

PROCEEDINGS

# XIII | DBMC

XIII International Conference on Durability  
of Building Materials and Components

02-05 September 2014 São Paulo - Brazil



Proceedings  
PRO 96

# XIII DBMC

Proceedings of the XIII International Conference on  
Durability of Building Materials and Components

Edited by M. QUATTRONE and V.M. JOHN

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**XIII DBMC - XIII International Conference on Durability of  
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São Paulo, Brazil**

Edited by M. QUATTRONE and V.M. JOHN

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*The ability to predict the service life – the durability – of a new building material is being ardently sought after in many parts of the world. Widespread efforts are correspondingly being made to increase the durability of materials already in wide use. Any estimate of the economic losses resulting from failures in durability lead inevitably to dollar figures so astronomically large that they are usually regarded with incredulity.*

R. F. Legget  
Proc. of the 1st DBMC  
Ottawa, 21-23 Aug. 1978.

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157 rue des Blains  
F-92220 Bagneux - FRANCE  
Tel: + 33 1 45 36 10 20 Fax: + 33 1 45 36 63 20  
E-mail : dg@rilem.net

**XIII DBMC**

**XIII International Conference on  
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Components**

XIII DBMC - XIII International Conference on Durability of Building Materials  
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# XIII International Conference on Durability of Building Materials and Components

São Paulo, Brazil

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## A METHODOLOGY FOR EVALUATING MAINTAINABILITY AS A TOOL FOR DURABLE AND SUSTAINABLE BUILDINGS

**Nicolella, M.**

Department of Civil, Construction and Environmental Engineering, University of Naples Federico II, Naples – maurizio.nicolella@unina.it

### ABSTRACT

Maintainability is a very important requirement in construction projects for making maintenance and management phases easier and less expensive and achieving durable and sustainable buildings. It can be defined as the capacity of a component to be subjected to maintenance interventions.

Nevertheless, maintainability is currently an abstract – although recognizable – concept, that could be very useful for evaluations that could allow, for example, a designer to evaluate the best technological solution or a Public Administration to choose the less expensive among different projects in terms of maintenance.

A method for estimating the “Maintainability degree” of a building was implemented and tested in a range of research programs on planned maintenance that have been carried out since 1988. The method is based on an index which considers, through evaluation, several factors regarding the components in which a building can be broken down.

This *Maintainability Index* is able to measure the capacity of a building to be subjected to maintenance interventions

**Keywords:** maintainability, durability, costs, index.

### 1. INTRODUCTION

Several definitions have been suggested for the term “maintainability”, mainly in two different acceptations. One relates to the ease of doing interventions on a component, with the aim of bring the performances of a component back to the values that were defined in the project (qualitative definition: “aptitude of receiving interventions of maintenance”), while the other one provides the value of this so-called aptitude in probability terms (quantitative definition: “the capacity to conform to certain conditions in a certain period of time, during which maintenance takes place”).

Four variables interact with the concept of maintainability, and they represent the objects of study for the operative applications. They are:

- the *ease* with which maintenance interventions take place, that is to say the “aptitude” or the predisposition of the element or of the system, to be object of maintenance. It is not only characteristic of technical elements, but also of the of the organizational structure where technical elements are located;
- the *operative organization* for the recovery of the performances of the component or of the system through maintenance operations;
- the *time* necessary to the development of maintenance operations;

▪ the “value” assumed by *maintenance*, in which quality improvement consists in the *increase of the probabilities* of being able to complete the maintenance operations of recovery in a certain time.

The maintainability of a component, of a sub-system or of a full building structure is one of the *project requirements* that most express the sensitivity and the carefulness a designer should have towards the management and the life of the building, mainly through its maintenance. It would be dangerously wrong to think that the requirement of maintainability is simply related to decisions made only in the phase of the management of the building product.

The present work suggests a methodological hypothesis that evaluates maintainability through an “index” that is function of the morphological, typological and technological characteristics of buildings.

## 2. MAINTAINABILITY FACTORS

The maintainability factors are elements that have influence on maintainability for different aspects: they are designing factors, organizational factors and operative factors, that are synthetized in the following chart. It explains how it is possible to make influences on the ease of carrying over maintenance interventions in the designing-decisional phase, in the operative one, and also – eventually – in the organizational one, more related to the industrial environment.

Table 1. Typologies of maintenance factors

MAINTENANCE FACTORS		
Designing factors	Organizational factors	Operative factors
Level of complexity of the entity	Availability of an informative system for the management of the maintenance	Labour ability and its level of specialization
Typological, distributional and geometrical characteristics		
Level of divisibility	Logistic organization of the maintenance service	Availability of technical documentation for the execution of interventions
Accessibility of the building structure, sub-systems and components		
Dislocation, dimension, organization and ergonomics of the operative spaces	Efficiency of the organizational structure	Number and quality of the technical means employed for the interventions
Visibility of components	Level of involvement of customers for management and maintenance	
Mobility of components		
Modularity of components		
Standardization of components		
Ease of replacement of the components		
Flexibility of the system		
Designing definition of the performance levels of components		
Availability of a maintenance plan		



### 3. THE INDEX OF APTITUDE TO MAINTAINABILITY

It can be initially argued that the aptitude to maintainability of a building can be considered as the summation of the aptitudes to maintainability of the single components, sub-systems and systems. So, defining the index of aptitude to maintainability  $N$  as the parameter that measures the ease of executing maintenance interventions for a certain component, it results that:

$$N_{tot} = \sum_{i=1}^n N_i \quad (1)$$

The index of aptitude to maintainability is a function of the cost of the intervention of maintenance,  $C_{int}$ , and of the impracticability that the intervention causes,  $T_i$ .

$$N_i = f(C_{int}, T_i) \quad (2)$$

In particular, this coefficient is inversely proportional to these two variables since maintainability obviously decreases as they grow.

The numerous other variables to consider, for example everything related to maintenance (construction typologies, connections between the various elements, actuation modalities, etc.), and also the impracticability that is consequent to the execution of maintenance interventions, have been translated into economical values, in the aim of a necessary dimensional homogenization of the index of maintainability.

### 4. THE TEMPORARY IMPRACTICABILITY DURING MAINTENANCE INTERVENTIONS

It is easy to understand that MTTR (Mean Time To Repair) plays a major role in the evaluation of maintainability.

Actually, MDT (Maintenance Downtime) should be considered instead of MTTR, and that is the time of total impracticability, the sum of the following rates (UNI 9910):

- time for the identification of the malfunction.
- ADT, Administrative Delay Time, null in the case of a preventive maintenance;
- LDT, Logistic Delay Time, due for example to a temporary unavailability of resources, and that should be null as well, in the case of a preventive maintenance;
- time to verify the functioning, to consider in the end of the maintenance intervention;
- MTTR, Mean Time To Repair.

The economical evaluation of the temporary impracticability was executed considering the economical implication of the impracticability of a building, that is to say the lack/decrease of the annual net income, that was calculated as:

$$NI = GI - (Q + Tr + Adm + Svc + VU) \quad (3)$$

meaning:

$GI$  = gross income;

$Q$  = rates, the expenses that the owner has to sustain for the conservation of the building (reintegration, insurance);

$Tr$  = tributes, include taxes and contributions;

$Adm$  = administration, the expenses that include the management of the contract of rent (consulting, chancery, fiscal assistance);

Svc = *services*, include the expenses of management of a building in charge of the owner (custody, conciergery, cleaning, illumination, waste disposal, etc.);

VU = *vacancy and unmanageability*, include the losses, intended as missed incomes, that the owner cannot receive when the property is not being rented, or when the renter does not pay, or pays the rates with a delay.

Once the annual net income has been defined, to obtain the cost of impracticability, it will be sufficient to calculate the income loss per hour, and multiply it for the time of total impracticability:

$$C_{impr.} = NI_{hour} \cdot T_i \quad (4)$$

## 5. THE COST OF MAINTENANCE INTERVENTIONS

The variable of cost is a function itself, both in relation with the single components, and with the whole building, that is to say in relation in the way the single component has influence on the building.

$$C_i = f'(X_{ij}) \quad (5)$$

This function depends on various variables, the  $X_s$ , which are characterized by two subscripts. The subscript 'j' indicates the variable, while the subscript 'i' indicates the i-th component the variable is referred to several variables have influence on the determination of the cost of maintenance for every i-th component:

- Length of the life of the component and forms of maintenance
- Frequency of maintenance interventions, and necessity to do them at certain times
- Competence, nature of the title of property
- Modalities of operation during the phase of management, and subjects in charge
- Technical and operational connections
- Dimensions, that is to say the physical and technical units of measure
- Constructional technology, what constitutes the component materials.

## 6. CONSTRUCCION OF THE MODEL

After preliminarily disassembling the structure of the building, for example using the WBS technique, it is possible to calculate the index of aptitude to maintenance N. This indicator N is inversely proportional to the cost of the intervention on the i-th component, and to the cost of the temporary impracticability that it causes, with the consequent discomfort for the residents:

$$N = \frac{100}{\sum_{i=1}^n C_{int,i} + \sum_{i=1}^n C_{impr,i}} \quad (6)$$

meaning:

$C_{int.}$  = the parametrical cost of the maintenance intervention for the i-th element;

$C_{impr.}$  = the parametrical cost caused by the temporary impracticability that the maintenance of the i-th element causes.

The value 100, present in the numerator, has the aim of representing maintainability as a coefficient of efficiency.

As it has been noted in the previous paragraph, the cost of maintenance depends on eight  $j$ -th variables, that are different for every  $i$ -th component.

$$C_{\text{int}} = f'(X_{j,i}) = f'(X_{1,i}, X_{2,i}, X_{3,i}, X_{4,i}, X_{5,i}, X_{6,i}, X_{7,i}, X_{8,i}) \quad (7)$$

meaning:

$X_{1,i}$ = form of maintenance used for the  $i$ -th component;

$X_{2,i}$ = length of the life of the  $i$ -th component;

$X_{3,i}$ = frequency of the interventions of maintenance for the  $i$ -th component;

$X_{4,i}$ = competence, nature of the title of property of the  $i$ -th component;

$X_{5,i}$ = subjects in charge of the maintenance of the  $i$ -th component;

$X_{6,i}$ = technical and operational connections of the  $i$ -th component;

$X_{7,i}$ = dimensions, that is to say physical and technical units of quantitative measure of the  $i$ -th component;

$X_{8,i}$ = construction technologies, the constitutional nature of the materials the  $i$ -th component is made up by.

Some of these variables will be carried out in the model using the factors of maintainability, that have already been quoted, while others will be subjects of a further analysis.

Regarding the operative and technological connections, it should be noted that the cost of intervention,  $C_{\text{int}}$ , can be higher or lower, depending on whether the technological connections, that make the maintenance cost grow, are prevalent, or the operative connections, which optimize the cost, are more present. A technological connection is intended as the necessity to operate on a certain element when an intervention is done on others.

Therefore, the technological connection is the interconnection between elements, that makes the intervention on two or more elements at the same time, unavoidable, and that interconnection is present, for example, between finishing elements, such as plaster and paint. It is necessary to clarify that the connection is not bi-directional: it is obvious that an intervention on a plaster necessary influence the paint as well; however, an intervention on a paint does not necessarily influence the plaster.

This final consideration allows to define opportunely the operative connection that, on the other hand, concerns elements that should be regarded by interventions of maintenance in the same periods of time, not because of an interconnection between them, but because they have similar executive and organizational characteristics, which create the opportunity to do interventions on an element when interventions are done on the other elements, in order to make use of the same means of maintenance with the same cost, and reducing the discomfort of residents during time. A typical example is provided by the inspections of the installments: if it is hypothesized, for example, to have various installments going through the same false ceiling, the interventions and the verifications should happen in the same period of time, in order to reduce the total costs of organization and site management, and also the residents' discomfort. Another example concerns all the interventions of maintenance that require the use of scaffolding (for evident reasons of cost and temporary discomfort).

MATRIX OF TECHNOLOGICAL AND OPERATIVE CONNECTIONS BETWEEN COMPONENTS (TECHNOLOGICAL UNITS, CLASSES OF COMPONENTS, COMPONENTS)	Founding structures	Vertical structures	Horizontal structures	Perimetral walls	External windows	Coverings	Partition walls	Doors	Internal stairs	Balconies	External stairs	HVAC plant	Water and sanitary system	Liquid waste disposal system	Gas distribution system	Electrical plant	Painted Finishing	Marble finishing	
	Founding structures																		
Vertical structures																			
Horizontal structures																			
Perimetral walls																			
External windows																			
Coverings																			
Partition walls																			
Doors																			
Internal stairs																			
Balconies																			
External stairs																			
HVAC plant																			
Water and sanitary system																			
Liquid waste disposal system																			
Gas distribution system																			
Electrical plant																			
Painted Finishing																			
Marble finishing																			

In order to easily examine all the connections existing between the components of a building, a “Matrix of Connection” (see figure 1) can be realized: it highlights the typology of connections that exist between any two components, and their intensity.

In the matrix, every square individuated by the intersection of lines and columns is divided in four triangles that define different connections according to the different colors, as shown in figure 2, which can be:

- weak technological connections;
- strong technological connections;
- weak operative connections;
- strong operative connections.

Figure 1: Typical matrix of connections.

Technological connections		
Strong	Weak	No connection
Operative connections		
Strong	Weak	Total connection

Figure 2: Chart of connections.

In order to consider these connections, the expression of the coefficient  $N$  can be rewritten as:

$$N = \frac{100}{\sum_{i=1}^n [C_{int,i} \cdot (1 + \lambda_i^t - \lambda_i^o)] + \sum_{i=1}^n [C_{impr,i}]} \quad (8)$$

In this formula:

$\lambda_i^t$  is the ratio between the weighted number of technological connections and the number of total connections that the  $i$ -th element has with all the other elements;

$\lambda_i^o$  is on the other hand the ratio between the weighted number of operative connections and the number of total connections that the  $i$ -th has with all the other elements:

$$\lambda_i^t = \frac{\sum_n L_i^t}{\sum_n L_i^t + \sum_n L_i^o} \quad \lambda_i^o = \frac{\sum_n L_i^o}{\sum_n L_i^t + \sum_n L_i^o} \quad (9-10)$$

The coefficient that multiplies the parametrical cost is greater than 1 if there is a prevalence of technological connections increasing the cost, is equal to 1 if the technical connections are the same number as the operative connections, or lesser if there are more operative connections (that optimize the cost of maintenance). Every connection, both technological and operative, has a value of 1 if it is weak, and of 2 if it is strong.

The factors of maintainability, defined before, should be considered as well: they can be indirectly calculated using the norm UNI 8290, that is to say non-tarnishability, buffability, viewability, repairability, relievability, complexity, decomposability, moveability, standardizability, and availability of maintenance plan .

It is important to note that, while some factors can only be referred specifically to the single components, or to the single sub-systems, other factors can be referred to the whole building structure. Some factors can also be referred to multiple entities, for example the identificability of the state of functioning can be related to a whole sub-system, or to each of its single components. So, the first step is to refer each interested factor to the various entities that could be conditioned by the value that can be attributed to the factor.

The second step is that of expressing them as percentages whose sum is always equal to 1. Each of the chosen factors of maintainability  $K$  has also to be corrected with a factor  $h$ , which is used to quantify the level of influence of each component to the value of the factor itself. The value of  $h$  is also expressed in a percentage, the nit varies between 0 and 1:

$$\sum_{j=1}^n K_j^i \cdot h_j^i \quad (11)$$

$C_{int}$  is then divided by this summation, because, the smaller is the unitary behavior of the  $i$ -th element, the smaller is its maintainability, and since the value of the summation  $K_j^i \cdot h_j^i$  is between 0 and 1, this is placed in the denominator of  $C_{int}$ . But the same reasoning can be made for the cost of impracticability  $C_{impr}$ : in fact, some factors of maintainability mainly influence this cost, rather than the cost of the intervention itself. Of course, this coefficients can also vary in relation to the end use of the building or of its parts, because the end use can attribute different functional importance to the same typology of sub-system.

Taking account of this, the previous expression becomes:

$$I_m = \frac{100}{\sum_{i=1}^n \left[ \frac{C_{int,i} \cdot (1 + \lambda_i^t - \lambda_i^o)}{\sum_{j=1}^n K_j^i \cdot h_j^i} \right] + \sum_{i=1}^n [C_{impr,i}]} \quad (12)$$

Concerning the cost of impracticability  $C_{impr}$ , it represents the loss of income that is verified in the period of time during which the substitution or the restoration of the  $i$ -th component takes place. It is influenced by two main aspects:

- the *localization of the element* that has been submitted to a specific operation of maintenance, the criticality of the component or of the sub-system examined, in the context where it is located;
- the *duration of the intervention*, that is the total impracticability, as it has already been defined.

So, the cost of the impracticability of the  $i$ -th element has been defined as the percentage rate estimated in relation to the total cost that has been predicted for the interventions of maintenance in a period of 50 years. The mentioned costs, in order to be summed, have been first projected in the valuable period of life according to an annual medium increase (slightly more than 3% for the cost of interventions and a bit more than 2% for the cost of impracticability, in relation to the lease), and then summed according to the VAN function with a rate of annual discount equal to the rate of legal interest (2,5%).

## 7. CONCLUSIONS

Thanks to the application of the model to a series of case studies, it has resulted that the value of the index of maintainability can be approximated to a value between 0,9 and 1 in the case of medium-normal costs of maintainability, assuming the connections and the corrections made according to the costs of maintenance do not influence this costs positively, nor negatively. It is lesser than 0,9 if the technological connections are more present than operative connections, and/or if the values of the factors of the  $i$ -th element are close to 1; greater than 1 if there is a prevalence of operative connections and/or when the summation  $K_j^i \cdot h_j^i$  tends to 1, and therefore does not influence the final value of the index.

If the intervention takes place in a period where there are no diseconomies, approximable to a duration that is lesser than 15 days (it can be considered that the monthly income has been completely lost after the 15th day), then the second term of cost in the denominator is null.

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