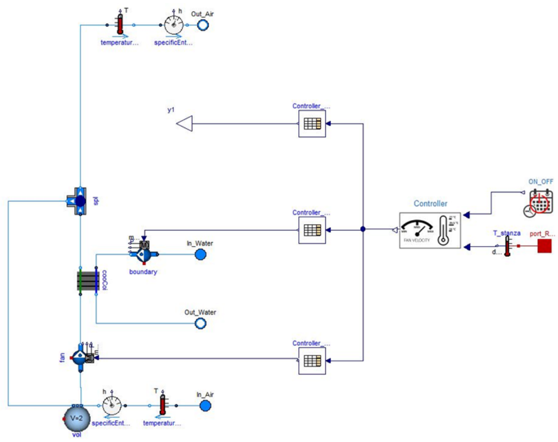

Figure 4. The sub-model of the fan coil.

Every component of the sub-system was progressively created and integrated in the model, namely: the heat exchange battery, the fan, the controller that is in charge of mass flow regulation through switching the heat exchange battery and adjusting the fan coil speed over three levels, a mathematical component representing the ventilation's effectiveness and, finally, all the connection devices.

The model of the fan coil (ref. Fig. 4) was connected to the thermal zones of the building (A), each grouping several rooms of the building and whose boundaries were chosen according to the use, orientation and reciprocal positions of the rooms. Every thermal zone was modelled through the "Room" component from the Modelica Building's library.

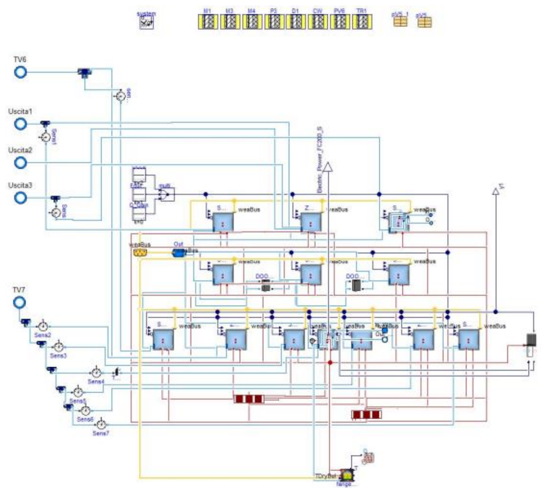

Figure 5. The layer with the thermal zones of the third floor

In Fig. 5 the thirteen thermal zones of the third floor are shown. Every thermal zone of the Dymola model was assigned the corresponding thermal characteristics of the Eustachio envelope, floor, ceiling, internal gains and windows.

Validation of the class component of the fan coil was carried out by means of comparison with the data collected during a dedicated experimental campaign. Most of the sensors were installed inside room no. 90, and the remaining ones were installed in the rooms located at the boundaries. Hence, a parametric study made of a number of simulations was carried out, while varying several parameters (e.g. heat exchange battery efficiency, ventilation efficiency, air flow figures), until simulated outputs matched with temperature and humidity measures. The model was refined until there was a good matching between simulation and experimental results.

All the remaing components mentioned at the beginning of this Section was validated against experimental data, similarly to what done with the fan coil's sub-model. As a result, the whole building model depicted on Fig. 3 was worked out and validated.

The time step used to perform simulations was equal to 300 seconds. The simulation time window was restricted to the the months from June to September, that is when the cooling system was on. The indoor comfort can be evaluated by means of many parameters. Among them, the Eustachio model was assessed in terms of energy consumption of the chiller unit, comfort level measured as PMV and PPD.

These values were plotted against the simulation month (x-axis), in such a way that for every month the average, confidence interval and standard deviation of the relevant parameters are provided on the y-axis. In Figs. 6 and 7 the electrical energy consumption and the thermal comfort of the benchmark (e.g. current state of the building's south block) are depicted.

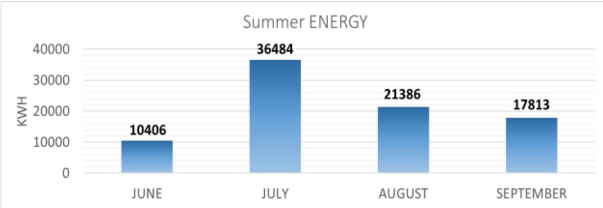

Figure 6. Electrical energy consumption during the summer.

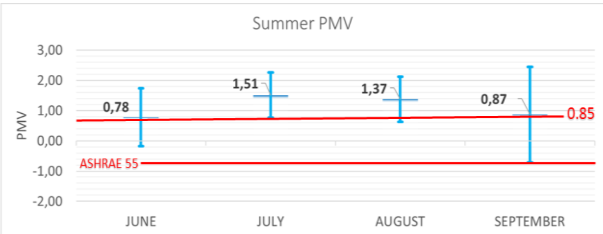

Figure 7. Thermal comfort during the summer and comparison with ASHRAE thresholds.

The overall electrical consumption within the considered time window exceeds 86.000 kWh. This value is in accordance with the estimateion carried out in sub-Section 2.2. Furthermore, every month an environmental discomfort with average index higher than ASHRAE 55's threshold is experienced [7], that is in accordance with complaints and witnesses reported by the interviewed users.

For that reason, some energy enhancement action strategies customized to the building and having the objective to improve the environmental comfort and decrease energy consumption were analyzed.

3.2 Energy enhancement scenarios

Four enhancement scenarios were analyzed to improve the building's comfort, each of them was compared with the current scenario in order to evaluate the benefits that could be had in terms of environmental comfort and energy saving. Per each of these scenarios, a Dymola model was developed, following the approach described in sub-Secton 3.1.

3.2.1 Enhanced ventilation effectiveness (A)

Ventilation effectiveness is an index representing the ability of a system to mix efficiently supply air with the indoor air of the building. According to literature [8], ventilation effectiveness in all the rooms of the southern block is particularly low in the current scenario. Ventilation effectiveness was estimated by means of the index sugeìgested by the ASHRAE's table [9] and approved by the guidelines provided by Rehva asscociation [8], that considers the adoption of a tracer gas as the standard technical approach.

From the technical point of view, this enhancement enatils moving the supply air inlet of the fan coil from the current position, that is above the entrance door, towards the centre of the room, through an extension of the air supply duct. Thanks to this enhancement, ventilation effectiveness would rise from 0.65 up to 1. As reported in Table 3, the adoption of this scenario would save 3563 kWh per year, that is equal to 4% of the overall current electric consumption for cooling, while the average PMV would be increased as of 6%.

3.2.2 VRF cooling system (B)

The second scenario asks for the installation of Variable Refrigerant Flow (VRF) system, that can replace the AHU currently serving the fan coils. In Dymola, just the cooling behaviour of this system was simulated, hence it was simulated as a two pipe VRF without heat recovery to serve the fan coil situated in the southern zone of the Eustachio's building. This enhancement would cause 8780 kWh of energy saving, but with no improvement in terms of environmental comfort.

3.2.3 Solar shading system (C)

The third scenario is a solar shading system installed on the southern façade of the Eustachio southern block.

Dymola allows users to simulate the shading feature through re-setting some parameters on the glazed surfaces: change of two coefficients of the glass component (i.e. solar transmission coefficient τ and solar reflection coefficient ρ). The new parameters were computed by means of a software that is based on th technical standard UNI 13363 [10]. The solar shading system giving the lowest solar transmission value G was selected. Furthermore, a control system to adjust the fan coil operation according to the solar shading system's performances was simulated. A fixed set point temperature regulation was assumed.

Thanks to the described improvement, 10612 kWh of energy can be saved, corresponding to 12% of current consumption. PMV would increase up to 58%, and its mean would often fall within ASHRAE 55 recommended values.

3.2.4 Exchange of RTD on the AHU (D)

Finally, the replacement of the resistance temperature detector sensors in order to regulate precisely the air supply temperature by the AHUs was simulated. This scenario would allow to adjust air supply temperature according to Italian standards, and would determine energy savings as high as 11240 kWh, that is equivalent to 13% when air supply temperature of the AHU is set at 26°C in the summer period. Conversely, there is a worsening of the environmental comfort, because air is currently kept at a lower temperature, due to inaccurate controlling devices.

Table 3. Comfort and energy improvements expected from the four enhancement scenarios.

Scenario	**Energy saving (kWhel)**	**Energy saving (%)**	**Δ average PMV**	**Δ average PMV (%)**
A	3563,94	4.13	0.08	6.19
B	5261,83	6.11	0	0
C	10612,22	12.33	0.47	58.28
D	11240,83	13.06	-0.09	-8.18

3.2.5 Combination of enhancement scenarios

Table 4 lists all the combined energy enhancement strategies that were simulated and compared with the current scenario. The marginal improvements generated by the various combinations were exploited in the following cost-benefit analyses and labelled as energy and comfort benefits. Eight combinations were considered on the overall.

Table 4. Comfort and energy benefits determined by the combinations of enhancement strategies.

Code	**Energy saving (kWhel)**	**Energy saving (%)**	**Δ average PMV**	**Δ average PMV (%)**
C+D	24656,94	29	0,43	38
A+D	15984,72	19	0,01	1
B+D	19994,78	23	-0,09	-8
A+C	11815,00	14	0,47	42
A+C+D	26756,94	31	0,44	39
A+B+C+D	27613,67	32	0,44	39
A+C+D+fc	21556,94	25	0,75	66
A+B+C+D+fc	23018,48	27	0,76	67

The last two combinations in Table 4 are similar to the 6th one, except that the indoor temperature was set at 24°C.

4 The BIM Model

Cost-benefits analyses requires an accurate cost estimation. Traditionally, the bill of quantities was prepared based on detailed drawings and specifications [11]. Bill of quantities is a very important document which provides a structured assessments for cost estimation of construction projects. Hence, a Building Information Model (BIM) of our case study was developed, because it can provide detailed estimates, 3D visualization, cost estimation in an electronic format and can easily be extended to further scenarios or be updated with as-built information.

4.1 BIM Model development

Every enhancement scenario described in Section 3 and the current scenario of the building were developed in the form of BIM models. This process required a parametric modelling of the whole building and the definition of a hierarchical structure of the relevant information. All the data collected through surveys and from desing drawings were transferred into the BIM. In our test case, we developed first the model of the bearing structure, secondly the architectural model and, finally, the mechanical system (i.e. MEP).

Autodesk Revit™ was used as the development platform, where the main components were included: terrain, walls, roofs, floors, ceilings, doors, windows, curtain walls, stairs and railings based on the project's drawings and specifications. Additionally, we modelled all the components relevant to describe the project geometry and its use.

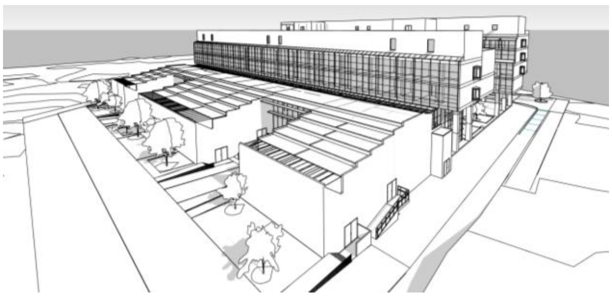

Figure 8. Structural and architectural BIM models of Eustachio building.

Since the enhancement strategies concerned specifically the mechanical system, a deep concern was posed in the modelling of the mechanical system.

To this purpose, Autodesk Revit MEP™ was adopted, which allowed us to integrate both plumbing, hydronic and air supply system. More specifically, we modelled ducts, flexible ducts and their joints, the air vents and the mechanical equipment like the Air Handling Units and the VAVs; similarly, we modelled the chillers, the boilers and the fan coils.

Thanks to this model, the construction cost was estimated for each scenario, and a bill of quantities was worked out, along with a management plan of the construction work and layouts for site organization over the execution phases.

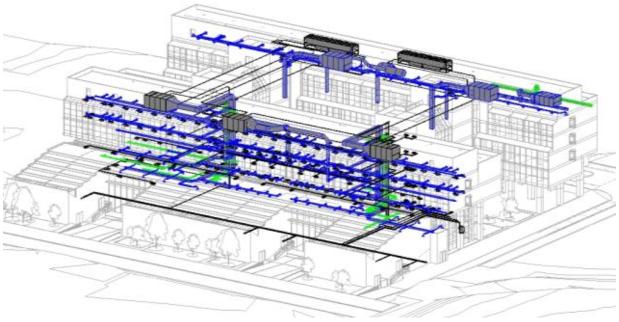

Figure 9. BIM-MEP model of Eustachio.

5 Cost-benefit analyses

Thanks to the definition of construciton phases in the BIM models, the bill of quantities relative to every demolition and construction phase were automatically generated by means of Revit™ tools. These documents were then used to estimate the total cost starting from unist costs of all the components. The relative grouping of all these quantities led to the cost estimation of every enhancement scenarios, as listed in Section 3.

5.1 Assessment of requalification strategies

As a result, this procedure allowed us to estimate the cost relative to every enhancement strategy. Economic benefits related to electric savings were estimated based on the unit cost worked out from bills, that resulted equal to 0.23€/kWh$_{el}$. Then, one cash-flow was developed for each of the considered scenarios, where positive cash-flows were determined by energy cost savings, and negative cash-flows were determined by the cost caused by technology enhancement. First, a simple comparison between cost and benefits (B/R ratio) was provided, like in Table 5.

This approach was used to perform a first evaluation, limited to the economic point of view. Checking Table 5 and given the renovation cost provided therein, the fourth scenario is ranked as the best one. In fact, installing new sensors in the AHUs is quite cheap, much cheaper than the other scenarios, because it costs only 2'410.86 € (Table 5) and would provide 2'585.32€ saving in annual electric bills (in fact it would be paied back in one year).

If the strategy of the user is just maximizing energy savings, then the combined scenario (A+B+C+D) in row number 10 would work best. It includes installing new sensors in the AHUs, the solar shading system on the south facing façade and the VRF cooling system. It would provide rather high saving, as high as 6'351.14€ per year, but the installation is very expensive.

Table 5. List of enhancement strategies, with costs and benefits and estimation of the cost/benefit ratio.

Scenario's Scenario	**Requalification (€)**	**Annual bill saving (€)**	**Δ B/R (%)**
A	8'700.86	819.72	9,42
B	134'952.74	2'019.46	1,50
C	232'086.08	2'440.76	1,05
D	2'410.86	2'585.32	107,24
C+D	234'496.94	5'561.10	2,37
A+D	11'111.72	3'676.49	33,09
B+D	137'363.60	4'598.80	3,35
A+C	240'786.94	2'717.45	1,13
A+C+D	243'197.80	6'154.10	2,53
A+B+C+D	378'150.54	6'351.14	1,68
A+C+D+fc	243'197.80	4'958.10	2,04
A+B+C+D+fc	378'150.54	5'294.25	1,40

Once the data provided in Table 5 are integrated with those ones that are provided in Table 4 about thermal comfort improvement, if facing thermal discomfort becomes of primary importance, we must select one between the last two combination scenarios, because they could provide respectively 66% and 67% improvement in the average PMV values.

As a further step, a ten year long financial evaluation about the convenience of every enhancement strategy was worked out, simulating the situation of a contractor that is committed to renovate the building in the first year and to manage the building over the 10 year period. Hence, the contractor would benefit from renovation because it lowers management costs. Table 6 reports a sample analysis about the costs involved in the third scenario, that is the solar shading system.

The technology enhancement costs reported in Table 6 were estimated by means of the BIM Revit models (Fig. 10); benefits were derived from simulations carried out in the Modelica/Dymola^{TM} models (one example is provided in Fig. 11, where the solar shading component of the Dymola model is depicted).

Every scenario considered in this step was assessed by means of the Net Present Value (NPV) approach, which evaluates the financial convenience that a contractor would have at the end of a 10 year long period, if committed to manage the building. The 10 year long horizon was justified by suggestion provided in guidelines for EPC contracting. As a result, Table 7 splits two relevant controbutions. In the second column, that part of the the overall investment that would be re-paid back as a result of energy savings, that can be defned as the private contribution. In the third column that other part of the investment that must be covered by the owner of the building, which is complementary to the first part, as compared to the overall investment cost.

Table 6. Summary of the management costs before and after the enhancement due to the the third scenario.

Cost incurred in the "CURRENT SITUATION" scenario	
Operation cost	62'314.79 €
Gas consumption cost	192'955.98 €
Electric energy consumption cost	418'755.58 €
Total bill consumption cost	*674'026.35 €*
Cost incurred in the "ENHANCEMENT YEAR" scenario	
Technology enhancement cost	232'086.08€
Operation cost	62'314.79€
Gas consumption cost	192'955.98€
Electric energy consumption cost	396'788.74€
Total bill consumption cost	*884'145.59€*
Cost incurred in the"post-ENHANCEMENT" scenario	
Operation cost	62'314.79€
Gas consumption cost	192'955.98€
Electric energy consumption cost	415'777.85€
Total bill consumption cost	*670'848.62€*

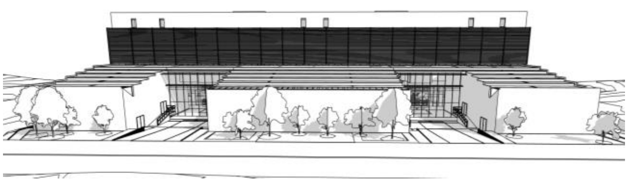

Figure 10. BIM model of the solar shading system.

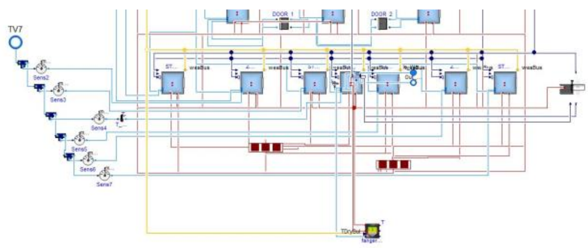

Figure 11. Dymola^{TM} model of the solar shading system.

Apparently, the fourth scenario is again the best one, because benefits pay back the whole investment cost in far less than ten years.

However, this scenario is very limited and does not provide relevant comfort improvement. When energy and comfort evaluations are integrated, the last two scenarios are more advantageous, being the first one able to save 38'604.57€ out of the overall investment, and the second one to save 41'221.61€ out of the overall investment. These figures represent the amount of money saved by the owner in case the investment is carried out by the contractor that manages and operates the building.

Table 7. Estimation of costs that would be covered by energy savings over a 10-year-long investment.

Scenario's Scenario	Private financing (€)	Owner contribution (€)
A	6'382.43	2'318.43
B	15'723.77	119'228.97
C	19'004.02	213'08205
D	2'410.96	0
C+D	44'155.77	189'421.47
A+D	10'399.35	712.47
B+D	35'806.75	101'556.95
A+C	21'158.36	218'708.78
A+C+D	47'916.46	194'361.64
A+B+C+D	49'450.70	327'780.14
A+C+D+fc	38'604.57	203'673.83
A+B+C+D+fc	41'221.61	336'009.23

6 Conclusion

The case study described in this paper is representative of many large public buildings, which are often outdated. As a consequence, they are high energy consumers and do not provide optimal comfort for users.

In this paper we showed that Modelica/Dymola™ models are accurate enough to simulate even customized and partial energy enhancement scenarios. In addition, BIM models can facilitate and make more accurate the process of cost estimation. Once those data are available, informed cost-benefit analyses can be done.

Cost-benefit cannot be the only approach to perform evaluations. Rather, user satisfaction should be considered as another more important parameter.

The approach presented in this paper can be useful both to owners of large outdated public buildings, who are willing to evaluate several enhancement scenarios or who want to control sub-contractors, in charge of the management of those buildings, such as in EPC contracting.

Also, this paper showed that even cheap technology enhancement can cause dramatic improvement in terms of comfort perfromances and energy savings. The development of a BIM model can act as a hierarchical information database to track the status of the building and to check whether contracts were applied as agreed.

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