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Publisher's version / Version de l'éditeur:

11th International Conference on the Durability of Building Materials and Components [Proceedings], pp. 1-9, 2008-05-11

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NRCC-51168

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May 11, 2008

A version of this document is published in / Une version de ce document se trouve dans:
11th International Conference on the Durability of Building Materials and Components, Istanbul, Turkey, May 11-14, 2008, pp. 1-9

FMECA and Management of Building Components

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T 72

ABSTRACT

In accordance with the principles of "sustainable development" and "performance-based building", building components are expected to maintain their required performance levels over their service life. This is typically achieved through the use of planned maintenance interventions. However, providing relevant management of building components likely requires both the identification and evaluation of the most critical degradation scenarios. Failure Modes and Effects Analysis (FMEA), is a method developed in the 1970s in the industrial domain, and has more recently been adapted to the construction domain as a mean to identify all the possible degradation scenarios. From all the available results obtained from the FMEA, the most critical scenarios are established on the base of a further analysis of the criticality of these scenarios, so obtained through a FMECA ("C" for criticality). In this paper, two variations of methods are proposed to complete the criticality analysis. The first method is based on the formalisation with expert's system of the relation between elements, environment, functions and degradation in order to perform FMEA. The second one is based on unifying and aggregating relevant service life data in order to obtain the service of building component in a given environment. This paper provides: (1) An overview of the FMECA method; (2) A brief review of the state-of-the-art on FMECA research for and application to the construction domain; (3) Method based on expert's system to perform FMEA (4) Method of service life prediction of building components based on FMEA; (5) Application of the FMECA in a maintenance planning project of building facades.

KEYWORDS
Building components, Degradation scenarios, Maintenance management, Maintenance planning, Service life prediction

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1 INTRODUCTION

Building components are expected to maintain their required performance levels over their service life (SL). This notion is in accordance with the principles of sustainable development [Charlot-Valdieu & Outrequin 1999] and those of the "performance-based building" as espoused in the PeBBu project [Lee & Barrett 2003]. Over the life of a building component, its' performance levels depend, on the one hand, on the quality of the design and, on the other hand, on the quality of the maintenance affected during its SL. Research has evidently been completed in these both areas; however in this paper emphasis in placed on the SL of building components as it relates to the management and planning of maintenance.

The management and planning of maintenance of building components focuses on information, of two types: (qualitative and, quantitative information). Qualitative information regroups the knowledge of the structure and the function of the building component, as well as the phenomena that deteriorate the component, the causes of these phenomena and their possible consequences. Among all available methods of failure analysis (e.g. hazard and risk analysis, failure tree, butterfly knot, etc.), the failure modes, effects and criticality analysis (FMECA) seems to be the most appropriate for obtaining such type of qualitative information.

In this paper, a succinct presentation of the FMECA method is provided followed by a brief overview of the state of the art on FMECA research as applied to the construction domain. Given that different building components may be comprised of similar materials, functions and degradation scenarios, an evident idea is to formalise the commonality among components such that the process of conducting a FMEA can be automated; this approach is presented in a subsequent section of the paper. The quantitative information necessary for the management and the planning of maintenance are, on the one hand, information related to the SL of the building component and the duration of the respective degradation phenomena and, on the other hand, information on the cost of the maintenance or repair actions. A method that allows obtaining these durations is presented and the final section offers information on a project in which FMECA is used within a maintenance management model for building facades to help plan maintenance actions.

2 AN OVERVIEW OF THE FMECA METHOD

The FMECA is a method that is used to identify all possible degradation phenomena of a given building component in a specified in-use environment. The in-use environment relates to the specific context in which it is used, namely its function, performance requirements and environmental factors affecting its long-term performance. As well, it permits determining the series of degradation phenomena, referred to as degradation scenarios, associated to a particular component and environment. For each degradation phenomenon that is identified, the causes, consequences, and related damaged functions of the building components is determined; in this manner, the failure modes of the building component may be then determined.

Historically, the FMECA was developed in the 1970's in the development of nuclear arms domain and thereafter, in the aeronautical domain [Dyadem Press 2003]. This method has since been widely used in different industrial fields such as the aerospace, chemical, automotive fields as well as in the highly critical field of design of nuclear power plants. At the present time, this failure analysis method is one of the most universally used in the industrial domain.

Before undertaking an FMECA, it is essential to have in-depth knowledge of the building component being analysed; that is to say, have knowledge of the elements and materials of which the components is comprised, the functions ensured by this building component and its in-use environment. This may entail categorising several sub-environments (e.g. for a façade component, defining external and internal environments) and the corresponding environmental agents (e.g. rain, temperature, thermal shock, etc.) associated to each of these situations. This knowledge may be obtained by first completing a component constituent analysis and thereafter, a functional analysis of the building component. To facilitate this first step in the analysis, certain databases have been developed [Talon 2006] that provide information on: (1) environmental agents (regroups all environmental agents that may compound the primary environments of building components); (2) function of building components (regroups all generic functions ensured by building components) and; (3) degradation phenomena (regroups 120 generic degradation phenomena).

The results of FMEA are quite often summarized in an FMEA table in which the information is typically provided in five columns: (1) functions identified during the functional analysis, (2) elements of the building components identified during the constituent analysis, (3) degradation phenomena appropriate to the component and function, (4) causes of these degradation phenomena and, (5) consequences arising from theses degradation phenomena as these relate to the function as provided in the first column. A same degradation phenomenon can cause damage to several different component functions and can also generate other degradation phenomena. For this reason: (1) there is as many lines in the FMEA table as there are {function, phenomenon} pairs and, (2) FMEA is necessarily an iterative process. Specifically, in an initial review all information "triplets" (i.e., environmental agents, functions, elements) are searched and subsequently, in a second review, the degradation phenomena generated in the first review likewise searched, and so on, until all degradation scenarios that lead to failures of the building component are identified.

Given that FMEA is a systematic process, it is capable of being exhaustive in identifying degradation phenomena; however, the quality of the result depends directly on the knowledge level of those expert seeking to use it for failure analysis of building components and their related degradation phenomena.

An example of FMEA carried out for a solar panel is provided by Talon *et al.* [2004]; it provides details of the different phases of analysis including constituent and functional analysis, and FMEA.

The "C" in FMECA corresponds to criticality analysis; this analysis is one that completes FMEA. The intent of carrying out such an analysis is to estimate the consequences of failure arsing from each degradation phenomenon or degradation scenario, as the case may be. This then permits classifying the consequences of failure by degree of criticality such that these can then be used to determine which maintenance actions are most important to complete.

Generally, the degree of criticality corresponds to the product of three criteria: (1) the likelihood of occurrence of the phenomena, (2) the level of significant related to the consequence of failure of the component and, (3) the degree of detectability of failure [Faucher 2004]. Each of these criteria is typically assessed with quotation grids that are scales varying from [0; 10]. Several variants of this formulation are used when two criteria [Sctrick & Goussy 2003] or five criteria [Department of Defence 1980] are considered, or when the criteria product is replaced by a weighted product [Sahraoui 2006] or by fuzzy inferences [Bowles & Pelaez 1995].

3 BRIEF STATE OF THE ART ON FMECA RESEARCH FOR AND APPLICATION TO THE CONSTRUCTION DOMAIN

A succinct review of different approaches in the construction domain that are based on FMECA is presented here in which information is provided on the use of FMECA in different international projects carried out in the past 9 years; a more detailed description of this state of the art is provided in [Talon *et al.* 2006].

The approach adopted by the Aspen Research Corporation [2002] is based on carrying out FMECA in order to qualitatively and quantitatively explain the degradation mechanisms of double-glazed insulated glass (IG) units. This study corresponds to a Department of Energy (US) project entitled: "An Insulating Glass Knowledge Base". This knowledge base of the more critical failure modes of IG units provides behaviour models so as to determine the characteristics of accelerated short-term exposure tests to be used in validating these models.

At the Building Research Establishment [Barlett & Clift 1999] the use of FMECA is integrated in a global approach for the improvement of the supply chain of buildings during their whole SL cycle. In this context, FMECA is used as a method for identifying the more critical failures of the supply process. In this way, this approach allows supplying a "Reliability Centred Maintenance" program that aims to optimize the process reliability. As such, it provides descriptions of corrections actions or modifications required during either the management or during design phases.

In the context of a project led with cladding manufacturers, the Centre for Window and Cladding Technology [Layzell & Ledbetter 1998] applied FMECA to study cladding failures at the elemental, system, and building process level. The aim of this study was to improve cladding quality during the design phase and to facilitate the inspection and survey actions during the installation phase.

The SP Swedish National Testing and Research Institute [Carlsson *et al.* 2002] applies a method quite similar to FMEA, referred to as the Initial Risk Analysis (IRA). IRA is completed in order to determinate possible failure modes of solar panels. The aim of this study was to qualitatively define the parameters that influence the durability of the building component. These parameters were then studied by completing ageing tests on specific components of the assembly. The development of mathematic models and their correlation with experimental test results allowed assessing the SL of the solar panels. This study was completed in the framework of an international project entitled: "Durability assessment methodology development" (International Energy Agency Task 27 Proj. B1).

The approach undertaken by the Polytechnic of Turin [Pollo 2003] was improvement of the SL of building components from the design phase and consisted in combining three methods: FMEA, "Life Cycle Cost", and "Maintenance Cost Planning". This method aimed to: (1) foresee the degradation rates of components when taking into account their in-service use; (2) improve their maintenance, and; (3) optimise their global cost over their SL.

The approach proposed by Wyatt [Wyatt 2005] consisted in integrating FMEA and the fault tree method into the control and audit procedures for assessing building performance. The FMEA is used to identify any possible errors made during the building design phase.

In France, the Cemagref [Peyras 2002] integrates FMEA in a novel method for the management of dams; this method combines a knowledge base of ageing mechanisms and a database of ageing history of dams that facilitate the failure diagnosis for a specific dam. FMEA allows developing the knowledge base by, on the one hand, structuring expert opinions relevant to the ageing of dams and, on the other hand, by establishing the cause-effects relations and possible degradation scenarios.

4 METHOD BASED ON AN EXPERT SYSTEM PERFORMING FMEA

The objectives of an expert system are to assist FMEA by computer in order to:

- Accelerate the "time consuming" phases of the study;
- Obtain a better formalisation and reuse of existing information such as degradation phenomena, results of previously performed FMEA on other building components;
- Build and to feed the knowledge base on environmental agents, functions, materials, and degradation scenarios.

The use of an ontological approach, which is simply a formal model that allows expressing assertions in a structured manner, permits thereafter to render the model "computable". Ontology is a formal representation of a system from a certain point of view, a specific perspective. Such a representation provides details of concepts of the system and the interactions or interrelations that exist between concepts [Gruber 1993]. For instance, one can study a low-emissive, double-glazed, insulated glass unit in its environment, from the point of view of its thermal properties or its thermal performance. Once the model is developed, it is then possible to capitalize on different aspects of knowledge of the unit as different "instances" of this model, and in so doing, ensure that this knowledge is completely structured and hence, computer accessible. These instances are expressed as for example:

My **component** Frame *is composed of* **material** "Aluminium". My **component** "Frame" *has as a* **function** to be watertight. My **Environment** External *contains* the **environmental agent** Humidity, Gas, UV, rain, etc.…

An example of providing information on the interrelation between concepts one may have:

The **Environment** External is in contact with the **component** Frame…

In the example, words in bold face are concepts of which the model is comprised, those in italic give the relation between concepts, and underlined words are specific instances of the model). Hence, the set of "instances" allows describing a building component on which one wants to perform the FMEA. Figure 1 provides an example of a generic building component model.

The various "instances" that together describe the product form the basis on which one identifies the possible set of degradation scenarios according to the information one can extract and thereafter, studies the consequences of these scenarios.

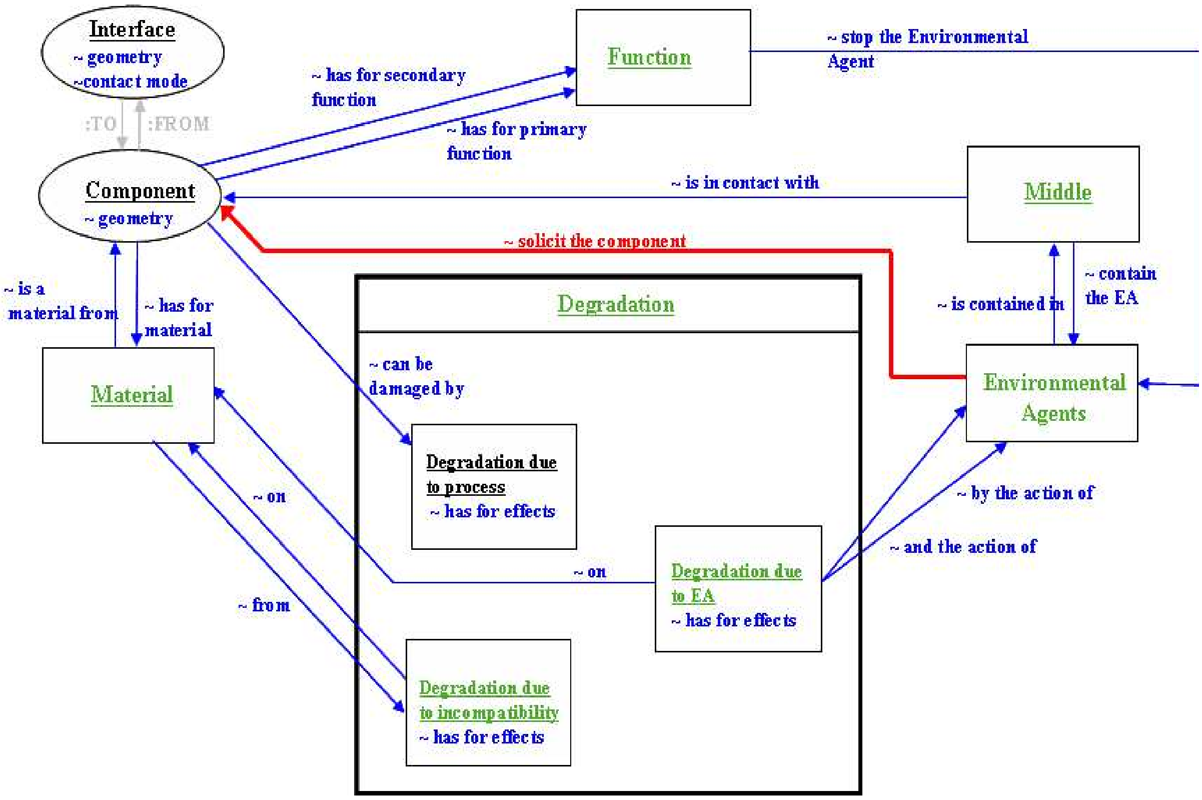

Figure 1. Description of the ontological-based product model from which FMEA can be performed on building components.

5 METHOD OF SERVICE LIFE PREDICTION

This paragraph provides a summary of a method based on FMECA that assesses the SL of building components; this SL estimate is essential information for the planning of maintenance of buildings.

This method uses all available data collected from several sources. The intent of the assessment process is to obtain the SL of a given building component in a given environment when all degradation phenomena and degradation scenarios implicated in the deterioration the functions of this building component during its SL are taken into account.

Two key practical elements must first be considered when retrieving SL data for a given building component and complimentary environment data. Data is: (i) not often available and, on the other hand, data does not necessarily have an acceptable level of quality. Given this situation, the following two-phased approach was proposed as a means to render the information useful: (i) the first phase is used to assesses the quality of each collected data set and; (ii) the second phase consists in combining all collected data of acceptable quality in order to obtain a harmonized data set that regroups those sets that together reflect the maximum consensus among the data sets, and an indicator of the quality of concurrence of the service life data.

The second phase may be formalised as a procedure. The process is initiated by carrying out research for all relevant SL data related to the given building component and its intended in-use environment. Thereafter, an assessment of the quality of each of the collected data sets is completed. Should the quality of the data be acceptable, then the entire collection of SL data is transformed into a plausibility format that allows categorising the different types of available data as being, e.g., derived from expert opinion, based on statistics, or extracted from a probabilistic method of SL estimation. Thereafter, the SL data set is harmonised using data fusion rules. From this process, the quality of concurrence of the SL data is obtained and related data quality indicators are provided (i.e., values for belief, Smets's probability, and plausibility functions respectively [Talon 2006]).

In the case where the quality of the SL data collected is not acceptable, research is then focused on the degradation phenomena identified during the FMEA and information on the duration of the phenomena is sought. Similar steps are then taken in this portion of the process: the quality of collected data is reviewed; data is transformed into a plausibility format, data is harmonised; the quality of the concurrence of the data is provided in terms of the data quality indicators. Finally, the results are aggregated at the phenomenon level in order to obtain the SL of the building component, thus taking into account all the degradation scenarios of the component. Specifically, for each degradation scenario identified from FMEA, the duration of each phenomenon of which the scenario is comprised is assessed. The duration of each scenario is then equal to the sum of the durations of its constitutive phenomena. The same assessment process is completed for all identified scenarios. Finally, the service life of the building component corresponds to the minimum value of durations extracted from these degradation scenarios. The proposed method for SL prediction is provided in more detail by Talon in [Talon 2006].

6 APPLICATION OF FMECA IN A MAINTENANCE PLANNING PROJECT FOR BUILDING FACADES

This project focuses on the development of a Markovian-based, building façade maintenance management (BMM) model that permits the optimization of maintenance planning, and introduces software that permits a user to initiate building maintenance actions. The intent was to provide building managers who are faced with having to maintain their buildings assets more efficiently, with a tool that could reduce the short and long-term costs of maintenance and rehabilitation. In essence, the BMM software can either optimize maintenance planning actions based on an expected maintenance budget or determine the budget required to maintain the façade to a minimum acceptable level of performance. An overview of the project is provided in [Kyle et al 2008] and a schematic of the primary components of the software is given in Fig. 2; details in respect to the Markovian approach to façade maintenance management is given in Lacasse et al. [2008]. The façade was first considered in development of the BMM software given that it is a significant element of the building envelope and of the building itself.

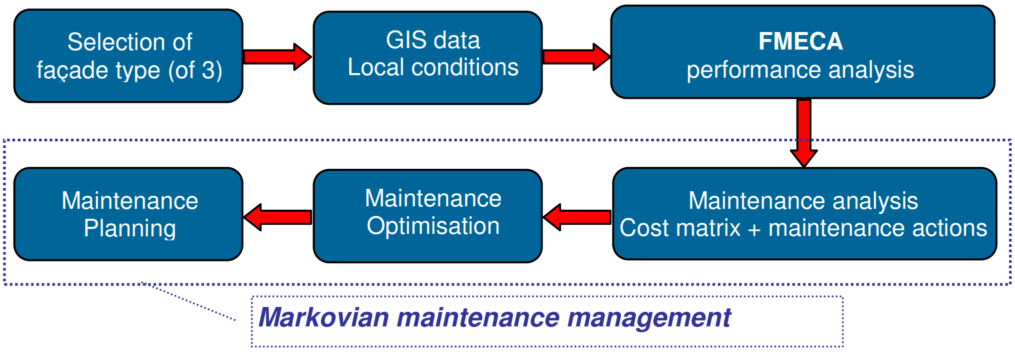

Figure 2. Schematic key project components of BMM model [Lacasse et al 2008].

The BMM model is built on several parts, however one of the key components is FMECA and performance analysis of the façade and related components; the several steps of this process are provided in Fig. 3 [Lacasse et al 2008]. The first step consists of developing a façade component criticality index. This is based on outcomes of a FMECA and permits determining the relative importance assigned amongst the different façade components, as proposed by [Talon 2006].

The basis for determining component criticality resides with understanding the criticality of the different degradation scenarios. Since the criticality of the different degradation scenarios is known and given that a degradation scenario may affect various components, the component criticality is equal to the maximum scenario criticality of the component, or simply:

$CC_j = \max(C_{r_{ij}})$ criticality of component j

where $C_{r_{ij}}$ represents the criticality of degradation scenario i affecting component j. Once the degree of criticality of the component is known, classifying components in respect to their relative degree of criticality is given by the ratio of the component criticality to the overall criticality of the façade system comprised of a number of components, i.e.:

$IC_j = CC_j / \Sigma CC_n$ degree of importance of component j

where, CC_j is the criticality of component j and ΣCC_n represents the sum total of criticality for n components of the system.

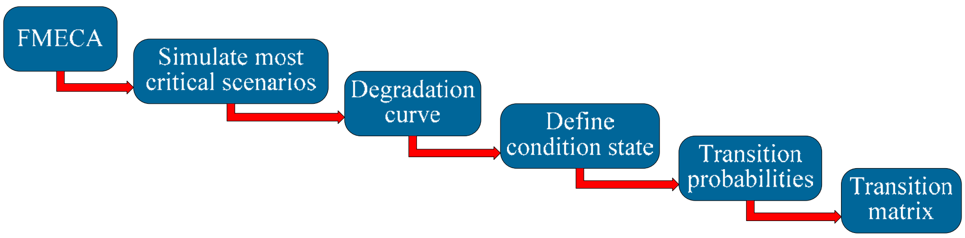

Figure 3. Description of performance analyses and development of Markov condition state matrices for service life estimation.

Given that building managers do not necessarily dispose of unlimited budgets for maintenance actions, only the most critical set of components are further analyzed by simulation of the deterioration process. These simulations provide degradation curves of the change in condition state of façade components as a function of time. The different condition states are then defined ensuring that it is possible to observe these conditions during an inspection. The condition state matrix provides information on the likelihood of a component remaining or changing state at given inspection intervals. Thereafter, the transition probabilities that correspond to the different sates are deduced that in turn permits obtaining the transition matrix. Such a matrix permits estimating the service life of components, or assembly of components, through an analysis using the Markovian model.

7 CONCLUSIONS

FMECA has been shown to be an essential method for failure analysis in the planning of maintenance and maintenance management of built assets. Indeed, this method allows obtaining a broad range of qualitative information (phenomena, causes, consequences) useful for planning maintenance. It provides a hierarchy of and direction for maintenance and repair actions to be undertaken by providing the real causes of degradation or failure. This method is also the basis, on the one hand, of an expert system for performing FMEA, representing a primary advantage for the efficient use of this method and, on the other hand, of quantitative methods for assessing the service life of building components, this latter item, essential information for planning maintenance. The wide range of different applications based on FMECA as well as its use in a maintenance planning project for building façades helps illustrates the relevance of this method in the construction domain.

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