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Cost-Oriented Tool for Life Cycle Planning

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The Industry 4.0 opens to the sector of building constructions a new perspective, especially in relation to the digitalization of information and to the use of Big Data Analytics to manage them. Gathering data on new and existing buildings to provide a more and more complete view on the outcomes of the choices of construction, in order to ideally optimize the designing process, has already been identified as one of the main purposes. Yet, despite the available data are much less, the same vision can also make it possible, by enhancing and emphasizing monitoring activity in this field, to build another kind of database, involving an aspect that is equally crucial for a building and its components: the building management phase, that is to say the planning of maintenance activities, the cost of which cannot be overlooked. Looking ahead to the possibility of developing such database, multiple ways of making use of it to guide designers in the choices related to life cycle planning, unfold. Considering a necessary step that of realizing tools to evaluate such choices according to at least one parameter, in order to guide designers towards choices that are consistent with their purposes, this work investigates the possibilities in this field, and proposes a software tool to elaborate strategies and compare them on the basis of the cost parameter. Finally, hypothesis of inclusion of this kind of software in a BIM platform are suggested, in a view of facility management of BIM 7D.

INTRODUCTION AND STATE OF THE ART

Every year, the building sector is interested by significant cash flows: building works are one of the most 'expensive' items in the market, and Italy in particular is suffering from a significant decrease in the number of new constructions, a phenomenon which can be attributed to many reasons of various nature, among which financial ones. Consequently, in the analysis of building operations, interventions on existing buildings are becoming more and more relevant in comparison to new constructions, following a trend which had already shown several signals in the last decades.

It must also be pointed out that, for a building, initial costs of construction only represent a small part of the global cost, while management costs, which include maintenance as well, constitute a much more relevant share.So, together with the less and less consistent presence of new constructions in the Italian building market, it seems correct to state that, in order to reduce the cost of the building sector, intervening on the costs of maintenance is an important and necessary focus.

Too often, designers thought that there was always an economic benefit in intervening on a component to restore its performance instead of substituting it.Following this purpose, muchresearch has been carried out in the field of restoring interventions, but actually, at least from an economic point of view,the evaluation on whether it is convenient or not, depends from the service life of the component, the cost of substitution, and the cost of the restoring intervention considered.

This reasoning can be applied to any maintenance intervention, and by extension to a maintenance strategy: what is the global cost of the maintenance that is executed on a component? Then, how much do these interventions lengthen its life? Is it a choice that realizes the higher economic benefit? Asking these questions has actually a standard since a relatively long time ago in the industrial field, in which the consequences related to the increase of performance can be directly seen in terms of productivity. In fact, Preinreich (1940) elaborated a model for the determination of the economic benefit deriving from equipment maintenance quite early; then, Eilon, King and Hutchinson (1966) studied the same subject focusing on the trucks. Christer and Goodbody (1980) applied their models in order to find the limits of convenience, and some years later proposed an application on medical equipment (Christer and Scarf, 1994). Their approach consisted in setting the periods between interventions and the costs of interventions as variables, then finding the values that maximise and minimise the functions related to economic incomes.

One of the first applications to buildings is that of Blazenko and Pavlov(2003), specifically concerning real estate investments: in this work, the net values of maintained and unmaintained investments are defined and compared, making use of the concept of risk to compute the negative consequences deriving from poor maintenance. Later, Harding, Rosenthal and Sirmans (2007) identified maintenance as a non-negligible factor of cost depreciation, and suggested a model in which the maintenance activity that is executed is parametrized through its cost over time. In the listed models, though, especially the ones on real estates, the issue of different typologies of maintenance activities and interventions is not fully taken into account. This makes it less realistic, as even with the same costs, different maintenance strategies can lead to different effects on components and buildings. Manganelli (2013) indeed emphasizes the close relationship between maintenance and building depreciation, recognizing at the same time the difficulty to quantify it. The variation of the economic value of a building could in fact constitute a reliable parameter to compare maintenance choices according to cost, as Del Giudice et al. (2016) suggest, in particular in relation to the cost depreciation method.

Unfortunately,itmustalsobesaidthatthe main difficulty in modelling the relation between maintenance and economic value in a building, is also caused by the issuesin predicting with precision the effects that maintenance has on the components. In fact, there is some uncertainty on determining the service life of a building component even in absence of maintenance interventions, as several factors, including climate, position on the building, constructive features, affect this characteristic. Moreover, experience shows that the effect of a maintenance intervention on a component can change deeply according to the moment of its life at which it is executed. So, evaluating this variation might apparently seem an unreachable goal.

Thankfully, there are two more elements to consider. For example, Gottfried (1992), by making use of statistical analyses, approximations and evaluations, estimated the mean values of service life for several building components, in presence or in absence of maintenance interventions. Some theorists of the cost depreciation method, for example, use them as reference values for its application. This set of data could not be used directly to evaluate the most convenient maintenance activity, as it was obtained considering a bi-stable logic – with or without maintenance – so the matter of choosing among different possibilities of maintenance scenarios is not taken into consideration at all. Yet, this approach provides the suggestion to obtain similar values by carrying out statistical analyses on different degrees of maintenance, rather than on these two opposite scenarios.

The other element is constituted by an encouraging research carried out by Serrat et al. (2017), constituted by the monitoring of a high number of buildings in the city of Barcelona, in order to evaluate and measure the performance of their components over time, on which maintenance interventions are executed. The purpose is that of

obtaining performance-time curves that define the behaviour of components, and mathematical models that describe the effect of the various maintenance interventions on those components.
Looking forward to the realisation of these purposes, and to the possibility to adapt the results to other contexts by using tools such as the Factor Method or by comparing the results to those of hypothetical future similar experimentations, it seems that this kind of work may be a good path to gather reliable information on the parameters needed to perform economic evaluations on maintenance choices. This paper will explore the process to perform this kind of evaluation and analyse which kinds of software could be good for its actuation.

ECONOMIC CONVENIENCE OF MAINTENANCE STRATEGIES

COMPONENTS

For a given component A, the number of years of which its spontaneous duration, that is to say service life in absence of maintenance interventions, consists, can be named v_A. Then, during its life, the component can be subjected to ndifferent types of maintenance interventions I_{Aj} (I_{A1}, I_{A2}, I_{A3}, …,I_{An}). Each of the interventions is characterized by a cost C_{Aj} (C_{A1},C_{A2},C_{A3},…,C_{An}) and by an increasing effect on the residual (and then, the total) service life of the component. The amount of this increase changes according to the time of execution of the intervention, with a tendency that depends on the typology of the intervention and of the element. For example, tendentially a layer of paint applied on a plaster covering remains in a good state for about 5 years, then starts showing signs of decay, until the point, at around 10 years, when there is a drastic decrease in the protection it offers to the plaster. Considering the direct relation between the protection that paint offers to the covering and the duration of the latter, a painting intervention produces a more significant increase in the service life of the plaster covering if it is executed after 10 years, than after 5 years or less. Moreover, this connection with time is not only in relation to the year of construction, but also to the interventions that have already been performed on the element. Also, this reasoning cannot be applied in the same way to ameliorative maintenance, as it is not true that carrying it out shortly after the beginning of service life produces little increases in it. So, since these laws of variations may change in every case, and none has ever been modelled for any intervention nor for any component, it is necessary to avoid making it explicit in the description of this evaluation. It is possible to introduce a proxy parameter which takes into account all the interventions that have been executed before a given time t_i, named Maintenance History before the time $t_i$or $MH(t_i)$. So, the increase of service life related to the execution of a maintenance intervention I_{Aj} on a component A at a time t_i can be expressed as $\Delta v_{Aj} = f_{Aj}(t_i, MH(t_i))$. It must be said, though, that a simplified solution could also be represented by the use of a stochastic function.
So, considering a maintenance strategy α_k on the component A, and the homonymous set of the interventions that are executed on it in that strategy, then the total service life of the component in this maintenance strategy is calculated as:

$$v_{\alpha k} = v_A + \sum_j \Delta v_{Aj}\,, j \in \alpha_k$$

$v_{\alpha k}$: service life of component A in strategy α_k;
v_A: spontaneous duration of component A;
Δv_{Aj}: service life increase related to the j-th maintenance intervention of strategy α_k.

In order to evaluate the economic benefit deriving from the extension of service life to v_A to $v_{\alpha k}$, it is possible to make use of a model recently suggested for the evaluation of the convenience of restoring interventions by comparing the increase of service life and the cost of the intervention by calculating the economic value related to the employment of a component for n years, named Component Employment or CE(n). It can be calculated as:

$$\mathrm{CE(n)} = \mathrm{A_v} \cdot \frac{1-(1+\mathrm{i})^{-\mathrm{n}}}{\mathrm{i}}$$

CE(n): Component Employment for n years;
A_v: annual value of a series of constant annuities, obtained from the equation below;
i: interest rate;
n: duration of service life.

A_v is obtained from the following equation, which equals the initial cost of construction of a component, reduced by the back-discounted residual value at the end of service life, if present, and the expression of v constant annuities, which correspond to the v_A years of the spontaneous duration of a component A:

$$C_0 - V_r \cdot (1+i)^{-v} = A_v \cdot \frac{1-(1+i)^{-v}}{i}$$

C_0: cost of construction of the component;
V_r: residual value of the component at the end of the service life;
i: interest rate;
v: spontaneous duration of the component;
A_v: annual value of the substitutive series of constant annuities, unknown term of the equation.
So, if the service life of the component A is increased to n years through a

maintenance strategy α_k, then it results that CE(n)>CE(v), and the difference between the two is indeed the economic benefit deriving from execution of the maintenance strategy α_k on that component.
Of course, the cost of the strategy α_k on the component A corresponds to the summation of the back-discounted costs of the interventions executed over time, indicated as Maintenance Cost or MC(α_k). By reducing this value by an amount that is equal to the difference between CE(n) and CE(v), the effective cost of the maintenance strategy is obtained, and this, named MC*(α_k), represents the parameter on which the evaluations on the economic convenience of the strategies can be based.

Whole building

As when evaluating the economic convenience for a single component, for the whole building as well the reference parameter is constituted by the lowest effective cost MC*¬. Yet, components are not mutually independent parts of a building, but rather two types of connections have been identified by Nicolella (2003):

- technological connections, those where two elements are bound to each other, so that it is necessary to intervene on both at the same time. For example, plaster and paint have a strong technological connection: when intervening on plaster, paint is affected by the intervention too, and so an intervention has to be performed on it as well;
- operative connections, related to the convenience to associate interventions on two elements, because of reasons of executional nature, such as equipment, provisional works, work yard organization. For example, the entity of the installation cost of scaffolding makes it particularly opportune to carry out at the same time works on all the components that require its employment: plaster and paint of vertical enclosures, cornices and balconies with all their components, coverings, downpipes, gutters, etc.

This means that, while two strategies on two different components could respectively be the most convenient for those components, their combination could produce a lower benefit than another set of two strategies, as they might not too compatible, considering the connections that exist between the two components.So, their influence on the global convenience can be noticed only in the combination of the different maintenance strategies on the single components. Heuristically, this could be solved by applying small adjustments to the times of intervention of the

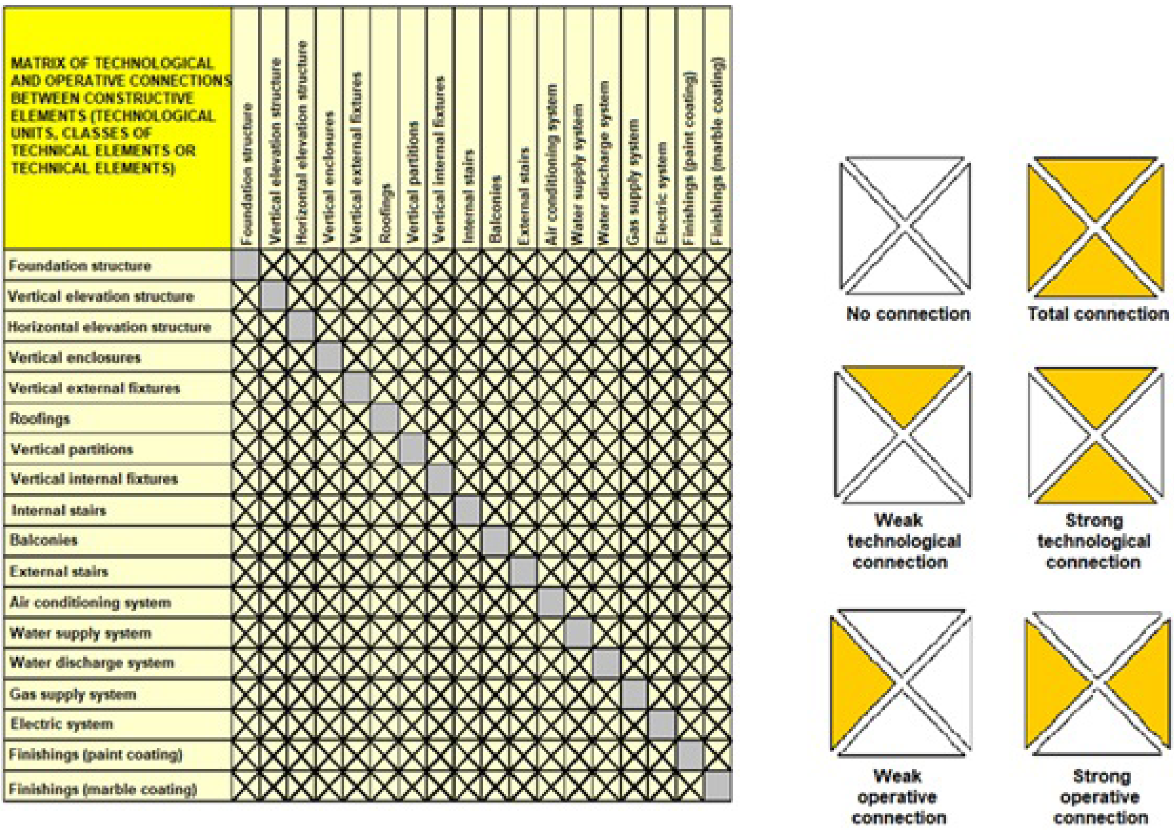

Figure 1: Blank pattern of connections matrix and connection symbols legend

single maintenance strategies on the components that have shown to be respectively the most convenient; of course, this process is on one hand easily applicable, but on the other hand hides other combinations which may have higher synergies.

SOFTWARE-BASED EVALUATION

As it has been shown, technological and operative connections make it necessary to consider the combination of the maintenance strategies on the whole building together, rather than ranking the convenience on the single components separately, to reach the conclusion of which choices lead to the most proficient result, in economic terms. It is evident, though, that the approach of evaluating all the combinations, even if a selection were applied to the total number of combinations, is a task which could hardly be performed manually. So, it was chosen to experiment hypothesizing and developing a software which could run this process automatically, by:

- generating all the possibilities for maintenance activity on each of the components for a chosen period of time, drawing information on the interventions from a database;
- calculating, within a range, the resulting service life for each strategy;
- combining the single strategies on different components to generate maintenance scenarios for the whole building;
- evaluating MC and MC* for the single components and for the whole building;
- ranking the maintenance scenarios.

The software, which is currently in development,is structuredthrough an offline client/server model, with a Java client and a PostgreSQL database server. The database schema contains the interventions, and has a relation for each of the components, in the form: ElementA (name,code,cost,package,servlife,tools1,tools2).

The first two terms correspond, respectively, to the detailed name of the intervention, and to the short code that is used to ease the visualization of the strategies and combinations; the cost is the unitary cost of the intervention, derived from price lists; 'package' indicates the technical solution of the component on which the intervention is executed (for example, if the considered component is the vertical enclosure, masonry or plasterboard); 'tools1' and 'tools2' refer to the equipment, machinery and provisional works needed to carry out the intervention, if the costs needed to put them in use are relevant (for example, the operations of mounting and removal of a scaffolding or the use of hammers or drills); 'servlife' is the form of the function, indicated in the previous paragraph as $f_{Aj}(t_i, MH(t_i))$, which is used to determine the increase of service life of the component related to the maintenance intervention. Since the software is still in development, and a full database on the possible maintenance interventions has not been implemented yet, the current one only contains placeholders. The placeholders take the form of codes containing the initials of the category they belong to (the letter of the components for the packages, M for machineries, W for provisional works and E for equipment regarding the tools); the relationships that are used to determine the service life are currently modelled as generic basic functions.

Every relation also contains additional strings, as many as the technical solutions hypothesized for the corresponding component, which are used to simulate the lack of execution of maintenance interventions (for one year).

name	*code*	*cost*	*package*	*tools1*	*tools2*	*servlife*
Intervention 1	A-I1	5	A1	M1	-	t+4
Intervention 2	A-I2	10	A1	M1	M3	5-t
Intervention 3	A-I3	10	A1	M2	M1	t+2
Intervention 4	A-I4	15	A1	M1	E2	6
Intervention 5	A-I5	5	A2	M3	W1	2
None1	-	0	A1	-	-	0
None2	-	0	A2	-	-	0

code	*name*	*c-area*	*c-length*	*c-volume*	*c-mass*	*c-unit*
M1	Machinery 1	5	7	6	3	2
M2	Machinery 2	4	2	5	7	1
E1	Equipment 1	8	9	3	5	8
E2	Equipment 2	11	7	9	1	2
W1	Prov. work 1	4	6	8	6	6
W2	Prov. work 2	2	5	3	9	7

Table 1: Sample attributes of the relation of component A
Table 2: Sample attributes of the relation of equipment, machinery and provisional works

In the database, another relation contains the attributes related to the equipment, machinery and provisional works indicated above. In particular, the strings contain data on their unitary cost, in function of as many parameters as they are available in the price lists. Specifically, the strings are: 'code', corresponding to the code also indicated in 'tools1' and tools2; name, the extended name; 'c-area', 'c-length', 'c-mass', 'c-volume', 'c-unit', which are respectively the unitary costs which have to be multiplied by the quantitative measures of area, mass, length, volume or unit of the components to obtain the cost of the interventions.
The last relation is made up of the technical solutions, consisting in only one string whichreports spontaneous duration.
The following input data are required by the client:

- period of maintenance activity (in years);
- list of components (selectable from a list);
- technical solution of each component (selectable from specific lists);
- quantities of the components.

The specification of the technical solution is necessary to restrict the set of interventions of reference, for each component, to the ones in which the package corresponds to the chosen item. Then, the first operation run by the client is the generation of the combinations corresponding to the maintenance strategies for the single components, through a script for Combinations with Repetitions, where the size of the selection, l, corresponds to the duration of the period of maintenance activity. The computed set S is, of course, the one constituted by all the interventions automatically selected through the package parameter in the relation of the specific component. Then, given the cardinality of the set p, the total of the generated strategies is p^l. Most of these will present interventions almost in every year, so only a few of them will be relevant when evaluating the economic convenience.

For each of these sequences, MC, $v_{\alpha k}$ and MC* are calculated. Through Java functions, the unitary cost of every intervention is multiplied, for every time it appears in the sequence, by the quantitative measure that has been specified for the component, and the single costs are summed. In the same way, a Δv_{Jj} is calculated for each intervention by executing the function related to the interventions. In the current form of the software, the function only depends from t_j, as the shape of the dependency from $MH(t_j)$ has not been researched yet; then, the single increases are summed to spontaneous duration to obtain the total one. Finally, MC* is calculated as the difference between MC and the difference between $CE(v_{\alpha k})$ and $CE(v_A)$.

The following operation is the generation of possible maintenance strategies for the whole building, by combining those obtained above. In this case, the client runs a script for Combinations of Elements of Multiple Arrays and produces all the combinations between the arrays containing the previously obtained sequences, forming an extremely high quantity of maintenance possibilities. Clearly, as stated before too, most of these combinations will have no relevance in terms of practical use. Then, MC and MC* are recalculated by the software - service life of the components does not change as it has been hypothesized that its value for one of the components is not affected by the actions on the others. When calculating the total cost of maintenance MC, technological and operative connections have to be taken into account. While technological connections are mostly present between the elements within components, and so their effect is actually visible in the evaluation of the convenience of the combinations of the single components, operative connections can be considered through the strings referring to common machinery, equipment and provisional works. The software runs, in fact, a process of correction of the total cost based on the verification of the presence of common values in the strings 'tools1' and 'tools2' of the interventions taking place in the same year on components that have an operative connection between them. Then, it calculates the cost of the tool for both components, by multiplying the unitary cost corresponding to the unit of the quantitative measure that describes each of the two and applies to the global cost a reduction corresponding to the 50% of the lower cost between the two. This appears to surrogate the economic benefit deriving from the chronological optimization of the interventions on components with operative connections.
Subsequently, MC* is calculated as before. Eventually, the software runs a Ranking Method script to show a ranking of the strategies according to this parameter.

HYPOTHESIS OF INCLUSION IN A BIM PLATFORM

Thinking of the typology of input data required by the software, it seemed appropriate to analyse its possible link to a BIM platform. The software illustrated above is actually mainly conceived as the practical verification of the possibility to build a software architecture to automatize the whole process of evaluating the economic convenience for a high number of possibilities in regard to the maintenance of a building. So, the consideration of a possible inclusion in a BIM platform does not specifically refer to this software, still in development, but to any software realized with the logic and with the purpose explained until now. For this reason, the following statements mainly stand as speculative hypotheses, rather than being related to ITissues, considering in fact the possibility to create similar computing

architectures with different systems, codes and computer languages.
In particular, the possibility to develop a plug-in feature to automatically obtain the data related to the quantities of each component by making use of the computing functions of BIM platforms, could drastically simplify the tasks of the users. The same principle applies to the definition of the technical solutions, which could be indicated in a more open way in the software, in order to draw directly information on the components of components from the BIM model; this would be subordinated, though, to the manual selection of the number and nature of the components.

CONCLUSIONS

Although national regulations have been undoubtedly pushing forward programmed maintenance, and in some local cases have deeply enhanced its implementation, objective criteria for the definition of life-cycle planning of buildings are rarely considered an item of discussion, and often the task of designing maintenance results limited to adapting pre-established patterns to the specific cases.
The purpose of exploring the theoretical process to realize an objective evaluation of different possibilities in the field of maintenance, and providing the guidelines to follow this path, was indeed conceived as an encouragement to carry out quantitative analysis on the characteristics of maintenance planning, in order to choose the most suitable solution.

It must be stated however – once more – that the project of developing such apparently quantitatively accurate software is probably an excessively anticipated aim, considering that objective data on the durability of building components are far from becoming available and comprehensive of a sufficient range of technical solutions. Despite that, developing approaches for a beneficial use of such data presumably constitutes a step forward being able to improve the techniques of designing maintenance.

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