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A Decision Support System (DSS) for constructability assessment in seismic retrofit of complex buildings

V. Getuli[a], T. Giusti[a] and P. Capone[a]

[a] Università degli Studi di Firenze - DICEA, via di Santa Marta, 3- Firenze
E-mail: vito.getuli@dicea.unifi.it, tommasog@dicea.unifi.it, pcapone@dicea.unifi.it

ABSTRACT

Choosing the optimal strategy for the seismic retrofit of an existing building is a difficult problem. This difficulty increases in the case of complex buildings systems with different strategic requirements in terms of organization layout and structural features. This paper contributes to solving this complexity by combining management and technical strategies, especially in situations of comparable times and costs. It is demonstrated that the best way to obtain final results that are consistent with the initial requirements is to intervene at the beginning of the design stage. To this end the implementation of a Decision Support System (DSS) aided by Information Technology (IT) is presented for making a constructability assessment of the seismic retrofit of complex buildings. Different seismic retrofit scenarios compete to be the optimal retrofit solution. Several evaluation systems are combined with classic constructability-based tools to produce an organic framework. A rule-based engine that utilizes this framework can be implemented on top of user-friendly software. The DSS intends to control building management by prefiguring a real ongoing building execution after the early stages of the project. This is made possible by using the simulation of site safety layout in all compatible scenarios. By managing the output data of IT models it is possible to assess both management and structural strategies. In the end the DSS combines them to choose the most favorable overall solution. Looking towards future development, it can be seen that applications of a BIM Platform integrated with the proposed DSS have considerable potential in construction management practice.

Keywords –

Decision Support Systems; Project Information Management; Construction Management; Constructability.

1 Constructability concept, benefits, and implementation

Constructability has been defined as the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives [1]. This field has attracted the attention of many industrial and academic organizations in the past three decades [2]. These studies show that a lack of integration between construction and design has been the root cause of cost and quality issues in construction industries [3]. Paulson exposed the importance of inserting construction knowledge into design. This process was called “constructability” and has been the topic of research ever since.

The potential significant benefit associated with a high level of constructability has been amply demonstrated. The conclusions of Russel et al [4], reinforced by Griffith and Sidwell [5], highlight the benefits of improving constructability across the total building process. These include the following: better conceptual planning; more effective procurement; improved design; better construction methods; more accomplished site management; more effective team work; and more.

Nowadays constructability implementation, putting all of the essential concepts identified into a workable package, is the greatest challenge to researchers and practitioners. In general, the successful implementation of a constructability program depends on an understanding of some basic essential elements [6], including:

1. when a constructability process should be started in the project life-cycle;
2. who should be part of the constructability team;
3. what should be the main focus of a constructability program
4. how to implement a constructability program.

From start to completion, construction projects include several phases characterized by many tasks that aim at identifying, planning, designing, and constructing the existing facilities. In order to implement constructability, W. Thaber shows (Figure 1) that these phases may be grouped into two main stages: a Pre-construction Stage and a Construction Stage [7].

The design development phase, which is the one we are investigating more deeply, comprises: (1) the schematic design, where the design team investigates alternative design solutions and alternative materials and systems; and (2) detailed design, where the design team evaluates, selects, and finalizes the major systems and components of the project.

Different solution models for implementing constructability in the Pre-construction Stage have been given in the literature. Fischer proposed a Construction Knowledge Expert (COKE), who guides designers toward structures that are more constructable. Patty et al. presented a computer tool that uses multimedia to give the designer the ability to access constructability information at the point of design. Moore and Tunnicliffe described aspects of the production of an Automated Design Aid (ADA) that provides the designer with useful decision support regarding design corrections and adaptations. Kupernas et al. introduced a methodology to use a computer aided drafting (CAD) 3D model of a project to review design layouts and to identify design conflicts as part of a pre-construction constructability review [8].

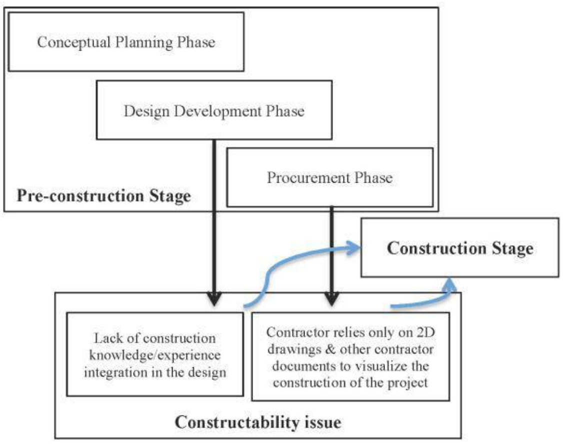


Figure 1. Preconstruction Stage and a Construction Stage, from W. Thaber [7].

The purpose of the studies that are recapped in this paper is to provide new constructability-based solution models for the seismic retrofit of existing buildings with a complex intended use (SRCB), such as hospitals, schools, libraries, and public buildings.

2 Research objectives

Choosing the optimal strategy for the seismic retrofitting of an existing building is a difficult problem. This difficulty increases in the case of existing buildings with a complex intended use due to different requirements, such as [9]:

1. *Structural Features*;
2. *Aesthetic Value* (These are often an important factor in selecting a retrofit strategy. Retrofit elements placed on the exterior of a building, including infill walls, new walls, buttresses, and braced frames, are typically perceived as having a negative impact on building appearance);
3. *Project Budget* (Cost is often the overriding factor in determining the project performance objectives, the retrofit strategy employed, and even whether a retrofit will be performed. Different strategies can have widely different costs);
4. *Construction Period Occupancy Disruption* (The ability to continue to occupy a building during retrofit can have a significant benefit with regard to overall project cost; often this ability is a fixed requirement to guarantee);
5. *Permanent Occupancy Impacts* (Many retrofit strategies will result in some permanent impairment of the use of the building. As an example, the installation of a vertical frame within the interior of a building will limit future activities or be incompatible with functions such as the case with recovery rooms in hospitals);
6. *Risks from interferences*.

According to the literature review, constructability implementation should contain and control all these factors to improve project quality [10].

In the case studied (SRCBs), the influence of the planning and management of the construction site on project quality has emerged; these are common factors that affect all the requirements listed above. Furthermore, if incorrect construction site planning and design are implemented, the result may be non-buildability and a building redesign. In any case there will be a substantial impact on project cost and time.

Therefore, the following objectives are envisaged:

- To provide a new constructability-based solution model, for the case of SRCBs, supported by a constructability-based tool, selected from a literature overview;

- To combine the practices and skills of structural engineers with those of building managers in a unique way;
- To take into account both the building owner's objectives and the exigencies of the building operating system after the start of the Design Development Phase.

Investigating, managing, and assessing several design solutions in choosing the optimal one should not involve the tout-court application of a compatible solution that is the result of the individual designer's skills.

3 Selection of constructability tools

Fisher presented an overview of twenty-seven constructability tools that have been included in the literature. The research further links these tools to a typical constructability planning process model so that the user can develop an implementation strategy with them [11]. The tools are listed and divided into *policy/process-baced tools* (thirteen), *modeling tools* (ten), and *technology-based tools tools* (four).

Fisher also introduced twenty-one steps for a generic constructability planning process. Each of the twenty-seven tools is then mapped onto this generic process model. These links between process steps and tools provide the user with a framework. This framework allows the user to know when exactly to implement these various tools during the life of a project [12].

According to the research objectives presented in Paragraph 2, constructability tools are chosen that provide a new constructability-based solution model for SRCBs.
Four different tools have been selected:

- Constructability Organization Structure. A team should be formed that includes expertise from all of the phases. Each team member has responsibility for a particular phase.
- Implementing Responsibility Matrix. A constructability issues matrix is a matrix that provides an architecture for documentation.
- Project Constructability Agreement. This is a drafted agreement for the design constructability team that states a commitment to constructability and the objectives set for the project.
- Formal Processes. A formal process is one in which steps and procedures are clearly defined.

These four tools have been implemented in a Decision Support System that is to be applied in the Preliminary Design in choosing the optimal retrofit alternatives for a complex building.

4 Framework of the decision support system

In the case of a seismic retrofit, the DSS-Model, before adopting a particular strategy, should evaluate a number of different alternatives with respect to their feasibility and applicability and, together with the owner, should select the combination of strategies that appears to provide the most favorable overall solution.

The main idea, developed in the DSS-Model below, is to overturn the classical approach of evaluating site management only after the structural choices have been made. In order to evaluate the site management at the beginning of the Design Phase, the DSS-Model assigns the key role of optimizing simultaneously both structural management and construction site management to a unique procedure.

From this perspective, the authors have considered it appropriate to discern two families of strategies with regard to complex building systems:

- **Technical Strategies**, designed to increase the seismic performance of the building (System Completion; System Strengthening and Stiffening; Enhancing Deformation Capacity; Reducing Earthquake Demands); and
- **Management Strategies**, which regulate the way in which a technical strategy is implemented in managing both construction site tools and site interferences (Occupancy Change; Demolition; Temporary Retrofit; Phased Retrofit; Retrofit with Occupied Building; Retrofit with Vacant Building; Exterior Retrofit; Interior Retrofit).

Only by analyzing the different retrofit strategies is it possible to select the most favorable overall solution. Thus, the general objectives of the DSS-Model are as follows:

1. to assess a range of alternatives that represent the technical and management strategies compatible with the case study, within all the existing strategies;
2. to consider the final strategy as the combination of one technical alternative and one management alternative;
3. to locate the strategy that complies with requirements more than others;
4. to plan the responsibility matrix of the DSS-Model;
5. to support the DSS-Model with some mathematical models for decision making so that it may guarantee the attainment of the above requirements and aims [12].

Figure 2 shows the general framework of the DSS-Model.

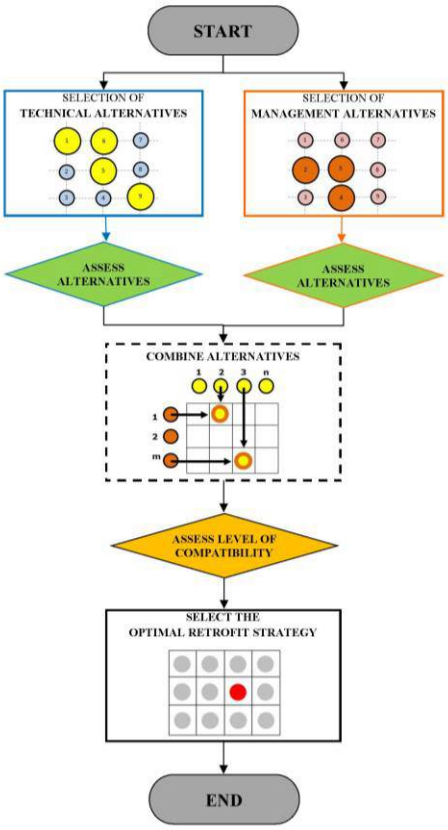


Figure 2. General framework of the proposed DSS-Model

It therefore remains to identify the processes and tools for assessing and connecting the alternatives and for selecting the optimal final strategy, taking into account that for any decision there are inevitably a number of aspects that must be kept under control. Going further, the proposed DSS-Model programs the decision problem as shown below:

A) the ***alternatives*** represent the different choices of actions available to the decision maker, in a finite number and determined in the initial phase;
B) a set of ***attributes***, associated with each class of alternatives, represents the different points of view under which each alternative can be judged;
C) each attribute has a ***weight***, which represents its level of importance compared to the others.

An important step is represented by the evaluation of alternatives.

For each alternative a set of information must be acquired and synthesized in pre-set data tables as shown below in Figures 3 and 4.

1. **Technical Alternatives**

The data the Decision Maker (DM) must acquire are:

a) graphical representation of constructive detail;
b) breakdown of the strategy in executive phases;
c) identification of construction site areas for each executive phase;
d) technical attributes;
e) weights of attributes.

Figure 3 shows the organization of these data in the specific table.

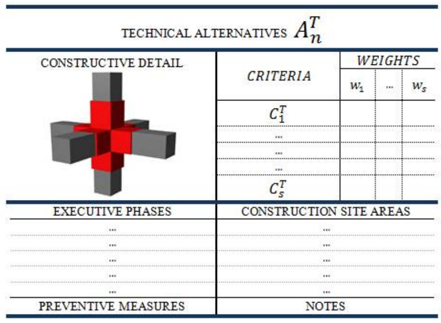


Figure 3. Data tables for technical alternatives

2. **Management Alternatives**

Using 3D modelling of a construction site in a building taken as a model (Figure 5), the data the DM must acquire are listed below:

a) design of construction site layout;
b) planning of construction site phases.
c) analysis of compatibility level with respect to each technical alternative – this step aims to understand how the proposed organization layout out is compatible with all the technical alternatives;
d) management attributes;
e) weights of attributes.

Figure 4 shows the organization of these data in the specific table.

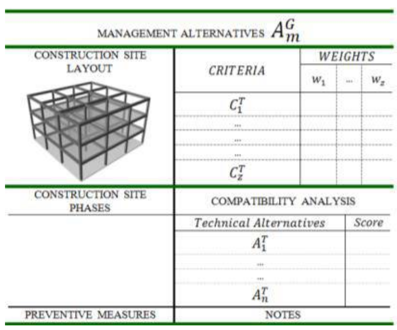


Figure 4. Data tables for management alternatives.

The decision making problem will choose the optimal retrofit solution A^* as that solution that demonstrates the best global response to the objectives.

5 Numerical methods

In this paragraph the analytical approach to combining alternatives, criteria, and weights is presented.

One of the most common approaches to solving this kind of problem is Multi-Criteria-Decision-Making (MCDM) [14].

This approach provides the DM with several advanced tools for selecting the solution when different parameters are involved. MCDMs do not locate the optimal solution in an absolute sense but they provide a ranked list according to the DM's evaluation attributes.

The problem of defining the importance of the criteria is a fundamental aspect of MCDM methods. From among the existing MCDM methods (depending on input-data – Deterministic, Stochastic, Fuzzy – or depending on the number of DMs – Single DM or Multiple DM [15]) two have been chosen:

- A method based on *Direct Assignment*. An expert DM may be able to assess the relative importance of each attribute over the others by assigning a preference score on a standard scale;
- The *Eigenvalue Method* proposed by Saaty, which gets around difficult measures of preferences. This method permits a comparison of strategy performance with respect to a given criterion, two-by-two, and to associate it with a value on a linear scale [16].

Direct assignment has been used first to choose the weights and criteria scores, which are useful in building both the technical and the management decision matrix. In this case we make use of a Determinist Method that uses cardinal information with a Single DM. Ranking the alternatives is a purely technical choice that can be performed by any DM, without any reliance on their experience.

The Eigenvalue method has then been used to define the level of importance of Technical Strategies compared to Management Strategies. To make the data reliable, a Delphi support technique has been performed. The Delphi is a procedure for obtaining a consensus of opinion from a group of experts [17, 18]. An essential feature of the Delphi technique is its framework; the main characteristic is that experts express their opinions individually and anonymously while having access to the other expert's views as the process progresses.

The Delphi uses as input a set of options for which consensus is needed. To process the data a group of experts are questioned using a semi-structured questionnaire [19]. The experts do not meet so their opinions are independent.

In this case authors have created two teams of experts. The first team was composed of 5 managers and the second team was composed of 5 structural engineers. These groups had somewhat different perspectives, but this design permits a comparison of the perspectives of different stakeholder groups. The decision was made to populate the panels with experts with a common background with respect to the topic. The experts were asked to assign an importance score (using Saaty's scale) to the technical strategies with respect to the management strategies; when consensus was reached in each of the panels an arithmetical average was calculated to assign the definitive score.

With this procedure the user is able to compare technical and management strategies by taking advantage of the experience that is enclosed in the score assignation of the procedure.

Figure 5 shows experts and numerical methods with respect to the Formal Process.

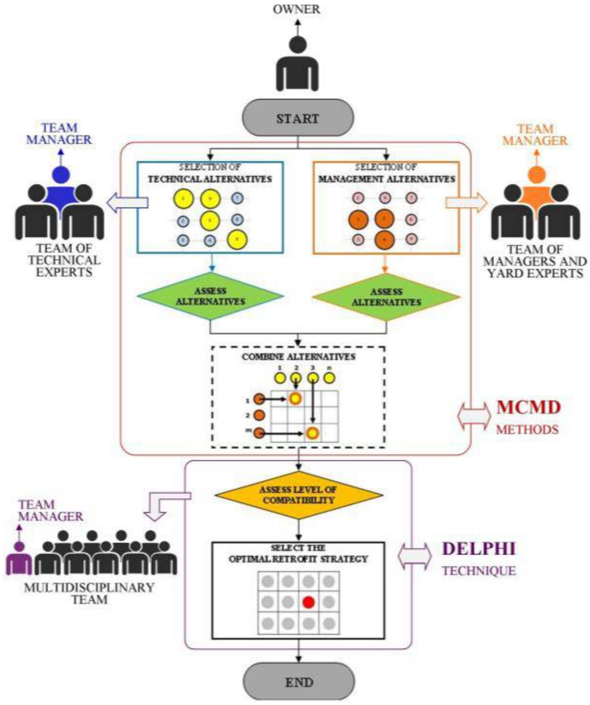


Figure 5. Experts and Numerical Methods with Respect to the Formal Process

The application of the numerical methods, according to the general framework (Figure 2), is described step-by-step in Figure 6.

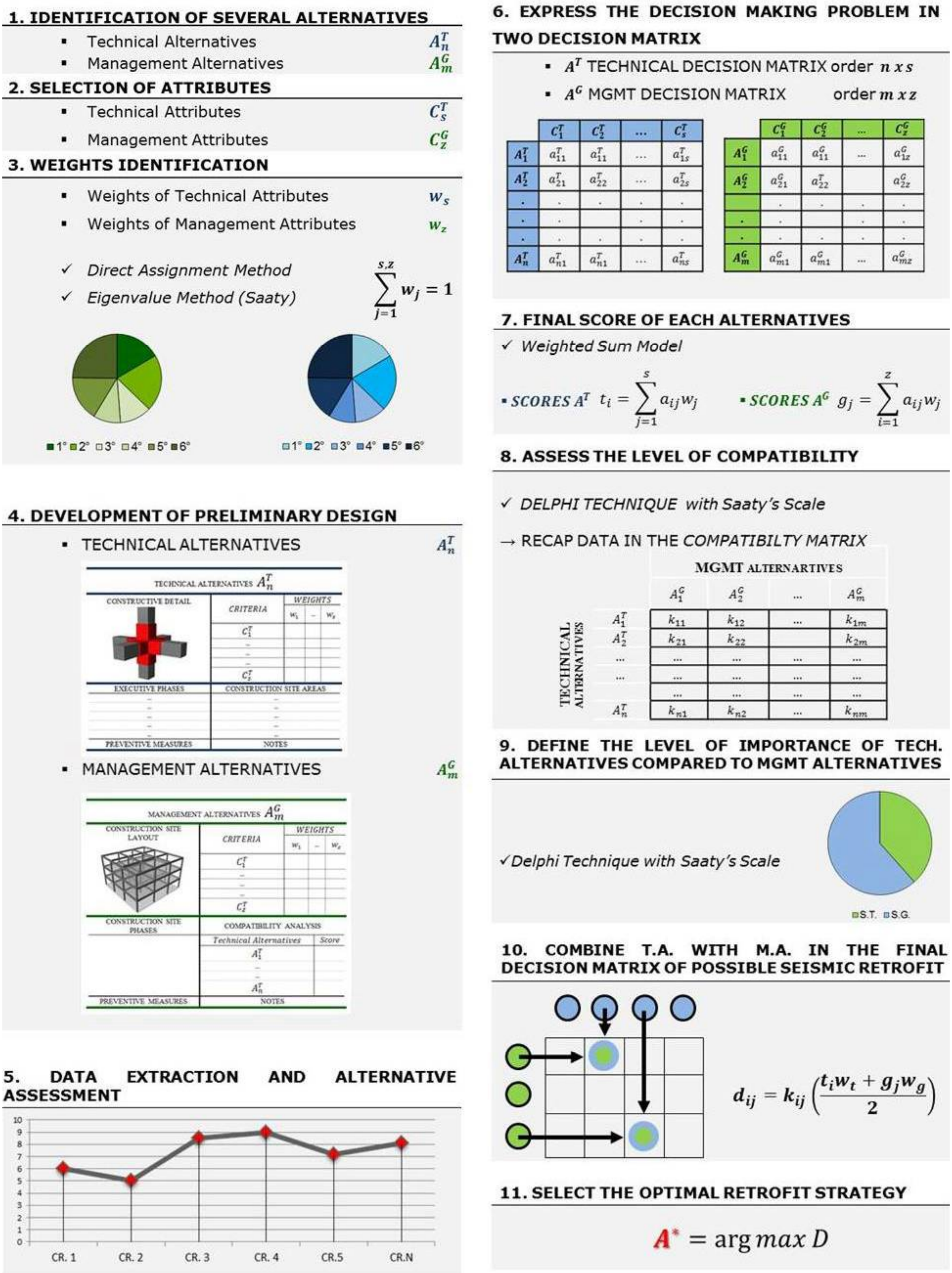


Figure 6 DSS described Step-by-Step

6 Application to a case study

In order to validate the proposed approach, the selection process was applied to the seismic retrofit of an Italian Hospital called "Cardarelli" in Campobasso, built between 1968 and 1988.

The hospital layout is composed of 13 different concrete-frame buildings intended for different services.

Before inserting the decision making process, several data about the case study were acquired in order to select compatible alternatives across a range of possible strategies. The possible strategies have been assimilated to the document of the *Applied Technology Council* (ATC 40) [9].

The results obtained are shown below:

(i) Analysis of the strategies, definition of attributes, and weights and tables

i.1. Management Alternatives

Table 1 summarizes the results.

Table 1. Management Attributes and weights

	Attributes	Weight	
C_1^G	Low costs of construction site	w_1	0,14
C_2^G	Modest environmental impact	w_2	0,17
C_3^G	Functional compatibility	w_3	0,09
C_4^G	Limited trouble to the occupants	w_4	0,23
C_5^G	Limited presence of risks of interference	w_5	0,25
C_6^G	Availability of construction site areas	w_6	0,06
C_7^G	Short path length of materials	w_7	0,04
C_8^G	Few machineries on construction site	w_8	0,02

i.2. Technical Alternatives

Table 2 summarize the results.

Table 2. Technical Attributes and weights

	Attributes	Weight	
C_1^T	Shortness in realization times	w_1	0,06
C_2^T	Low costs of installation	w_2	0,1
C_3^T	Low costs of maintenance	w_3	0,16
C_4^T	Low aesthetic impact	w_4	0,22
C_5^T	Low disturbance to the hospital activities	w_5	0,14
C_6^T	Structural Compatibility	w_6	0,11
C_7^T	Functional Compatibility	w_7	0,18
C_8^T	Standardization of reinforcing components and working phases	w_8	0,03

(ii) Decision matrix of alternatives

Figures 7 and 8 show the score assigned to each alternative with respect to each attribute. The final scores are given in the last column.

	C_1^G	C_2^G	C_3^G	C_4^G	C_5^G	C_6^G	C_7^G	C_8^G		
A_1^G	5	4	5	7	6	5	6	6	→	5,60
A_2^G	9	9	8	6	7	7	5	9	→	7,44
A_3^G	1	8	2	8	9	8	7	7	→	6,67
A_4^G	3	5	6	8	7	5	5	6	→	6,02

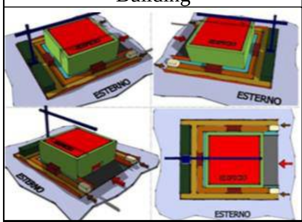
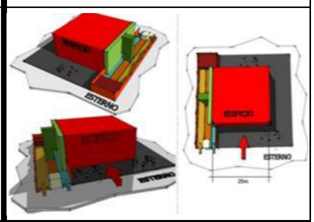
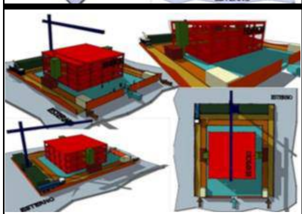
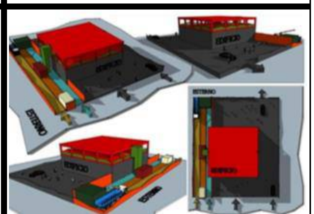
Figure 7. Decision Matrix of Management Strategies

	C_1^G	C_2^G	C_3^G	C_4^G	C_5^G	C_6^G	C_7^G	C_8^G		
A_1^T	7	9	7	6	5	5	5	7	→	6,12
A_2^T	4	5	6	6	5	4	4	6	→	5,03
A_3^T	6	7	3	5	4	5	7	9	→	5,14
A_4^T	5	4	5	7	8	9	9	8	→	6,57

Figure 8. Decision Matrix of Technical Strategies

The Preliminary Designs of the Management Alternatives, executed out using CAD software, are shown in Table 3. Input-Data for use in assessing alternatives, were manually extracted from the CAD-Models.

Table 3. CAD-Model of Management Alternatives

A_1^G Exterior Retrofit with Occupied Building	A_1^G Exterior and Phased Retrofit
	
	
A_1^G Interior Retrofit with Vacant Building	A_1^G Interior Retrofit with Occupied Building

(iii) Selection of the Optimal Retrofit Strategy.

After the evaluation, and in accordance with points 8, 9, 10, and 11 of the process shown in Figure 6, it has been possible to select the optimal retrofit strategy A* (Table 4).

Table 4. Optimal retrofit strategy

	MANAGEMENT STRATEGY	TECHNICAL STRATEGY
A^*	Interior and Phased retrofit with occupied building	Retrofit with Steel Bracing

7 Conclusion and future development

Looking toward future development, applications of Building Information Modelling (BIM) Platform integrated with the proposed DSS are seen to have considerable potential.

The authors addressed the field of research for creating a logical structure that was compatible with the "design and building process".

The preliminary design, both of technical/structural alternatives and of management/site layout alternatives, was carried out using CAD software. With this software, objects were manually gauged and data extracted, e.g., number of machineries, quantity of scaffoldings, path length of materials, functional compatibility by means of visual clash detection, time and cost evaluation, etc. At a later stage, output data were included in the proposed DSS, selecting the optimal retrofit strategy over a range of strategies compatible with the analyzed building.

The potential benefits arising from the integration with BIM-software are listed below:

- BIM is characterized by the creation and use of coordinated, internally consistent computable information about the objects of the building model;
- ability to associate specific information to objects;
- computable information;
- automatic clash detection.

Standardizing the process of modelling will make it possible to automatically process information with a DSS, implemented in a plug-in that is compatible with the BIM-platform.

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