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Civil Engineering

7D BIM FOR SUSTAINABILITY ASSESSMENT IN DESIGN PROCESSES: A CASE STUDY OF DESIGN OF ALTERNATIVES IN SEVERE CLIMATE AND HEAVY USE CONDITIONS

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Abstract

Introduction: The emerging of energy and environmental thread has fostered a new cultural design approach to Sustainable Architecture that aims to conceive and implement buildings with a low environmental impact. In this context the role of Building Information Modelling (BIM), as a support tool for sustainable integrated design, acquires great relevance. The purpose of this study is to investigate BIM potential in both addressing preliminary design choices and supporting complex analysis during the advanced design phase, within the whole sustainable design process. A technological rail building is assumed as a case study: the Operation Control Centre for the new Oman Railway, whose preliminary project was elaborated by the Italian engineering society Italferr s.p.a. **Methods:** The BIM approach is used to identify possible problems and deficiencies in the preliminary project, which may represent a good basis for a next design improvements proposal. The next phase consists in investigating and experimenting BIM tools potential in supporting the Conceptual Design, by using Autodesk® Revit® and IES VE® software suites, for the modelling and the energy analysis of different conceptual design solutions. Once the optimal building shape is established, the study focuses on the evaluation of sustainability effects brought by the structural building component, in particular for what concerns its materials environmental impact. **Results and discussion**: The analysis of the preliminary project shows the potential of BIM in the control of many performance parameters of a building in the design phase, revealing all the design problems associated to the lack of an integral multi-disciplinary approach during the initial phases of the process. The possibility of looking into a series of solutions in a quick and in-depth manner permits an accurate assessment of the most adequate form for a building based on the place in which it is set, thus joining current technological design methods to traditional bio-climatic methods, reinstating the strong and inevitable link between site and building.

Keywords
7D BIM, sustainability, life cycle assessment, design of alternatives.

Introduction

With the growing emergence of environmental and energy-related issues and new requirements in terms of sustainability of built systems, a new cultural approach to the project has become necessary, aimed at the design and construction of Sustainable buildings, that is with a low environmental impact, combining practical criteria related to the “on time, within budget” requirements with social and environmental factors (Banuri, 2007; United Nations, 2016).

However, for the term Sustainability to assume a comprehensive meaning in architecture, it is necessary for architects and designers to use not only the analytic tools that are related to their discipline, but also tools for combining and synthesising, following a synergic logic which should guide the entire building and design process. It is thus clear in this context how Sustainable Architecture, identifying itself with a variety of disciplinary fields, all equally important for establishing the perfect balance between environment and built system, requires a multi-disciplinary and integrated approach to the project (Allione, 2008; Szokolay, 2004). The main objective of sustainable design is surely energy efficiency, the first factor that permits the reduction of the consumption of resources by the building and justifies successive choices in terms of materials and technological solutions which allow limiting as well the environmental impact during the construction and disposal phases of the building, always limited if confronted to the one determined by the period of usage (Fowler, 2006; Bertagni, 2016).

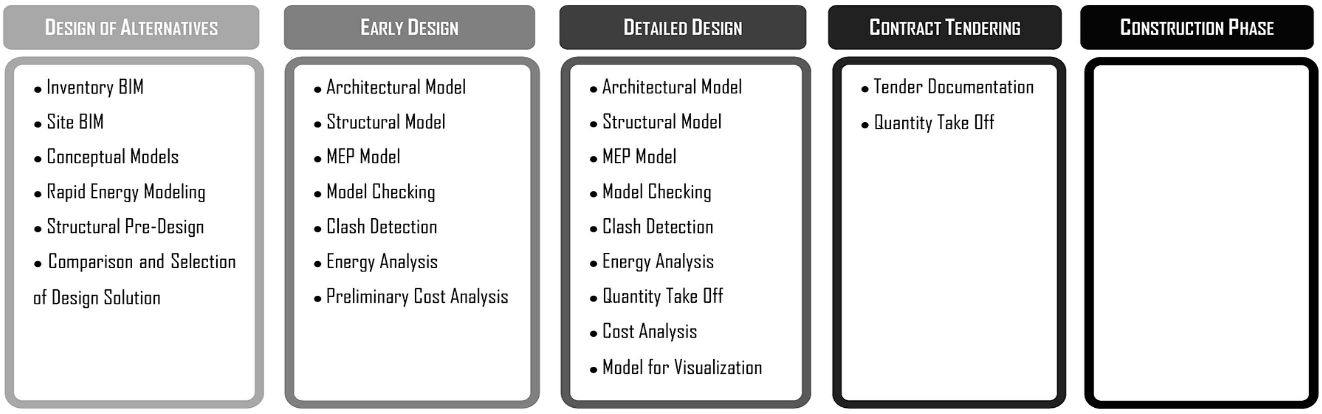

Figure 1. BIM design phases according to "Common BIM Requirement".

In order to consider all the energy fluxes in play, the most correct and sophisticated criterion envisages carrying out an LCA (Life Cycle Assessment) analysis on the building to assess the environmental impact of the building through an objective procedure, considering the energy and environmental loads regarding all the processes involved in the construction, usage and disposal phases of the building in question (Bank, 2011; Baldo, 2008).

Sustainability assessment methods can be configured as tools in support of design, assuming a different role during the various design phases. During an initial assessment phase regarding design alternatives, they can be used for defining the requirements of Sustainability and the determination of the aims regarding environmental performance in order to choose among a variety of design solutions; during the successive phases of definitive and executive design, these methods are defined as support tools for designers, helping them to obtain a clear perception of how the environmental performance of the building is influenced by design choices and how to intervene for optimising the cost/benefit ratio (Kensek, 2016; Berardi, 2012).

A solution for making a more expedite assessment is offered by BIM technology, which is capable of simplifying the optimised management of the data of the project, and permits in-depth energy analysis, also for the less advanced design phases, thus offering support for quicker and more efficient decision-making processes (Kota, 2014; Nguyen, 2010).

The role that BIM can play in offering support to sustainable and integrated design is different according to the various phases of the project considered. According to “Common BIM Requirements” (BuildingSMART Finland, 2012), it is possible to distinguish the typologies and contents of parametric models carried out in support of the 5 main phases (Figure 1): the initial phase of preparation of the various design alternatives (Design of Alternatives), in which the modelling of the existing situation is envisaged, as well as the realisation of various conceptual models on which to carry out expedite analyses with the exclusive purpose of comparison; further elements are a preliminary design phase (Early Design) (Aksamija, 2015; Stumpf, 2008) in which architectural, structural and installation schematic models are developed, and an additional, more advanced design phase (Detailed Design), which reaches a more in-depth degree of analysis in support of more precise assessments of the performance of the building. Finally, the parametric model can be used as a tool in support of the production of documents for competitions to tender and for the management of data regarding the building in its usage phase (Eastmam, 2011; Eadie, 2013).

Scope, Objectives and Methodology

In order to examine in detail the potential of parametric modelling and of the interoperability between BIM systems as tools for optimising projects in terms of sustainability, it was decided to trial them in a case study: the Operation Control Centre (OCC), of the new national railway line of the Sultanate of Oman (Figure 2). The project for the entire infrastructure, developed by the engineering company Italferr S.p.A., envisages the construction of 9 railway segments for the transport of goods and people (for a total length of 2135 km) that link the main urban centres of the country, crossing the desert from the North, on the border with the Arab Emirates, to the coastal regions in the South, on the border with Yemen.

The OCC houses the management centre for the entire railway and, as such, must contain all the functions and equipment necessary for the control and security of the railway traffic. The control rooms constitute the most relevant “human component” in an OCC, clearly counterpoised to the “technological component”, which includes the ever-present machinery; the former include all the equipment directly used by the operators, which consist mostly of integrated work stations, with monitors for visualising the segments and controlling traffic, and telecommunication devices that are essential for its coordination. In the machinery rooms, instead, are placed all the equipment in support of the activities of the operators (telecommunication cabinets, machinery for the automation of signalling and distancing systems, etc.) with the respective electricity supply units.

The contrast within the building between the two “components”, one human and the other technological, is manifested in both terms of mere function and in terms

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of requirements demanded from the built organism: the interior spaces, in fact, must be conceived so as to house a variety of activities, respecting the needs of both in terms of accessibility, distribution, environmental conditions (for the functioning of equipment and for the comfort of the operators), and seeking a perfect balance in what is called the Man-Machine Interface, from an environmental point of view, but also from that of ergonomics and functionality (Stanton, 2009). Consider the peculiar nature of the building, both in terms of its location and of its usage, it is particular interesting to apply on this case study the energy considerations regarding the interaction between the form, orientation and the local climate, from a perspective of the general optimisation of the performance.

Modelling and simulation

The whole intervention is structured according to the scheme proposed by "Common BIM Requirements" previously cited, from the Design of Alternatives phase to the last step in the design process, the Detailed Design. Various formal solutions are analysed, with the aim of identifying the one with the greatest energy efficiency, from which variations are developed in terms of the structural constructive system (to be compared through LCA analysis), with the objective of including, among the impact indicators under examination, also those relative to construction materials. At the end of the comparison, the model potentially more sustainable will be taken to the successive phases of Early and Detailed Design, in which the interferences between disciplinary models are controlled and united into a single object, after which the executive reports are drafted (Eastman, 2011).

Design of Alternatives. In the framework of the first phase of Design of Alternatives, BIM modelling in Revit® in LOD 200 of the preliminary project, carried out by the company Italferr s.p.a., consists in the definition of general wall elements and in the layout of the sun screen louvers for protection from direct solar radiation.

The "rooms" defined inside the BIM model were exported, through the conversion into the format gbXML, into the energy analysis software IES VE®, which is capable of extrapolating information from it related to the location of the building and associating them automatically with the relative climatic data. The Building Energy Model (BEM) obtained is used for carrying out analysis of the efficiency of the external sun screen louvers, on the level of natural lighting of the spaces, and more generally, on the aspects relative to solar radiation and on its influence on the building itself, considering the important role that it plays in the geographic context in question.

Once the phase of analysis of the preliminary project has concluded, a verification of the efficiency of the BIM tools is carried out in the phase of comparison of the various design solutions, generating several

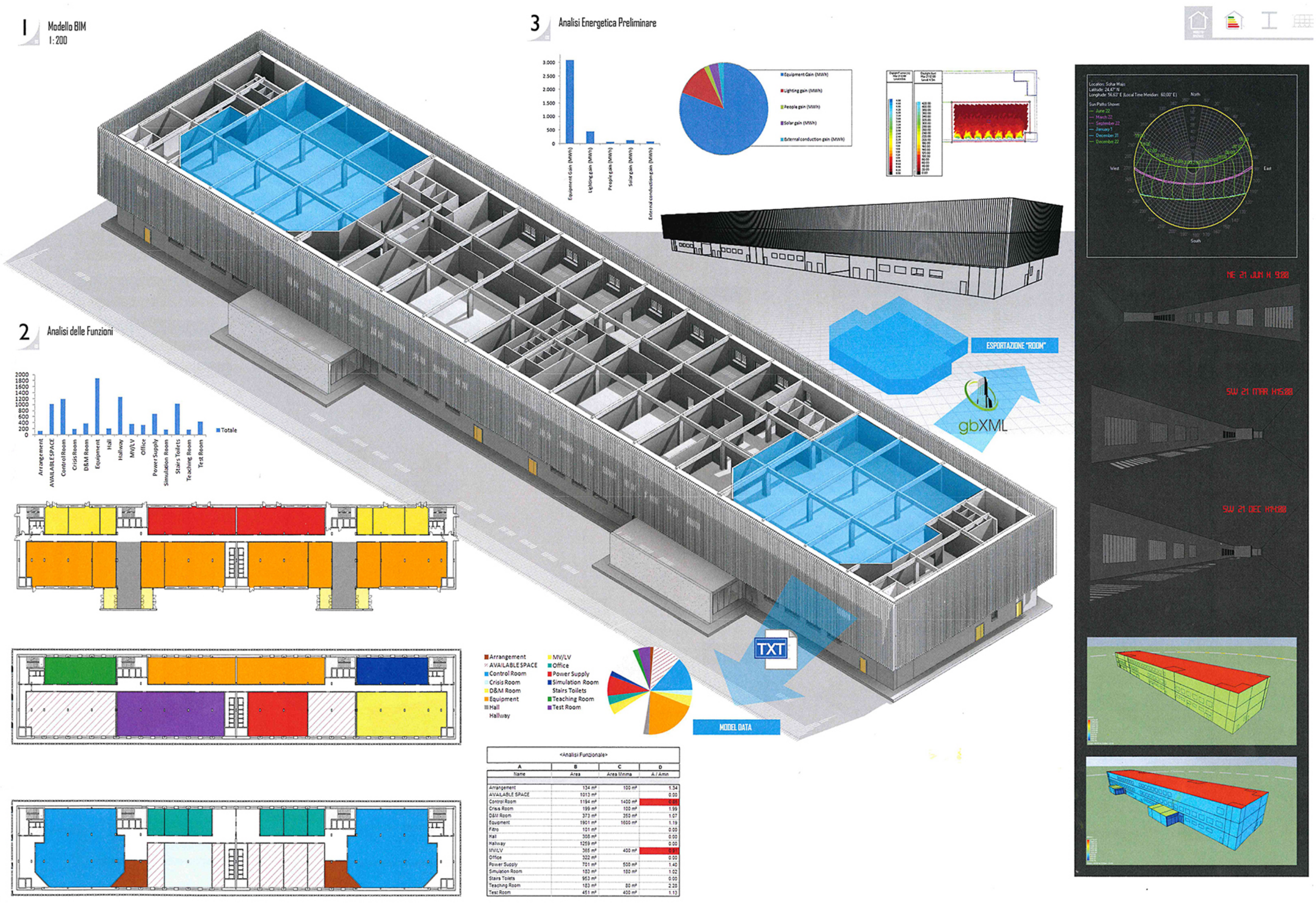

Figure 2. Modelling in LOD 200 from Italferr s.p.a. project - Preliminary Analysis.

conceptual models and comparing them from the point of view of energy usage. In particular, the purpose is set to investigate whether there is an optimal shape of the building for optimising both the distributive aspects and limiting the solar radiation, guaranteeing however a good degree of natural lighting for the spaces used by the OCC personnel. An approximate evaluation of energy consumption is made and the impact of a photovoltaic system on the overall performance is analysed (Kota, 2014; Stumpf, 2009).

Once the phase of analysis of the preliminary project has concluded, a verification of the efficiency of the BIM tools is carried out in the phase of comparison of the various design solutions, generating several conceptual models and comparing them from the point of view of energy usage. In particular, the purpose is set to investigate whether there is an optimal shape of the building for optimising both the distributive aspects and limiting the solar radiation, guaranteeing however a good degree of natural lighting for the spaces used by the OCC personnel. An approximate evaluation of energy consumption is made and the impact of a photovoltaic system on the overall performance is analysed (Kota, 2014; Stumpf, 2009).

For the various alternatives a series of common conditions were set, such as a correct orientation of interior spaces, based on the awareness of a lesser incidence of solar radiation on the Northern fronts in comparison with the Southern ones (related to the latitude of the site, which lies between the Tropic of Cancer and the Equator), the placement of glazed surfaces only on the North-Eastern and North-Western fronts of the buildings (those which house the operators), the placement of 3 m deep horizontal eaves and hypothesising that the photovoltaic system will be placed on the South-Eastern and South-Western fronts (faced by the machinery rooms), as well as the entire covering.

The specific workflow adopted is analogous to that of the preliminary project: the only difference is that this time a modelling of conceptual masses in Revit® is carried out for each solution, which permits a quick functional analysis through the automatic generation of abaci of the areas for the verification of the correspondence to specific surface requirements.

Then the same mass models can be converted into analytic models, carrying out a selective export of data necessary for energy analysis, using a gbXML format.

The models thus obtained are therefore exported into the software IES VE®, where the bio-climatic analyses mentioned above are carried out, aimed at the identification of solar contribution, the conditions of natural lighting of the spaces which house the OCC personnel,

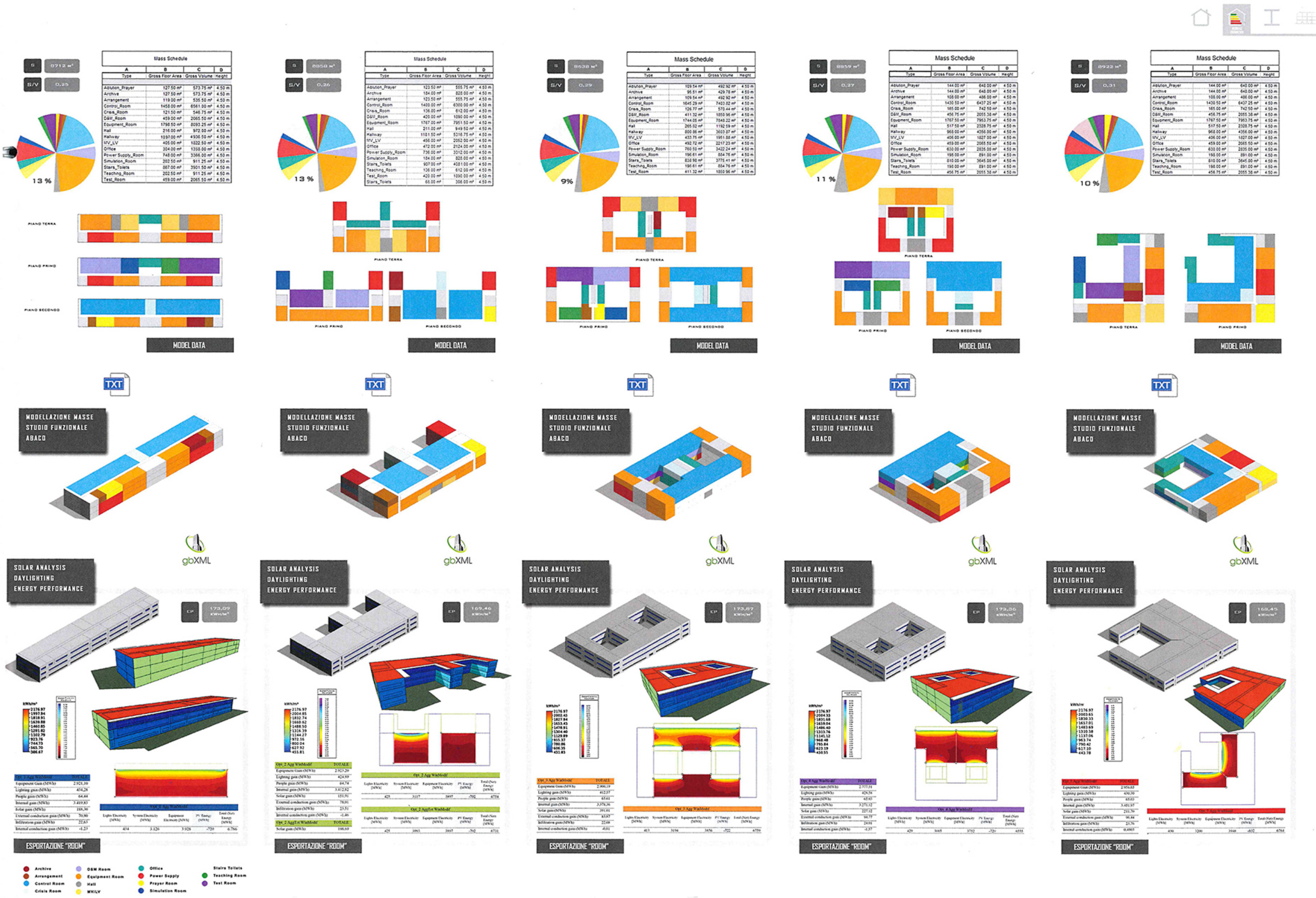

Figure 3. Design of alternatives - Rapid Energy Modelling for 5 design solutions.

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the productive potential of a photovoltaic system and of the index of overall energy performance.

he tested design solutions are 5 (Figure 3):

1. Solution corresponding to the preliminary project, modified in accordance to the bio-climatic approach described above;

2. “Comb” solution conceived for investigating the efficiency of the said parts of the building in the shading of the spaces between them;

3. Solution which retakes the traditional typology of the courtyard building, very common in those climatic contexts, with the possibility of control rooms in opposite positions, one facing the North-East and another the South-West of the building;

4. Courtyard solution in which the Control Rooms are one next to the other, both facing the North-East, which receives less solar radiation;

5. Solution developed on only two levels, unlike the precedent solutions, and conceived for assessing the impact of a greater extension of the photovoltaic system and a slight increase in the Surface/Volume ratio.

The results of the “Conceptual Energy Design” phase reveal how there is no solution capable of optimising at once all the design aspects considered for the comparison; from the analysis it is however evident that the variation in the extension of the photovoltaic system has a greater impact on the overall performance of the building in comparison to all the other design parameters considered.

Once the more efficient architectural solution in energy terms has been identified, the next step is the development of various constructive solutions. The design phase of the alternative solutions addresses in fact a dimensioning of the structures which, in this case, from the point of view of sustainability, is carried out for various building systems, assessing which among those examined may be more adequate for the project in question (Oti, 2015; Kensek, 2015).

The developed solutions are then assessed based upon various criteria: first of all the environmental impact during the entire life-cycle of certain materials or processes connected with certain building components is assessed; subsequently the compatibility of the building solutions with the architectural project is assessed, which derive, for example, from the absence of pillars within the large occupied spaces; finally, a comparison is carried out in terms of pre-fabrication, which is a very important aspect of sustainability, for cutting down costs and construction times of a project, as well as for bettering the work conditions in the work-site.

BIM system is still used for the analysis of environmental impact. Some tools offer an important support in the computation of materials and the calculation of the impacts, following once again the path of interoperability which, in an integrated process, involves the project of the structures as well. The BIM workflow regarding the structures is based on the construction of an initial physical model in LOD 200, characterised by geometric shapes of the transversal sections derived by a pre-dimensioning which, through the generation of an analytic model, can exchange information, taking advantage of the IFC standard format, with the structural resolution of the finished elements. Once the structure has been calculated and the features of the components modified, it is possible, thanks to the bi-directional nature of the process, to turn back through the analytic model, carrying out an updating of the physical model, which can reach a LOD 300. The updated physical model, including all the quantitative information regarding the components and materials, can be used directly for undertaking an analysis of the life-cycle of the structure and to assess its environmental impact (Eastman, 2011).

The first part of the process permits developing 4 different structural solutions in LOD 300 for the OCC, briefly described below (Figure 4):

1. Traditional solution in reinforced concrete (in line with the preliminary project), for which BIM families present in the software's database are used, from the rectangular beam to the pillar, to the pre-fabricated hollow-core slab in pre-compressed reinforced concrete; the latter used for maintaining the features of the individual elements, is modelled as a beam. The sections in reinforced concrete are modelled as wall elements.

2. Mixed structure in steel and cement, with hollow-core beams placed along the main reflecting surface, supporting pre-fabricated hollow-core slabs in pre-compressed reinforced concrete: the families used are hollow-core beams present in the software's database, while for the mixed pillars ad hoc families are used. The pre-fabricated hollow-core slabs in pre-compressed reinforced concrete are the same as those for the previous solution.

3. The third typology is entirely analogous to the preceding one, except for the fact that in this case the use of predalles slabs is envisaged: the beam and pillar families are thus the same as for case 2, whereas the floor slab is modelled as a “floor” element.

4. The last solution envisages the inversion of the framework of the beams-slabs, placing the first along the smaller reflecting surface and the others, once again of the pre-fabricated hollow-core type, along the larger one: the families used were the same as in solution 2.

Once the BIM model of the structures is complete a full comparative analysis of the environmental impact of each structure during its entire life-cycle is made, from the production of the material until its disposal, with the aim of choosing the “most sustainable” construction system (Eleftheriadis, 2015; Soust-Verdaguer, 2017). To this purpose the Revit® Tally® plug-in is used, which includes various categories of environmental impact; for the analysis of the life-cycle of the structure reference is made in particular to the Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Smog Formation Potential (SFP), and Primary Energy Demand (PED).

As in the “Conceptual Energy Design” phase, also in this case it is not possible to identify a solution that is

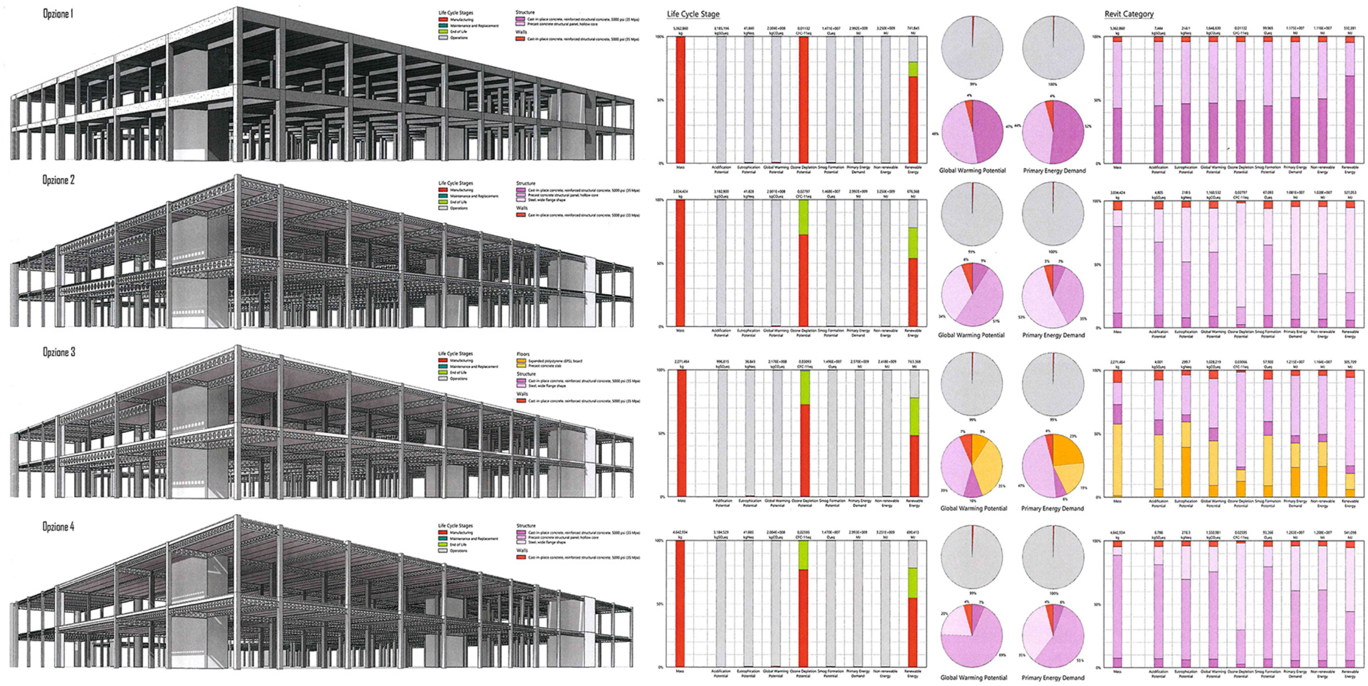

Figure 4. Design of alternatives - Analysis of environmental impact for 4 structural solutions.

clearly better than the others, considering the numerous and different categories of environmental impact.

Early Design. The next step is the Early Design, in which a BIM architectural and structural comprehensive coordination model is developed at LOD 200. It is in this phase that the first union of the two specialised models takes place, something which necessarily requires an accurate control of interferences among the various components (Aksamija, 2015; Eastman, 2011). From an architectural point of view the re-designed building develops along a main North-South axis, orthogonally to an East-West axis which places the building itself in the direction of Mecca. In this diagonal distribution of spaces, each floor has a clear separation in distributive terms between occupied spaces and spaces for equipment, most of the first facing the courtyard, which is the most privileged area of the entire structure, the others facing the South-East and South-West fronts, that is those most exposed to the sun.

In the insertion of an exterior covering over the courtyard, the synthesis of the solar analysis and of the projecting elements described previously may be used. The objective is that of creating a filter area between the inside and the outside which confers to the courtyard a strong architectural significance and protects the rooms from direct solar radiation; in order to guarantee both the protection from the sun and the natural lighting of the courtyard and the interior spaces, it was chosen to adopt transparent panels for the covering, characterised by a good luminous transmission and by a low solar factor.

The solar analysis for the optimisation of the geometry of the entire system is carried out directly on the BIM model in Revit®, paying special attention to the areas facing the interior courtyard. The verification of the efficiency in terms of natural illumination, instead, is made possible once again by inter-operability: the workflow followed in this case is the same for the energy analyses, with the difference that the initial model is no longer conceptual but architectural, and in it are defined the “rooms” to be exported to the analysis software through a gbXML format (Kota, 2014).

In particular, within the IES VE® the translucent panels of the roof are modelled specifying the solar factor and the luminous transmission and the assessment of the natural lighting conditions is carried out checking the degree of average lightings (lux) and its uniformity in the areas where work is undertaken which envisages the use of video display terminals. The design of the structure for the covering is based on remaining faithful to the main architectural theme, that of developing along the diagonal. A steel structure is envisaged for this with secondary beams placed parallel to the said axis, and main beams placed orthogonally to them. In order to confer architectural value to the covering, and thus to the courtyard, the use of tree-like pillars is envisaged. The pre-dimensioning of the exterior covering follows the same workflow as the structures, from the physical and analytic models to the FEM software and the updating of the initial BIM model.

Once the modelling of the exterior covering is complete, the next step is to unite the two different disciplinary models and to analyse the architecture-structure interferences: the two models may in fact be connected through a link which permits to keep them separate, yet visible within a single object. The modification of each of the linked models implies the updating of the overall model (Kensek, 2015). Linking the coordination model to the model of the exterior covering completes the Early Design phase (Figure 5).

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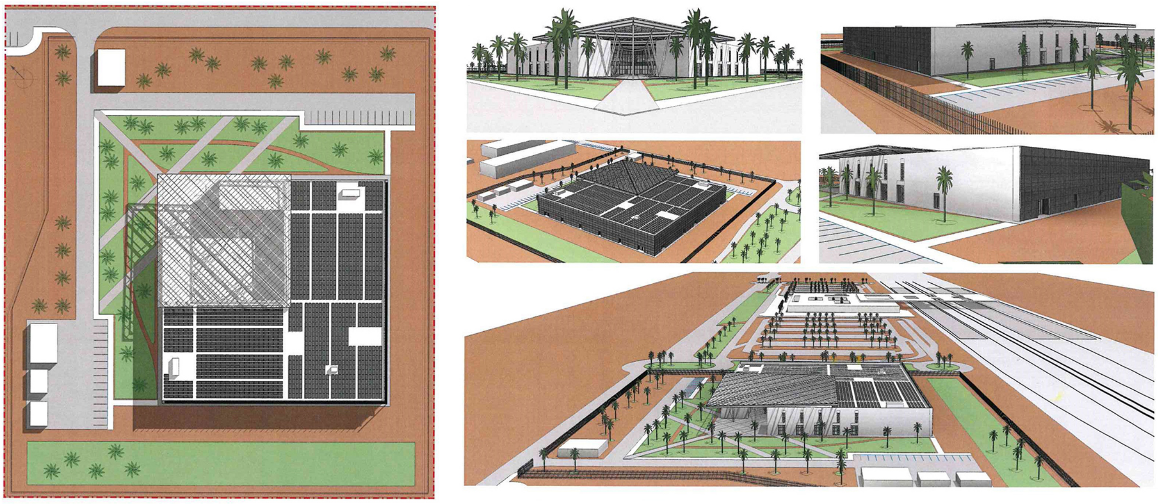

Figure 5. Early Design.

Detailed Design. In the Detailed Design phase the coordination model completed in the previous phase is continued in more depth. In order to reach a LOD 300 the various families that compose the building are modelled (Eastman, 2011).

In particular three categories of families are identified:

a. “system families”, which correspond for example to walls and floors, which are analysed in terms of optimal performance and stratigraphy with the use of the IES VE® software, and then developed in Revit®;

b. “hosted families”, to which doors and windows belong, that is those families which are necessarily housed within a mother family, such as a wall;

c. “loadable families”, which represent all additional external components, such as furnishings and photovoltaic panels, to be inserted in the overall model, completing it in all its parts.

One example of the first typology regards the exterior buffering, made of autoclaved aerated concrete, which gives the walls a solid mass and low transmittance. An interesting example for the third family type is represented by decorative panels in GRC envisaged for the protection of the North-East and North-West fronts from direct solar radiation. They are modelled as parametric generic families, placed within the overall model for its completion and for assessing their efficiency in terms of solar shading. The conformation and correct dimensions of the loggias certainly contribute to positive results.

Regarding the facades which face South-East and South-West, in front of the AAC buffering a photovoltaic facade in amorphous semi-transparent glass, modelled in Revit® is placed as a “Curtain Wall” element whose efficiency is once again evaluated on IES VE®. In order to assess the electricity effectively produced by the entire photovoltaic system, including the “stand-alone” panels of the covering, their placement is studied bearing in mind the obstacles and spaces necessary for the heat pumps and air treatment units for ventilation, as well as the shade offered by the exterior metal covering. It is understood that, for every small modification of the model (orientation, shading of the context, etc.), the model itself updates the energy performance.

With the modelling of the building with all its components and with the insertion of the various typologies of families, the maximum detailed reached is LOD 300 (Figure 6).

In order to increase the level of detail and development of the BIM model and of the information included in it, executive 2D drawings are carried out, and inserted directly as links, or “call outs” within the automatic sections: in this way, thanks to the potential of the two-dimensional design in terms of the relationship between level of detail and computational lightness of the models, it may be possible to reach a LOD 400.

Once the executive details are complete, the project is concluded with the calculation of the new index of energy performance derived by the optimisation of the form, of the transparent surfaces, and of the components of the shell and the system.

Results and Discussion

The analysis of the preliminary project shows the potential of BIM in the control of many performance parameters of a building in the design phase, revealing all the design problems associated to the lack of an integral multi-disciplinary approach during the initial phases of the process. This can be observed in the simple respect for the dimensional requirements of spaces, but also in the assessment of the efficiency of shading systems and in the orientation of the building itself.

The possibility of looking into a series of solutions in a quick and in-depth manner permits an accurate assessment of the most adequate form for a building based on the place in which it is set, thus joining current technological design methods to traditional bio-climatic methods, reinstating the strong and inevitable link between site and building. However, in the case study, the Index of Energy Performance does not vary significantly from one solution to the next, due to the destination of usage of the building, which means that the internal contribution of the machinery prevails clearly over the other elements in the

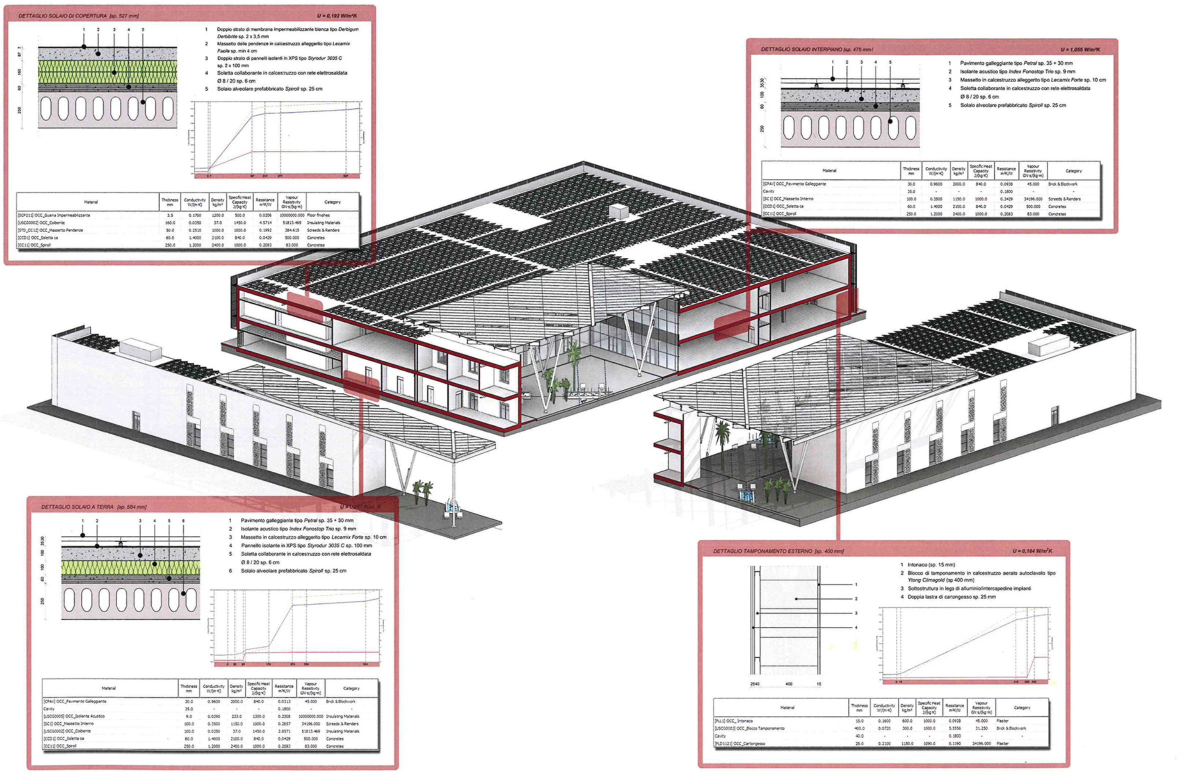

Figure 6. Detailed Design.

energy-balance. The aspect which has a greater impact on the overall performance, instead, is the production of photovoltaic electricity, and it is for this reason that the last conceptual solution analysed is the preferred choice.

What matters, however, is not so much the result of the said comparison with conceptual solution n. 5, but the process through which the said choice is reached: the efficiency of the BIM systems in making an innovative design easier, has been proven. It takes advantage of the result of the energy analyses not as simple means for assessment but as decision making tools and is capable of simulating the behaviour of the building, preventively identifying the problems derived from interferences between multi-disciplinary factors.

In this way a series of judgment parameters are available since the preliminary design phases, the assessment of which, without the use of BIM systems and their interoperability, would not be possible to obtain in a brief span of time and would be so expensive as to be almost certainly discarded. The same is true for LCA analysis of structural building systems, in which the automatic extrapolation of quantitative data on materials from the parametric models allows to include the subject of sustainability even in choice criteria and design of the structures, analysing a great amount of data in an expedite manner. On the other hand, the fact that the final choice is linked to requirements regarding pre-fabrication, shows how the said analysis cannot yet completely compute building aspect often of great importance for the economic success of the works.

During the phase of calculation of overall energy performance it is evident, once again and independently of the results obtained, that the assessments linked to the efficiency of the exterior covering, the type of shell and of system are possible, and especially in an expedite manner, thanks to the use of inter-operable BIM software. It is important to highlight, however, how the exchange of data between the platforms is not always efficient or even effective: in the case of the gbXML format, the conversion of 3D elements into surfaces makes the control of BEM necessary once the transfer has been completed, so as to avoid errors in the adjacencies between thermal zones; in the case of the IFC, on the contrary, the problems are mostly linked to the complexity of the structural models and their components, for example the hollow-core beams, which are not supported by the standard format and are therefore not transferred to the structural resolver.

Some considerations are finally necessary regarding the representation of models. Although levels of detail and development up to LOD 500 were envisaged, it is evident from the practical application that these objectives are not reachable for complex models if an adequate rationalisation is to be maintained, with the aim of allowing a correct management and an efficient usage of them. The cost of computing complex models with a high degree of detail, therefore, makes 2D drawings preferable to parametric modelling, especially in executive cases, making them more manageable and thus modifiable, leaving unvaried the potentials for use of the models, of which it constitutes a supplementary integration.

Conclusions

In view of the results obtained, especially in terms of method, a few interesting conclusion can be drawn. First of all, the analysis of a concrete case permitted experimenting with BIM applications on all key points of the sustainable project. For each phase of the process of the project it was evident how the use of BIM points toward sustainable design essentially because it permits the expedite management of great quantities of multi-disciplinary data associated to the project, eases the organisation of functions and process in terms of an integrated design and permits the quantitative comparison of various design solution from the preliminary design phases.

This last aspect permitted experimenting with an innovative design approach in which the preliminary choices were based on the results provided by energy and environmental impact analyses which normally would be undertaken at a much later moment of the design process.

On the other hand, the problems in managing complex BIM models must be stressed: the phase of preparation of the design alternatives provides a wide spectrum of assessment, however, due to the yet not perfect efficiency of the inter-operability, it may be very expensive, to such an extent as to be completely discarded in practice due its cost in both terms of money and time.

In this respect, despite its potential, the BIM must be enhanced in terms of efficiency – rather than effectiveness – in the transfer of data, both in terms of versatility and of the possibility of working outside precise methods of operation; the software used, in fact, are often too rigid, but especially too sensitive to possible errors in modelling or in the transcription of data in the standard protocols (IFC, gbXML, etc.), to the point of requiring a clearly greater degree of awareness by the designers, who must tackle problems that are no longer exclusively design-related, but also BIM-procedural and computational linked to the predisposition of the models or derived from the translation, during inter-disciplinary communication of languages that are often different.

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