FAILURE ANALYSIS APPLIED TO DESIGN OPTIMISATION

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ABSTRACT

The present work points out a procedure, conceptually based on lean thinking principles, that focuses on co-ordinating different design disciplines (architectural, structural, etc.), thus avoiding errors due to lack of design compatibility caused by inadequate management of information flow. A design protocol is developed, helping the designers to outline constructability guidelines, applied to the specific conditions of a project.

The procedure is based on the application of failure analysis methods, particularly the FMEA (Failure Modes and Effects Analysis), adapted to be used in building construction design.

The procedure allows the detection of potential failure modes related to the coordination of different building design specifications. Thus, it looks for “what could be wrong”, leading to the improvement of the design reliability. The application of FMEA as a phase of the procedure leads to failures detection, its prioritisation and the establishment of countermeasures against those failures. A set of guidelines has been generated and can be incorporated into later design phases.

Some results of the implementation of the procedure are briefly discussed.

KEY WORDS

Lean design, design coordination, failure analysis

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INTRODUCTION

The challenge of product development in the building construction industry, in a scenario of increased competitiveness, demands from many companies a continuous effort to develop new methods and tools, in which the design for quality, cost, constructability and reliability play an important role. In contrast to this tendency, the managerial rationale and the procedures to develop designs in Brazil are clearly insufficient, following the trend reported in the international literature.

First of all, the absence of a process flow notion and of a "pulled process" as exists in the lean thinking context, results in the design process being seen exclusively as a sequence of conversion activities in which individual solutions are gradually elaborated, changing hands successively, in a sequential manner**.** In this way, the interaction between the several subjects and the information exchange during the execution of the design is minimal. Very often, architects assume an information-centralizing role and the activities of coordination of the design are not systematized and rarely occur in a formal way. Summing up, each designer is seen as a creator of "individualized" solutions added on top of each other, i.e., the information flow is not continuous, in contradiction to what it should be according to lean thinking. These are the appropriate conditions for the design as a whole to be unstructured and chaotic (Huouvila, 1997; Formoso et al., 1998).

Second, the rationale underlying project development systems implies a "contract management" attitude (Ballard and Koskela, 1998) in which an integrated vision of the design / execution phases does not exist, and the focus of the activities are not centered on the customer, either it is the contractor or the final customer. What is evident is a continuous negotiation – more or less successful in each case - of responsibilities and duties, and the concept of value, how it is generated and how it meets the expectations of the customer, is not clearly delineated. As a result of this rationale, there are not formal mechanisms or models which allow the understanding of the expectations of the customer, that is, the task of converting these expectations into design technical specifications is not carried out in a systematic manner.

Consequently, as Alarcón and Mardones (1998) and Huouvila et al. (1997) pointed out:

- part of the requirements of the customer are "lost", or are not even taken into consideration in the beginning of the design;
- part of these requirements are lost during design drafting;
- there is no optimization of several solutions;
- there is a lack of compliance with quality standards;

That is to say, it is not clearly defined how the design flows and how value is added in each phase of the design.

From an operational standing point, both the experience of the professionals in the field and an analysis of the literature point to some critical failures. Among them, some factors stand out:

- The designs are incomplete and need additional specifications or, what is more common, "improvisations" at the site
- Many times the designs are not clear or explicit.
- There is an almost generalized absence of design execution standards, their presentation and communication.
- Design changes are frequent, partially due to the lack of mechanisms that allow

designers to understand, in the early phases of the project, the real expectations of the customer. The duration of the design drafting stage is prolonged, often making unattainable some constructive solutions due to the lack of interaction between the agents involved in the process.

- Lack of coordination among the subjects involved, which leads to the incompatibility and conflict between distinct designs.
- When considered in terms of cost, the constructive problems resulting from design failures make up the largest category (Josephson, 1996, cited in Ballard and Koskela, 1998).
- And finally, the cost of the design is only reduced at the expense of quality.

Faced with these problems, the reasoning structure underlying lean design proposes the use of design elaboration strategies that simultaneously embody the principles of "flow management", as pointed out by Koskela, and the management of value, and how it is created and transmitted in each one of the design phases. These make it possible to establish guidelines concerned with the task of translating customer's expectations into design targets, in which constructability and reliability (absence of errors) play an important role.

In this context the present work points to a procedure conceptually based on lean thinking principles that focuses on the coordination of the different design disciplines (architectural, structural, etc.), thus avoiding errors due to the lack of design compatibility caused by inadequate management of information flow. Additionally, a design protocol is developed, helping the designers to outline constructability guidelines, applied to the specific conditions of a project. The procedure is based on the application of failure analysis methods, namely FMEA (Failure Modes and Effects Analysis), adapted from manufacturing industries design review methods, to be used in building construction design.

The procedure allows the evaluation of potential failure modes. Thus, it "looks for what could be wrong", leading to improvement of design reliability. The application of FMEA as a phase of the procedure leads to failure detection, its prioritization and the establishment of countermeasures against those failures. A set of guidelines is generated and incorporated into following design phases.

The use of this procedure in building construction project and its results are briefly discussed.

GUIDELINES FOR DESIGN COORDINATION

DESIGN COORDINATION: AN APPROACH TO LEAN DESIGN

One of the lines of action in the development of lean design, called "flow view" (Ballard and Koskela, 1998) implies establishing design planning and execution mechanisms which make it flow and be pulled. One of the resources employed is the Last Planner method which has been progressively used in design management (Ballard, 1999).

The adoption of methods that ensure design plan reliability, as well as reduction of variability in the information flow during the execution of design tasks is not a guarantee, *per se*, that this flow represents the best way of interaction among designers during design development.

In this way, a second action line implies developing procedures and a design protocol that leads to:

- A clear definition of the stages of the design;
- The establishment of multi-functional teams which work since the early stages of the project;
- A definition of the documents and of the information which need to be available in the beginning of the design;
- The introduction of mechanisms which allow the logical concatenation of information among the intervening agents (designers from the several fields). In this respect, the recent works of Formoso et al. (1998) and Fabricio et al. (1999) stand out;
- The establishment of methods and techniques of design co-ordination by adopting interaction guidelines by the designers involved.

Faced with these challenges, the objective of the method presented below was to establish technical guidelines for the several designers involved (architects, structural calculation staff, electrical installation and telephony designers, etc.) as checklists containing potential incompatibilities among the several designs, and the preventive actions for these incompatibilities. In this way, a communication protocol was created for sharing technical specifications.

Another aspect that should be considered is that it is necessary to set up design procedures that assure that the customer's expectations are considered during the successive phases of the design process. In this light, two dimensions of value might be considered:

a) the technical characteristics of the building which actually meet the customer's expectations, including the constructive solutions detailed in the executive design;

b) the design specifications would imply eliminating uncertainties, rework and makeshift solutions during the execution, leading to an increase in constructability.

For this, the establishment of a procedure which implies preventing incompatibilities among the distinct designs will make possible, on the one hand, the absence of constructive problems which affect negatively the quality characteristics of the building, and, on the other hand, it will imply the increase of the constructability. The design co-ordination procedure proposed was developed in this context.

FAILURE ANALYSIS AND LEAN DESIGN

The procedure developed as a subsidy to design co-ordination used one of the failure analysis methods largely employed by the industry, FMEA, as a tool. Why use this method?

Every process presents problems (failures) that generate unnecessary rework, and in the specific case of design, unnecessary information flow, rework, and lack of reliability caused by the absence of co-ordination of specifications of the different designers. Summing up, waste. Some of these failures result from a mismatch between procedures and the way things are actually done. These failures may be detected - normally *a posteriori* - by the daily routine management, i.e., process design control mechanisms. This approach, sometimes based on the plan-do-check-act (PDCA) cycle, will reduce undesired results (outputs) by preventing failure occurrences from happening again. One of the most used methods is the “QC Story”, as outlined in Total Quality Management literature. The corrective actions are directed to avoid deviations from standards.

In order to achieve quality assurance, which will lead to a more effective waste reduction, lean thinking practice should incorporate a method that is currently rarely used in the design process. It requires taking into consideration not only “what we shall do to make things go on”, but also searching “what could be wrong (and we do not know)”. This approach will lead to another attitude: “how can we set up some countermeasures to potential failure modes”, in this case incompatibilities among the specifications of the different designs.

This approach to process design is based on the idea that there are many causes of failure that can not be detected by conventional controls (even dynamic ones), because these controls and management tools are based on our present knowledge of process variables. This kind of failures are implicit in building design directives, usually deriving from cause-effect relationships that are technically unanticipated at first sight, specially when we are working on the “detail level”. Therefore it is necessary to introduce mechanisms to detect and prevent potential failure modes.

In other words, “the search for what could be wrong” (an analysis of potential failure modes inherent to the design process) will provide a ‘filter’ to “time bombs”, problems that still have not arisen but, as mentioned before, are built into design specifications. This approach aims at increasing reliability, by anticipating and blocking potential incompatibilities in the design. To do so, the Failure Modes and Effects Analysis (FMEA) was adapted to be used in the building design process. A more extensive explanation of this method can be found in Andery at al. (1998).

GUIDELINES TO PROCEDURE DEVELOPMENT

To develop the procedure, some basic guidelines were considered. First of all, the need to create a procedure of simple use which did not require previous knowledge of failure analysis methods**,** and which allowed the drafting of a checklist to be used as a reference for the exchange of technical information among distinct designers, independently of the form in which the design is managed.

The method should also be flexible so it could be used by companies of different size, number of designers and with or without execution standards. Also, the procedure should be adaptable to distinct types of projects (buildings, facilities, industrial plants, etc.) and once executed for one of them, it should serve as a reference for similar projects.

The formation of a multidisciplinary team has been assumed as a previous requirement. This team is made up of experts from several fields and is under the co-ordination of an architect from the beginning of the project feasibility study onwards.

METHOD FOR DESIGN COORDINATION

To develop a procedure to be used in designs co-ordination, a multidisciplinary team was assembled, made up of two researchers who guide the execution of the job, a group of eight architects, a structural calculation technician, two engineers responsible for the hydraulic, electric and telephony designs, and two engineers assigned to the construction site. Most members of the team belong to the same design development office. The familiarity with Total Quality Management system and lean construction principles created an environment of motivation for the development and the implementation of the method, allowing an intense exchange of opinions among team members. The fact that most architects and engineers had worked together was considered a decisive factor, which facilitated the exchange of information and sped up the consolidation of the procedures.

For the development of the job, it was selected the design of a switching and control central of telephone exchange building, which involves conventional aspects of a building, added to the specific requirements related to the electrical (particularly cables and grounding), hydraulic and telephony designs.

DESCRIPTION OF PROCEDURE STEPS

The procedure used in the co-ordination of the designs is made up of the following steps:

First step: Establishment of a checklist containing the tasks of the distinct designs

Initially, a checklist containing all the activities of the design is drafted, that is, the activities which must be carried out, from pre-design to the detailing of the executive design. An illustrative example with part of one of the checklists of the architectural design is shown in Table 1.

Table 1 – Illustrative example: design activities taken into consideration (executive design of architecture, partial)

Floors
1. indication of all the coordinates of the design
2. indication of all total and subsets dimensions
3. dimensions of details which will not be drawn in large scale in the executive details
4. indications of cross and vertical sections, details
5. indication of the dimensions of the mortar bed and the finished floor
6. indication of the function and area of each floor and room
7. making architectural elements compatible with the structural elements
8. indication of masonry / finishes / water proofing / insulation
9. drain location
10. indication of the areas which will receive raised floor
11. indication of horizontal and vertical circulation areas – stairs, ramps
12. indication of guard rails
13. indication of ceiling, fillings, projections,. conduits
14. definition of openings from the use of inner space
15. definition and dimensioning of the kind of window frames
16. layout of wet areas
17. indication of door sills, breast walls
18. indication of linings / finishes / *brises*
19. reference square of window frame dimensioning
20. indication of window frames referred to the square
21. indication of parking spaces numbered according to the units
22. indication of outdoor floor finish
23. indication of the direction of slope of the outdoor floors

Second step: Refinement of the checklist
Once the checklist has been drawn up, it is refined, that is, the activities which are not expected to bring up interference problems with the other designs or critical constructive solutions concerning ease of execution were eliminated, either because of their object, or because the design standards had already anticipated, in such cases, possible interferences.

Third step: Drawing up correlation matrices among the design activities.
Once the items of each design to be taken into consideration have been determined, correlation matrices are developed pairing up the elements of one design (for instance the architectural design) with all the others (for instance, structural).

A diagrammatic example is shown in Table 2 .

Table 2 - Diagrammatic Example – Correlation Matrices

Architect./ Struct.	**S.1**	**S.2**	**S.3**	**...**
A.1	3	2	2	2
A.2	2	0	1	3
A.3	0	1	3	1
...	1	3	3	0

In the matrix shown in Table 2, codes A.1, S.1., etc., indicate the tasks of the architectural (A) and structural (S) designs considered, as shown in Table 1. The numbers indicate the correlation index between the topics of two designs, that is, the capacity of the resulting specification from an architectural design activity, for instance, to imply incompatibility with a topic of the structural design. Index 3 represents a high probability of interference, 2 indicates a moderate probability, 1 low and 0 indicates that the items considered will not imply coordination problems. The indexes are discussed with a team approach, and the contribution of the site engineers is considered quite important.

Fourth step: Analysis of the correlation matrices
In the next step, the matrices are analysed, assigning weights to the several lines and rows. The analysis allows the team members to select the items which are considered most critical, and which will be the object of the FMEA analysis. That is, the analysis of the matrix works as a first “filter”. This allows the team members to consider the critical activities that will be the object of design recommendations.

Fifth Step: FMEA analysis
A failure analysis is performed for each critical activity of the design, selected from the correlation matrix, considering the potential interferences with the specifications of other designs.

The FMEA analysis implies:

- Relating potential failures. For example, the location of the columns (structural design) has implications for the parking space assignment (architectural design).

- Relating the effects of these failures: interference, rework, need of using makeshift and non-optimised solutions, irreversible constructive problems, or the use of more expensive and inefficient constructive techniques.
- Determining the severity of the effects of the failures, using an index ranging from 1 to 10.
- Determining the probability of failure occurrence, having in mind the present design control mechanisms, previous designs and design technical standards of the company . Each failure receives an index ranging from 1 to 10.
- Establishing a risk index that enables to rank the potential failures. The risk index is the product of the two previous indexes.
- Establishing preventive actions for these potential failures.

To illustrate, Table 3 shows part of the analysis using FMEA, for some items of the architectural design.

Based on this analysis, the potential failures with higher risk indexes, that is, those which have a higher combined probability of occurrence and a larger significance of effects are highlighted as being critical design activities.

Table 3 – Example: FMEA analysis used to determine failures and countermeasures

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Constructive elements: pergolas, flower boxes, platibands, parking, courts, swimming pools;	• Use of flower boxes made impossible because they had not been foreseen; • Flat roof deformation, poor dimensioning; • Cracks in the court areas (dilation); • aesthetics jeopardised by poor dimensioning of the parts.	3	3	9	• Clearly define the location of the indoor swimming pools; • Make the location of the flower pots compatible with the dimensioning.
Definition of the type of structure.					
Pedestrian and Vehicle access;	• Implementation level incompatible with the existing level, creating problems to access the building; • Structure location prevents vehicle movement; • Inappropriate location of the shed and alignments.	3	3	9	• Implementation level adopted coherent with that of the design; • Make structural and architectonic designs compatible.

Sixth step: Drawing up a checklist with constructive recommendations
For the activities with a higher risk index in FMEA, preventive actions and guidelines are listed that prevent compatibility problems with other designs and imply the optimisation of the constructive processes. As illustration, Table 4 shows an example.

The checklists serve as a reference for the exchange of information among designers, and cover both pre-defined specifications and discussion guidelines.

Table 4 – Illustrative example of checklist of the architectural design used in first design stages (partial)

	1. Which is the specific use of each room?
	2. Which will be the load imposed on the structure in each room?
	3. Which are the characteristics of the special equipment? Overload, ventilation, water and electricity points, thermal acoustic elements
	4. Have the location of flower boxes and swimming pools been defined?
	5. Has the joint expansion of sports courts been anticipated?
	6. Are the dimensions of the parking spaces and the access areas sufficient ?
	7. According to the cuts made to the land, do the levels of implementation allow easy access?
	8. Do lining materials take into consideration the difference in elevation that is supposed to exist between the dry and the wet areas?
	9. Has the direction of the slope of the floor been indicated?
	10. Does the design foresee any kind of finish to prevent cracks in beams and masonry?

RESULTS OF IMPLEMENTATION

As mentioned, the procedure described above was used to draw up designs for a mobile telephone exchange building. The designs are under evaluation, but some positive aspects have already been noted. The following points stand out

- The procedure was considered simple in its implementation. For this particular design, the development time was two months. However, the resulting checklists will serve as a reference for other similar designs, reducing their execution time;
- It was noted that the checklists served as an excellent discussion list with the several designers. Besides, the design guidelines that were pre-defined in the checklists sped up the definitions to be made in the pre-design. The procedure resulted in more intense communication among the designers.
- The guidelines for the co-ordination of the designs were formalised, and the procedure standardised as this was considered useful for their application to other types of designs. The professionals involved felt more “confident” having a reference report for the exchange of information. The number of activities of the design which

may be simultaneously developed increased, based on the guidelines presented.

- The use of the procedure led to the observation of other failures in the way in which designs are developed, and raised the need to create new standards of documentation and presentation of designs in the team.
- A significant number of failures that had not been previously considered in other similar designs were brought up. That is, the reliability of the designs increased.

In the following stage of the research, standardisation procedures of the design activities will be developed in parallel by the several designers.

CONCLUSION

This paper presented a procedure to establish guidelines to co-ordinate designs based on the use of lean design concepts. In particular, it has been concluded that the use of the procedure allowed an increase in the efficiency of information flow among the several designers. In addition, the establishment of countermeasures to potential failures increased the quality of the design.

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