TECHNICAL RISK ANALYSIS IN CONSTRUCTION BY MEANS OF FMEA METHODOLOGY

Saverio Mecca and Marco Masera

Dipartimento di Strutture, Università degli Studi della Calabria, 87036 Arcavacata di Rende, Italy[1]

The aim of quality management is to identify an activity performance level or a grade of client satisfaction and link it up to failure risk, damage or performance loss. Risk management represents a strategic dimension of management methodology in order to plan more reliable and efficient processes. Numerous techniques are at present available for practitioners in project risk management. However, interest has rarely been focused on the question of technical risk analysis. The aim here, therefore, is to relate the latter to environmental, organizational and technical factors affecting production processes. An experimental Failure Mode and Effect Analysis (FMEA) procedure for analysing risk factors in construction phases is presented. Based on a scheme of integrated tools, the technique aims to provide a hierarchical knowledge of risk factors leading to a systematic approach that represents a non-conformance critical conditions analysis in construction management. An FMEA-style risk analysis supports quality management for determining a graduation of the appropriate prevention measures, in order to contribute to obtaining higher efficiency levels.

Keywords: failure, quality management, technical risk analysis.

INTRODUCTION

Risk management is becoming an important management method and tool in the planning of a reliable, suitable, adequate and subsequently more efficient project system (ECOSIP 1991, Giard 1991, Flanagan 1993). Also the analysis of non-quality risk is possibly the most important tool in the planning of a suitable, adequate and subsequently more efficient quality system for building in conformity to specifications (Mecca 1994). By ‘suitable and adequate’ is meant the grading of the quality system by singling out the specific level of criticality in every project and combining the most suitable and efficient prevention and control measures.

Numerous techniques are at present available to practitioners for project risk management (Giard, 4) and (Flanagan, 3). However, interest has rarely been focused on the question of technical risk analysis (Courtot, 2). Risk management has been developed mostly on cost and time risk, while there are few studies on technical or quality risk, which is related to the client’s main goal. Pursuing this goal the Failure Method and Effects Analysis, FMEA, (Andery 1998, Nichel 1992) can be borrowed to specify it in constructions; a good example in this sense is the pioneer work of Socotec (Socotec 1992). Other methods are borrowed from hazard and waste management (Adeli 1988). In order to transfer these kinds of tool, the specificity of construction processes need to be defined and the requirements of a technical risks analysis that plays a nodal role in improving project reliability.

[1] E-mail: lucat@fu.penteres.it

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A SCENARIO FOR RISK ANALYSIS IN CONSTRUCTION

Quality risks in construction processes are particularly complex because of the large number of technical characteristics of a building element. When failures and faults cannot be quantified, the analysis becomes qualitative and tends to describe the plan configuration with its functional relations and the cause and effect relation connected with faults on different levels. In particular, the complexity of characteristics associated with the diversity, multiplicity and interdependence of failure causes determine a lack of information on building phenomena; statistical data may be available only for a few items to quantify some sources of uncertainty in the on-site activities. When reliable probabilities can be determined they have to be thought of as an indication useful in a decision-making process, but the majority of potential failures have to be assessed subjectively.

If subjective judgement must dominate the whole risk analysis process, it is therefore necessary to develop a rational method, a systematic analysis of the building elements, of their required technical characteristics, of their criticality for identifying all actions aiming at reducing and preventing the risk of failure and to define the most effective organizational strategies to increase the operator’s reactivity to failure.

REQUIREMENTS FOR A TECHNICAL RISK ANALYSIS

Risk analysis and evaluation must be applied not only to the technical (non-quality) risk factors, but also to environmental and organizational factors, the former related to the environmental characteristics where work is carried out, the latter produced by the specific organization necessary for the project execution. Becoming qualitative, risk analysis tends to describe the plan configuration applied to a specific building and to a contingent organization, with their functional relations and the cause and effect relation connected with faults on different levels.

Starting just from a systematic analysis, all the actions in construction quality management may be identified to reduce and prevent failure and develop the appropriate organizational strategies to increase the operator’s reactivity to failure. Project and/or contractual failure, that is, organizational failure and functional failure, that is, technical failure are strongly connected in any risk analysis perspective. Organizational factors weigh on the likelihood of technical faults: a sub-contractor dissatisfied either with the contract, or time factor, can neglect quality and safety. Failure in planning or in cost-estimating can produce specific and general risks. Frequently many interdependencies may be found between different types of failure. An inadequate project definition, the lack of clear objectives and the lack of communication about problems, create the conditions for high risk impact in developing an activity. Some failure characteristics do not affect the finished product, however, they play an important role in the face of technical risk. For instance, project error or business failure causes and effects strongly affect management of the construction process.

APPLYING FMEA TO THE CONSTRUCTION PROCESS

Failure Mode and Effects Analysis is an analytical technique that can support decision-making and quality planning in different planning and management phases of the project (Andery *et al.* 1998, Nichel 1992, Silver 1998, Stamatis 1995). FMEA aims at foreseeing the non-conformity of the building and of supplying information for an effective quality management of the project. Its application to building constructions requires a careful conceptual development of the tool that makes it adaptable to the kind of information to be dealt with.

The typical phases of the FMEA for industrial processes are:

- identification of the error modalities, the faults, the non-conformities and investigate the cause and effects relationships for them;
- identification of a risks index on the basis of error probability, severity and visibility;
- provide adequate measures for risk treatment.

The FMEA is effective if it manages to deal with available information and to produce reliable evaluations. In the field of building constructions the challenge of correct information management is crucial because:

- risk dependence on numerous factors makes both a quantitative measurement and a qualitative evaluation difficult;
- factors vary notably from project to project and their contribution in cause determination is uncertain;
- risk assessment requires subjective judgement by an expert and is the result of great experience.

Unlike qualitative approaches that carry out risk ranking following fixed and generic evaluation schemes of probability, severity and non-detection, an FMEA for buildings needs the definition of:

- risk factors and conditions that explicitly and specifically produce failure owing to examined technological processes;
- objective and verifiable criteria;
- criteria in which the specific causes and effects of failure are recognized;
- a lower number of risk categories for every risk condition.

Satisfying these requirements allows the improvement in typical evaluation of the FMEA that works with synthetic numerical judgements/evaluations (Table 1). In the absence of reliable measurements the judgement does not point out the choice criterion that supported the decision and does not supply indications for appropriate prevention and corrective actions (Shammas-Toma *et al.* 1996).

The aim of an FMEA suitable to building construction is to make plain the knowledge base from which the expert draws to assess a specific risk and that justifies the decision-making process according to the principles of Total Quality Management.

THE MAIN TOOLS OF A QUALITATIVE APPROACH TO TECHNICAL RISK

The quality management tools can carry out a deep analysis of the performances required from every building element and related activities. Quality management strategies integrated with the performance theory permits the formulation of a full list of requirements for project activities. Thus an activity performance level or a degree of client (e.g. designer, owner, contractor sub-contractor) satisfaction can be identified and connected to a failure risk, damage and performance loss.

Table 1: probability ranking according to a qualitative or quantitative evaluation

Criterion	Failure probability Points or P	Probability P that the fault produces
Greatly reduced probability.	1 o 2	1/20000 -1/10000
Reduced probability.	3 o 4	1/2000 - 1/1000
Moderate probability	5 o 6	1/500 - 1/200
High probability	7 o 8	1/100 - 1/50
Very high probability. certainty that the fault can be repeated	9 o 10	1/20 - 1/10

A Failure Mode Analysis can be the core of a technique based on a set of tools like, among others, the followings:

- *Functional analysis* to identify hierarchical trees of objectives. Therefore, the main goals in the construction process can be listed and ordered in relation to their relative importance.
- *Requirements analysis* of activities inputs and outputs, either in the design phase or in the tender phases management, in order to define an acceptable final and intermediate quality level.
- *Failure analysis* following the fundamental principle of an FMEA approach, applied to the organizational and technical domain through cause and effects diagrams analysis to obtain lists of critical elements.
- *Risk analysis* applied to the list of criticality (critical points) emerging from the failure analysis. Risk analysis provides a risk value for every criticality through the study of both organizational and technical risk factors.
- *Risk reduction* based on corrective and preventive action in the design phases and prevention and control plans to reduce failure, faults and their consequences on the construction process.

A PROCEDURAL SCHEME OF TECHNICAL RISK MANAGEMENT IN CONSTRUCTION

The main function of the system is aimed at transforming knowledge of the pathologies of the processes and its potential faults into a framework of specific risk evaluation for a precise project. The necessary decision-making support at different project phases or with respect to various managerial activities, design, bid, planning, scheduling etc. is obtained by the use of flexible, integrated tools that adapt to quality, extension, the level of detail, reliability and stability of the specific information and output needed if relevant to the decision-making support or to control.

The Technical Risk management stages (Table 2) for building construction defined to satisfy the specific needs of construction management are:

- Process and design review,
- Pathology and failure mode diagnosis,
- Risk analysis

Table 2: Stages and tools of technical risk management

Stages	Tools		
Process and design review	Functional analysis	WBS, OBS, PBS	Flow chart
Diagnosis of building construction pathologies	Interface analysis	Cause and effects diagram	Fault tree
Risk analysis	Risk factors analysis	Risk condition analysis	Risk evaluation
Risk treatment	Risk support to decision	Risk support to prevention	Risk support to control

RISK TREATMENT

Process and design review

The preliminary action serves to identify all the system parts and all the building activities that can be affected by faults or non-conformity, that could provoke pathological conditions due to the technical element or to the work itself.

Functional analysis is applied as a support to obtain a technological system functions hierarchy, in order to better direct the technical risks analysis. By means of Work Breakdown Structure, Product Breakdown Structure and Organization Breakdown Structure (WBS OBS and PBS, respectively) the structure of construction activities, operators, building elements and of the related performances is obtained. From the basic WBS/OBS/PBS information the flow charts are elaborated, enabling building activity to be ordered and the clarification of its workability conditions and the intermediate characteristics of the technical elements being undertaken. A successive interface analysis may clarify the conditions and characteristics that allow the integration of building elements and interrelated activities.

Pathology and failure mode diagnosis

A wide failure analysis of the project WBS is conducted in two phases:

1. an initial recurring fault and possible non-conformity analysis phase through the data bases. Diagnosis of the pathological processes permits description of the effects of deviation from the required conditions and performance losses that can result from them;
2. a second phase pertinent to the project to carefully evaluate the lack of information in studies and documents related to the performance activity required. The gap between poor information conditions and an expected activity performances is considered as a pathological condition to be prevented.

The available tools for this aim are: cause and effects diagram analysis, the fault tree of organizational and technical pathologies, work sampling finalized to the detection of pathologies; managers and technician training. The result is a check list or WBS of potential failure modes specific to the project under consideration (Table 3). For constructions an FMEA tends to aim at satisfying the need to obtain a WBS in which different failure modes are represented on various detail levels. This enables the correspondence of different decision-making levels and analysis grading for an effective information management in the various planning activities, such as in the bidding management phase in which a synthetic evaluation is required of potential failure modes, whereas planning requires evaluation with a high degree of detail.

Table 3: Lists of faults in a stone cladding system

Faults relative to stone materials	Faults relative to the anchorage structure.	Faults relative to joints in the cladding
• mechanical strength faults • resistance to thermal stress faults • colour degradation • surface peeling • stains, dripping • measurement faults • cutting and milling faults, faults at slab edges • non-homogeneous slab colour	• oxidisation of metal elements; • chemical anchorage grip • plug grip • assemblage errors • non- respect of structural joints • absence of protection employed in EPDM in the fixtures • faulty interface anchorage • measurement faults (verticality, levelling) • noises due to the thermal strain on metal elements	• incorrect sizing of joints • execution of joints out of tolerance • incorrect choice of sealant • defective sealant • non-durable sealant • high or low setting temperature • damp and dust on the slabs • failure to use a primer • incorrect drying • breakage of seal adhesion properties of sealant

The characteristics of a construction process are such as to require the extension of the typical FMEA evaluation of the technical causes of failure to the assessment of environmental and organizational conditions in which the specific project is placed. This mainly improves sensibility in identifying the risks that may produce technically unacceptable results. Organizational and technical failure cause considerable conflict and economic damage to the engineering company. The building of a stone curtain wall offers the paradigmatic conflict condition and non-quality output that cause failure, thus affecting owner satisfaction, company image, all therefore causing evident damage to the project partnership.

Risk factor analysis

The passage from the analysis of failure modes to the analysis of technical risk requires the transformation of knowledge of the technological system pathologies into conditions of specific risk for the construction to be achieved under examination in a determined phase of the project management. The key to systematic consideration of each individual risk consists of guiding the analysis by means of risk factor grids.

In an FMEA for constructions it is also necessary to consider, besides the technical conditions of the fault, the environmental and organizational conditions whose possible effects should be foreseen for effective project management. The effectiveness of the activity of project management, the relationships among firms, are sources of risk of non-quality that may have a decisive impact on the technical quality of the construction. In a systematic approach, every organizational company level is involved to perform risk analysis. In the same way the environmental risk factors related to the environmental conditions where work is carried out are highly relevant. Such factors as geographic, regulations-standards and social-economic factors need to be examined. Each of these may contain further specific factors. Organizational risk factors are produced by the organization necessary for project execution.

The risk factor grid guides the definition of the evaluation criteria for each factor intended for consideration. With respect to traditional qualitative approaches that, in the absence of reliable probabilistic data, fall back on the schematization of subjective evaluation, risk analysts are asked to specify the criteria used to evaluate the individual factors. Validation of the risk evaluation procedure is based on requirements such as the objective and clear identification of the risk categories and their capacity to synthesize the significance of the causes and conditions. For each risk component, occurrence, severity and detection the specific environmental, technical and organizational risk factors are identified and the risk conditions are defined and the relative risk categories that enable an evaluation to be made.

Risk evaluation
The risk index comes from the multiplication of the probability, severity and detection factors for each critical point. The Probability Rating, Severity Rating, Detection rating, are distinct sums of the risk conditions recorded for each factor.

- The *occurrence factor* comes from the evaluation of the individual risk conditions that totalled allow a probability index to be established for the risk under examination. Instead of favouring the statistical recording of data usually only slightly homogeneous and affected by considerable conditioning, the definition of risk conditions in turn enables definition of conventional indices on the basis of observations carried out on cases that offer analogous conditions to those of the project for which the criticality should be established (Table 2).
- *Risk severity ranking* allows the entity of the risk to be established and its impact on things and people. Evaluations about quality loss, additional costs, or the lengthening of time required can be identified for every participant in the project, buyer, firm user etc.
- *Non-visibility* expresses an index of the timeliness with which a failure mode can be recorded, measured and treated. It is a crucial risk component for process quality management, because the possibility of preventing and acting upon non-conformities depends on it. The greater risk is evaluated with respect to non-visibility, that tends with time to exclude an effective treatment of non-conformities, as well as to increase the cost of repairs, to make ascription of responsibility more difficult and to make the effects of the failure mode weigh on the final user.

Risk treatment
The risk indices assumed as absolute values or fractions of the maximum indices obtainable are the basis for the classification of the risk analysed. The interpretation of the obtained index varies in relation to the expected function.

The actions that are generally taken are aimed at diminishing probability, limiting the severity of impact and at increasing the ability to detect failure. Other actions have the effect of clearly attributing responsibility to whoever has the greater competence to take the risk. All the actions of the organizational project can be affected by a risk evaluation corresponding to an alternative. Design can be supported by means of analysis repetition according to the modifications introduced, from which risk levels emerge that are then compared to obtain a progressive risk reduction.

APPLICATION TO CONTRUCTION PROJECTS

The application of FMEA to construction management requires a substantial methodological innovation with respect both to quantitative and qualitative approaches.

The innovation introduced results from a qualitative approach that requires a careful specification of risk conditions and effects in construction process, and that requires a validation of the evaluation criteria.

Table 4: Risk ranking relative to choice of stone type for a stone cladding systems by means of the identification of specific conditions

Design Phase	Choice of material for stone cladding	**Risk**	Choice of stone	
		Assessment of the Risk Occurrence (Probability)		
Risk factor	*Risk condition*	*Class A Low risk* **1 point**	*Class B med. risk* **2 points**	*Class C high risk* **3 points**
Climatic factors	Thermal stress	Walls exposed: to sunshine	Walls exposed to sunshine to thermal excursion	Walls exposed to sunshine to thermal excursion to thermal shock
Climatic factors	Conditions of atmospheric aggressiveness	Building constructed in rural area	Building constructed in industrial urban area	Building constructed in seaside area
TOTAL OCCURRENCE OF RISK				

Design phase	Choice of material for stone cladding	**Risk**	Choice of stone	
		Assessment of the Risk Severity or Gravity		
RISK FACTOR	*Risk condition*	*Class A Low risk,* **1 point**	*Class B med. risk* **2 points**	*Class C high risk* **3 points**
Performance level factor	Effects of exposure to sun on the parts involved in the project	The stone is durable in its main characteristics	The stone loses its surface pigment with time and becomes opaque	The stone is subject to degradation owing to exposure to sun
Climatic factors	Effects of aggressive atmospheric agents	Slightly exposed cladding. Negligible effects	Exposed walls, effects present, slightly visible to the public	Exposed parts, effects consistent and visible
Organizational factor	Effects of technological innovation	No presumable effects	Cost of substitution	Cost of substitution, importance of purchaser
Regulations uncertainty factor	Effects relative to failure to respect tolerance	Modest additional costs	Additional costs, short assemblage time	Additional costs, short time, visibly deformed joints
		TOTAL SEVERITY OF RISK		

Design phase	Choice of material for stone cladding	**Risk**	Choice of stone	
Evaluation of the timeliness of discovery and the possibility of treatment of the risk				
RISK FACTOR	*Risk condition*	*Class A Low risk,* **1 point**	*Class B med. risk* **2 points**	*Class C high risk* **3 points**
Factors relative to supply	Conditions and effects of the visibility and measurability and reversibility of faults	Perception by means of control of acceptance, simple treatment	Visible and easily measurable faults, that need treatment with times that affect the project	Faults measurable by calculation, tests, difficult to observe, difficult to treat
Factors relative to execution	Conditions and effects of the visibility and measurability and reversibility of faults	Evidencing by means of linking up tasks	Visible and easily measurable faults, but slightly visible	Faults measurable by calculation, tests, difficult to observe
Factors relative to delivery and testing	Conditions and effects of the visibility and measurability and reversibility of faults	Visible effects, assessable, low substitution costs		random or intermittent faults, difficult to evaluate, high costs,
		TOTAL TIMELINESS OR TRACTABILITY OF RISK		

The condition specification is obtained by means of the analysis of effective and particular factors which affect a project. The validation of the evaluation is achievable through objective and accurate criteria.

Some tests are directed to provide the knowledge base and procedures for quality and risk management in design, tender and construction activities to an engineering company specializing in the construction of large shopping centres. The application domains of the methodology are the stone wall cladding

- In design phase the FMEA proves to be a valid support to improving quality management, by cycling risk analysis and assessment in order to choose the best technical solution at reducing increasingly the risk rating. Through prevention and control, the risk and costs of non-quality can be reduced at every phase and the management of on-line residual risks or new risks can be introduced in the construction project.
- In the tender phase the FMEA is applied as support for the specification of the quality management requirements. In a performance perspective the contractors are required to provide an adequately graded quality plan to assure the technical risk control relative to the quality of performance and to reduce quality cost and conflicts which limit client satisfaction.
- In planning and in realization phase, the FMEA methodology for building construction has been obtained to assist contractors in quality planning. Risk plans are developed to deal a detailed FMEA analysis in order to support quality management decision by specific technical risk evaluation.

Planning documents substantially are derived from a collaborative risk analysis adapted to the customer's requirements and to the complexity of the activities, graded in relation to failure risks. The main functions of quality plan prevention, control and non-conformity treatment are concentrated on the critical events. The construction partner is involved to play actively his own role to avoid failure and conflicts towards an improvement in the quality of processes.

The pilot study carried out enables the evaluation of the general quality management implementation procedure, and the outlining of foreseeable results deriving from an extensive approach. The experimentation obtained information useful for increasing the understanding of tool usability by the personnel involved in the first project phases up to the on site management of technical criticality.

Further research developments are dealing to implement knowledge bases for risk analysis in collaborative networks construction networks and to support the project audit.

CONCLUSIONS

An FMEA technique for building construction could be the most important tool in managing quality plans to obtain a suitable and adequate and subsequently more efficient system to build in conformity with specifications. Given the nature of the construction process and specifically, the uncertainty and the environmental, technical and organizational complexity, a tool is needed that integrates the analysis and treatment of environmental, technical and organizational risk factors. The analysis of risk factors, the identification of criticality conditions and the evaluation of every critical point of the project together allow the linking up of data on failure modes, obtainable from technical literature, regulations, on-site findings, personnel expertise, to specific risk prediction for a precisely identified project. This allows the application of an FMEA-type tool to episodic production processes such as building sites and to make non-quantitative evaluations from which it is possible to identify judgement parameters. A common classification of risk factors can help technicians and managers in organizational and technical risk analysis. Technical risk assessment in building construction emphasizes the role of project quality planning in client satisfaction and should be one of the main tools for evaluating the reliability of quality systems.

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