IMPROVING THE DESIGN-CONSTRUCTION INTERFACE

Luis F. Alarcón[1] and Daniel A. Mardones[2]

ABSTRACT

In building projects customer requirements, constructive aspects and quality standards are defined during the design phase. However, this important phase is usually carried out with little interaction between the construction and design teams causing many problems during construction such us: incomplete designs, change orders, rework, construction delays, etc.

This paper describes a performance study of the design-construction interface. This study comprised: interviews with experts, data collection from several projects and design and implementation of improvement tools. A review of the most frequent design defects found during the construction phase in four building projects allowed the researchers to design several tools to prevent the occurrence of these defects. QFD was used to identify the most effective tools and to set priorities for implementation.

The proposed changes were implemented in a construction company participating in the study with significant impacts on performance. The implementation comprised new design and review procedures, standards for communication as well as explicit definition of internal customer requirements and design attributes. The implementation of these changes brought important reductions on design defects and their corresponding impacts in this company, some of these results are discussed in this paper.

KEY WORDS

Design quality; design process, continuous improvement, design-construction interface.

[1] Head Department of Construction Engineering and Management, Universidad Católica de Chile, Escuela de Ingeniería, Casilla 306, Correo 22, Santiago, Chile, e-mail: lalarcon@ing.puc.cl

[2] Design Quality Coordinator, Delta Construction Co., Huerfanos 812, Piso 7, Santiago, Chile

INTRODUCTION

It is in the design stage where the requirements of the client are identified and the constructive aspects and the standards of quality are defined through procedures, drawings and technical specifications. Currently, the work within the design stage is split into several temporary sequences, and it is delivered to different specialists for its execution. In building projects, first the owner selects the architects who prepare the architectural designs and specifications, then the structural design and other specialty designs are developed. Generally, the construction stage is the responsibility of a contractor selected by the owner.

The problems of this work sequence have been discussed for many years. The main problems that have been detected are the little interaction among design and construction and among the specialists, this situation compels the following phases to work on incomplete designs. The consequences are suboptimal solutions, lack of constructability and a great number of change orders (design and construction rework).

The impacts of changes are not understood and rarely recognized, in terms of costs and schedule. The work hours invested by the designers in the changes have been estimated in a 40 to 50% of the total of a project (Koskela 1992). In Latin American countries, it is estimated that between 20 to 25% of the total construction period is lost as a product of design deficiencies (Undurraga 1996). On the other hand, for some Chilean construction companies, the principal source of conflict in projects are the continuous changes in the designs carried out by the owners, affecting quality and productivity and impacting the schedule and the cost of the projects.

Based on the previous argumentation it is clear that the design-construction interface offers a great potential for improvement. To achieve this improvement it is necessary to identify those activities that add "value" and those that produce "waste" during the design and construction processes. This paper describes a performance study of the design-construction interface that comprised: interviews with experts, data collection from several projects and design and implementation of improvement tools.

A review of the most frequent design defects found during the construction phase in four building projects allowed the researchers to design several tools to prevent the occurrence of these defects. QFD was used to identify the most effective tools and to set priorities for implementation. The proposed changes were implemented in a construction company participating in the study with significant impacts on performance. The implementation comprised new design and review procedures, standards for communication as well as explicit definition of internal customer requirements and design attributes. The implementation of these changes brought important reductions on design defects and their corresponding impacts in this company, some of these results are discussed in this paper.

DESIGN AS A FLOW

Its duration, cost and value can characterize the flow processes. The value is referred to the satisfaction of the requirements of the client. Only the activities that can be converted to form valuables for the client are the ones that add value to the product. Huovila et al. (1997) suggested the model shown in Figure 1 for the design process.

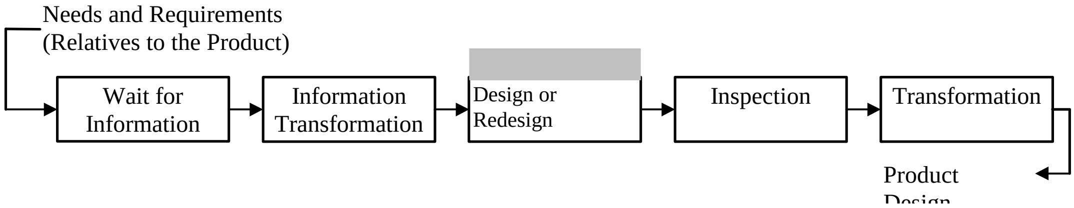

Figure 1: Design Flow (Huovila et al. 1997)

1) The design activities that do not contribute to the conversion are: inspection, moving, transformation and waiting of the information.
2) The only conversion activity is the design itself. Redesign due to errors, omissions, uncertainty, etc. is also waste.

If we examine the design process with this perspective we realize that only a small fraction of the total design cycle time is used in conversion activities. Thus, the reduction of these losses provides a large improvement potential. The value generating process is carried out through the fulfillment of the client requirements and needs. However, during this process there are several instances for value loss (Huovila et al. 1997):

1) Part of the requirements are lost at the beginning.
2) Part of the requirements are lost during the design process (for example, the design intention of a designer is not communicated to the following phases, and it can be spoiled by decisions in them).
3) There is very little improvement and optimization of the design solutions (for example, the actions or the opportunities of the following phases are not taken into account).
4) Quality errors of the design remain in the final product.

The corresponding actions to avoid these value losses are:

1) The rigorous analysis of the requirements and needs at the beginning, with a close cooperation of the client;
2) The systematical administration of the requirements with the application of Quality Function Deployment (Q.F.D).
3) Improvement and the optimization of the design process through rapid iterations among all the agents that issue design and construction information; thus, all the phases of the life cycle of the project should be considered simultaneously from the conceptual phase.

All these actions are necessary to eliminate those activities that do not add value and then return from the construction stage to the design stage.

PROBLEMS THAT AFFECT THE DESIGN-CONSTRUCTION INTERFACE

Generally, it is during the execution phase of the projects where design defects are detected; the problems associated with the designs are mainly:

1) Poor Design Quality: Design drawings are generally incomplete and they are not explicit, requiring a great amount of specifications. Specifications are difficult to handle and sometimes are ignored. Very often design documents have inconsistencies, errors and omissions, or simply lack of clarity in the presentation. This implies that those that should carry out the work do not have the necessary information or have the wrong information to do the job.
2) Lack of Design Standards: There is a lack of standards in the designs, and lack of suitability for the existing technology. In many projects of similar characteristics, or of the same type, the designs used are completely different with the consequent loss of efficiency in the construction phase.
3) Lack of Constructability: An important proportion of the problems detected during construction is due to lack of constructability of the designs.

The details not defined in the designs become problems that have to be solved by the contractor on site. Usually the problems are detected just before starting construction of the specific task and sometimes even after the task has been accomplished. The results are losses of different type and magnitude.

EXPLORATORY STUDY: IDENTIFICATION OF DESIGN PROBLEMS AND SOLUTIONS

As first step for the development of the improvement methodology it was necessary to collect information to obtain evidence about the type and frequency of design defects that affect the construction phase. This information was collected from four projects of a construction company; the construction sites were visited several times in each project in order to accomplish audits of the different control documents. Each problem that originated interactions between designers or owners and the contractor was registered. 457 records with total 673 observations were collected with detailed information to analyze the impact of the problem detected. The collection of information was carried out by studying different documents containing information from the beginning of the project—between 10 and 68 weeks—depending on the progress of the project. In some cases it was possible to easily reconstruct a “record of design defects” for several weeks, but in other cases only records of a few weeks were obtained.

Interviews and surveys with design and construction professionals were also carried out in order to identify the most common problems affecting the design construction interface. Each interview was split into four parts in order to obtain information for different purposes (Mardones 1997):

1) To determine the possible causes of design defects;
2) To know the impact of design defects on construction works;
3) To determine the information defects in the designs; and
4) To identify ways of preventing or solving these problems.

As a result of the interviews and surveys, it was observed that the most important problems present in the designs were: defects of individual specialists and the lack of coordination among specialties, changes introduced by the owner and the designers, inconsistencies among drawings and specifications, designers with little construction knowledge and non technical specifications (Figure 2). These problems, produce a series of impacts in the construction works such as: loss of labor, idle times, rework, abnormal use of machinery and equipment, delays, etc.

The most important design defects identified were: lack of information and wrong information. The most frequent problem was the continuous change and modifications of the design. The analysis of the information collected showed that the current design process is incomplete and chaotic and it does not allow the construction professionals a complete exposure to the completed design and it prevents the interaction among the different specialties that intervene in the process.

Nº	DESIGN DEFECTS	Weigth %	Acumulated Weigth %
1	Structure Elements Details	13.97%	13.97%
2	Lack of Architecture Detail Plans	12.78%	26.75%
3	Incorrect Cross References Between Different Specifications	11.59%	38.34%
4	Incorrect Structures Cross References	8.17%	46.51%
5	Lack of Definition of Architecture Elements	6.54%	53.05%
6	Structure-Bid-Plans Modifications	6.39%	59.44%
7	Lack of Architecture Dimensions	6.24%	65.68%
8	Lack of Identification and Location of Architecture Elements	5.65%	71.32%
9	Finishing Materials that Require Samples	4.75%	76.08%
10	Shaft Problems	4.46%	80.53%
11	Design Defects in Sewerage and A.P.	4.16%	84.70%
12	Architecture's Incorrect Cross Reference	3.12%	87.82%
13	Design Changes by the Owner	3.12%	90.94%
14	Electricity Design Defects	2.97%	93.91%
15	Structure Plans Late Delivery	1.93%	95.84%
16	Defects in A. C. Designs	1.49%	97.33%
17	Problems with Electrical Equipments	0.89%	98.22%
18	Equipments Structure	0.59%	98.81%
19	Problems with the Materials in the Market	0.45%	99.26%
20	Symbology Conventions	0.45%	99.70%
21	Gas Design Defects	0.30%	100.00%

Figure 2: Pareto’s Classification of Design Defects

The following are some of the recommendations suggested by the interviewees to avoid these deficiencies:

1) To incorporate construction personnel in the design stage; this would help to prevent problems before they arrive to the site.
2) To adopt standards for design information; this would avoid misinterpretations and loss of time in understanding design information.
3) To introduce continuous improvement in the design process in order to avoid repetition of design defects.

Another interesting result obtained was the response time to contractor inquires due to the defects in the designs. This was defined as the difference between response dates and detection date of the problems, then these differences were grouped by ranges (weeks) as shown in Figure 3. The projects that had formal systems to solve the design problems such as “design inquiries logs” or “design coordinators” showed reduced response time to solve these problems and reduced relative impact on the project.

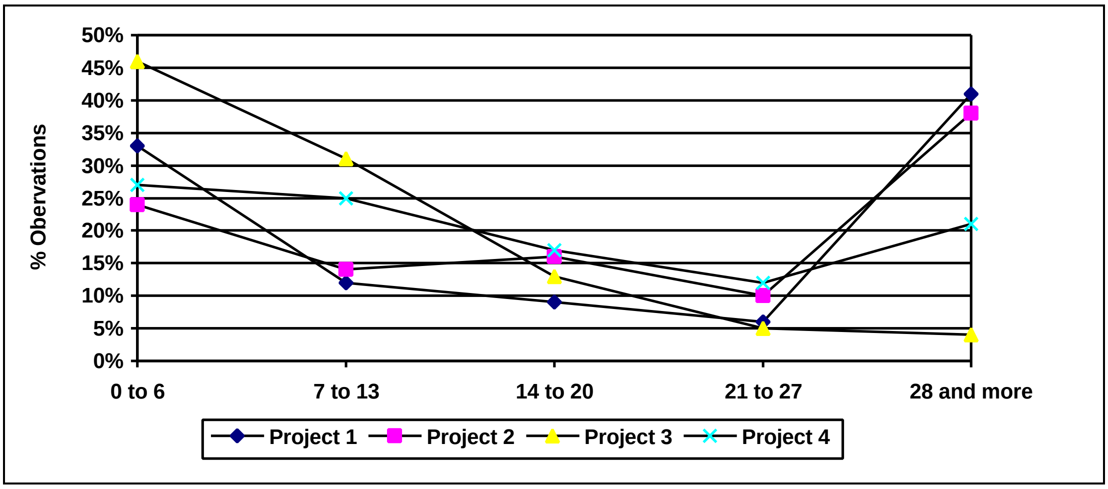

Figure 3: Response Time to Design Problems

A methodology to introduce continuous improvement of the design process was designed to give response to the problems identified. This methodology incorporates the elements suggested by the interviewees and some of the recommendations given by (Huovila et al. 1997), which were discussed before. This methodology is briefly described in the following section.

METHODOLOGY TO IMPROVE DESIGN QUALITY

The proposed methodology was designed to eliminate the causes of the defects detected in the identification phase of the research. These problems the can be solved acting through four different actions:

1. **Supervision**: of the design process. A construction company must participate in the design process, in order to avoid the problems related with lack of construction knowledge of the designers, providing its experience in design solutions.
2. **Coordination**: of the different specialties through a logic sequence of information transfer, avoiding incorrect assumptions, and giving a priority level for changes in order to avoid lack of coordination and to improve the design compatibility.
3. **Standardization**: of design information, to avoid the omissions, errors and continuous changes, that affects the normal development of the projects.
4. **Control**: of the flow of information, verifying that the requirements of previous processes are fulfilled, in order to avoid that design defects arrive to the construction site.

Four forms of actions are proposed to introduce continuous improvement based on the above elements:

1) Improve Coordination through:
   1) A planning scheme of the design sequence for building projects, in order to stabilize and control the information flow, to establish priorities among the specialties to avoid the lack of information or the use of assumptions when information is not available. This scheme also helps to coordinate the installation, location and lay out of different systems, equipment, and other items. The establishment of this plan for the information transfer through all the design process allows the users to organize the requirements of input data for each one of the specialties and the precedence order of these requirements.
   2) A plan to control and evaluate changes introduced during the execution stage, determining their impacts on the project.
2) Introduce Standardization through:
   1) The development of "task lists", in order to generate for each one of the designers, the input data for his own design process.
   2) The development of "work specifications", in order to standardize the presentation of the information and to establish requirements for the different designers.

3) Reduce the impact of the lack of construction knowledge of the designers by introducing construction criteria, in the" task list " and " work specifications ".

4) Improve Control by developing "check lists" to control the parameters established in the "task list" and the requirements imposed in the "work specifications".

This methodology is applied to each project and allows the compilation of data to provide an effective feedback for continuous improvement of the methodology. These lists, plans and specifications we will be called "Design Control Documents".

CHARACTERISTICS OF THE DESIGN CONTROL DOCUMENTS

TASK LISTS. The designer uses this document to specify all information related to his specialty that comes from external agents and other designers, before beginning his work. This document tries to avoid unnecessary assumptions and lack of initial information about the project. The task list allows checking in advance the availability of all the input data to accomplish the design.

WORK SPECIFICATIONS. They seek to standardize information introducing presentation formats and conventions for identification of elements and documents, in order to avoid omissions and misinterpretations of information. The work specifications establish minimal information requirements for drawings and specifications, technical characteristics of materials and constructive aspects.

DESIGN PLANNING SCHEME. It establishes a logical sequence for information transfer among the different specialties and priorities for design changes. This "design planning scheme" is the framework to develop the "task lists" to help each specialist to obtain all the necessary information to start his own design process.

CHECK LISTS. The checklists are used to assure that the designers fulfil the "work specifications" and to control the parameters defined for this purpose.

CHANGE CONTROL PROCEDURES. These procedures are designed to evaluate in advance the impacts of changes on the project. They include analysis of these impacts from different perspectives within a project.

SELECTING TECHNICAL RESPONSES USING THE "HOUSE OF QUALITY"

The methodology of the "House of Quality" was applied to select the technical responses that would be the most effective to avoid the defects in the designs detected in the exploratory study. The "House of Quality" is the first matrix used by the Quality Function Deployment (Q.F.D.) methodology (Figure 4). This matrix displays the requirements and needs of the clients and the technical answers that satisfy these requirements and needs are located in the upper part of the matrix. The technical answers that satisfy these requirements are composed by the "design control documents", that is: "tasks lists", "work specifications", " Change Control Procedures " and " Design Planning Scheme ". In this case, the internal client of the designer is the Construction Company and its needs or requirements are represented by the reduction of design problems. Because of this, the registered defects were classified according to the specialties and the problem type.

The relationship between the needs of the client and the technical answers was captured in the matrix. In this case, the relationship between a design defect and a "design control document" was specified using a relationship scale. Once the relationships were established, the weight of each answer was calculated. This calculation was an interrelationship between the detection frequency of the problem and the degree of relationship with the technical response. Once the values for each technical response were known, columns were added, and thereafter the information was normalized. The result of this calculation is presented in Figure 4.

The Pareto's classification of the response to design problems is presented in Figure 5. According to the results obtained from the "House of Quality", the technical response that potentially would prevent more design defects is the "work specification" related to the elements identification (18.27%) and the drawing identification (17.25%), followed by a program of documents delivery (11.75%). These three responses address almost 50% of the defects found.

	Design Cycle				Task List					Work Specifications							
	Information Cycle	Changes Cycle	Change Control	Similarity Control	Definitions	Equipment Location	Requirements	Documents Delivery Program	Document Identification System	Formats	Elements Identification	Plans	Shaft	Technical Specifications			
Structure Elements Details		1	3					9	3		9	9		3	94	13,97%	13,97%
Lack of Architecture Detail Plans		1	1	1				9	3		9	9			86	12,78%	26,75%
Incorrect Cross References Between Different Specifications	9	9	3	9	9	9	3					9			78	11,59%	38,34%
Incorrect Structures Cross References			3					3	3		9	9			55	8,17%	46,51%
Lack of Definition of Architecture Elements					3	3	3				9	3		9	44	6,54%	53,05%
Structure-Bid-Plans Modifications		9	9	3					9						43	6,39%	59,44%
Lack of Architecture Dimensions										9					42	6,24%	65,68%
Lack of Identification and Location of Architecture Elements											9	9			38	5,65%	71,32%
Finishing Materials that Require Samples					9						9	9		3	32	4,75%	76,08%
Shaft Problems	9	9			9	9							9		30	4,46%	80,53%
Design Defects in Sewerage and A.P.			3					9	3	1	9	9			28	4,16%	84,70%
Architecture's Incorrect Cross Reference			3					3	3	1	9	9			21	3,12%	87,82%
Design Changes by the Owner		9	9	3											21	3,12%	90,94%
Electricity Design Defects			3					9	3	1	9	9			20	2,97%	93,91%
Structure Plans Late Delivery								9							13	1,93%	95,84%
Defects in A. C. Designs			3					9	3	1	9	9			10	1,49%	97,33%
Problems with Electrical Equipments					9	9	9								6	0,89%	98,22%
Equipments Structure					9	9	9								4	0,59%	98,81%
Problems with the Materials in the Market														3	3	0,45%	99,26%
Symbology Conventions											9				3	0,45%	99,70%
Gas Design Defects			3					9	3	1	9	9			2	0,30%	100,00%
ABSOLUTE IMPORTANCE	972	1728	1586	980	1482	1194	456	2505	1335	459	3897	3678	270	783	673		
RELATIVE IMPORTANCE	4,56%	8,10%	7,44%	4,60%	6,95%	5,60%	2,14%	11,75%	6,26%	2,15%	18,27%	17,25%	1,27%	3,67%			

Figure 4: Results of the House of Quality

Nº	TECHNICAL ANSWER	Weigth %	Acumulated Weigth %
1	Work Specifications .Elements Identification	18,27%	18,27%
2	Work Specifications .Plans	17,25%	35,52%
3	Documents Delivery Program	11,75%	47,27%
4	Design Cycle .Changes Cycle	8,10%	55,37%
5	Change Control	7,44%	62,81%
6	Task List .Definitions	6,95%	69,76%
7	Document Identification System	6,26%	76,02%
8	Task List .Equipment Location	5,60%	81,62%
9	Similarity Control	4,60%	86,21%
10	Design Cycle .Information Cycle	4,56%	90,77%
11	Work Specifications .Technical Specifications	3,67%	94,44%
12	Work Specifications .Formats	2,15%	96,60%
13	Task List .Requirements	2,14%	98,73%
14	Work Specifications .Shaft	1,27%	100,00%

Figure 5: Pareto's Classification of the Technical Responses.

The "design cycle" is also important (8.1%), this response tries to prevent the lack of coordination of the designs before the execution begins. On the other hand, the "Change Control Procedures" (7.44%) are designed to reduce the impacts related with designs defects detected on site, assigning a priority and a sequence, to determine how the change will affect other designers and the project itself.

RECOMMENDATIONS FOR DESIGN QUALITY ASSURANCE

The proposed methodology to improve the design for construction projects includes the development of plans and documents to assure that a series of requirements are met, in order to avoid design defects. The principal characteristics are presented below, they were defined from the analysis of the information obtained during the diagnostic phase of the research and the proposals made by professionals as well as by the authors.

A. DESIGN PLANNING SCHEME. This plan requires two different cycles.

A.1. Information Cycle. Before the beginning the first stage of the "Design Planning Scheme", it is necessary to accomplish one of the most important and critical areas that a project requires: to identify the requirements of the client. The improvement methodology assumes that the requirements of the owner are communicated to the architect in a summarized form through the "task lists" and the contractor's requirements are established in the "work specifications". An Engineer during the development of the design advises the architect with a close collaboration between them. Once the design is accomplished fulfilling the "work specifications", it is delivered to the other specialties, which receive the "task lists" that contain the necessary information to develop their designs.

Once completed, a specialty design is subjected to a "similarity control" with the higher priority specialties, in order to detect potential inconsistencies among the drawings. This process is currently called "project coordination", but the proposed scheme is different because it establishes a sequence that must be accomplished before the execution of the project. The problems detected during the "similarity control" are communicated to all the agents to generate the necessary changes to complete the design. These changes are developed during the "second cycle" of the "Design Planning Scheme" that is described in the following paragraph.

A.2. Changes Cycle. Once the "similarity control" is completed it is necessary to accomplish the necessary changes in all the specialties. As the modifications that are accomplished in one specialty can affect other specialties, the sequence of changes is selected considering the ease to accomplish the changes. Each time a specialty generates a change, this is communicated to the other designers. Finally, the changes should be delivered to architecture to verify the fulfillment of the changes and the coordination of all the design documents.

Having in mind these schemes for the flow of information and a priority order for the changes, it is necessary to know the characteristics of the Design Control Documents.

B. WORK SPECIFICATIONS. These are technical documents where requirements for design documents are established (formats, elements identification, information, drawings characteristics, etc.).

C. TASK LISTS. These lists should contain the information that the designer needs from the previous subprocess (other designer or owner). They should make references to certain criteria for specialty designs such as: location of the pipelines, type of materials, location and quantity of elements and requirements of other specialties, etc.

D. CHECKLISTS. These lists must be used to verify that the "work specifications" are fulfilled and that the parameters defined in the design are in agreement with their characteristics. The structure of the checklists is a list of questions that are answered positively or negatively.

E. CHANGE CONTROL PROCEDURES. The objective of these procedures is to control any change that is introduced in the design during the execution stage of the project. To avoid the lack of control it is necessary to define the responsibilities of the designer, contractor and owner. The designers are responsible for communicating and identifying the modifications introduced to the designs. The contractor is responsible for detecting and communicating all the design problems that affect the constructability, operation and maintenance of the projects. He should also supervise the constructability of the changes, evaluate the direct and indirect economic impact on the project and determine the variations in the project schedule. The owner is responsible for knowing and understanding the impacts of the changes and he is the only one who can approve the changes.

F. ORGANIZATIONAL STRUCTURE. To introduce continuous improvement in the design process, taking into account the temporary character of the project organizations, it is necessary to have an organizational structure that supervises and controls the development of the design process. This is a Design Control Unit that depends on company management and that participates in the development of all the projects, obtains information and supervises changes made in each one of the projects in execution. The Design Control Unit (DCU) has as objective to prevent that design mistakes arrive to the field, to do this it should have some control of the design process to be able to collect enough information in order to improve work specifications. At the same time, the evaluation of the designers through the checklists allows the generation quality records for each design office to evaluate their performance for future projects.

CONCLUSIONS

For some field professionals one of the main problems present in the designs are the errors of the designers themselves and the lack of coordination among specialties. Other problems are caused by late changes introduced by the owner and the designers, the inconsistency between drawings and specifications, the lack of construction knowledge of the designers and specifications with little technical content. These defects produce a series of impacts in construction projects such as: delays, manpower losses and inappropriate use of equipment.

The principal problem found in the designs was the lack of information. The designers did not deliver enough information on time to the construction field and to other participants in the design process. This situation showed that the designers didn't plan for the requirements of information of their internal clients when planning their own work. These findings demonstrate that the current design process is incomplete and chaotic, since it does not allow the persons in charge of the project execution the adequate knowledge of the design and it prevents the interaction among the different specialties involved in the project.

The information collected from the site showed that every time there was a change of stage in the project there was a considerable increase of design defects, as a result of errors and omissions. This situation shows that there is no anticipation of design problems before beginning execution. On the other hand, most of the problems detected were due to a wrong translation of the requirements of the owner by the designers or due to a late understanding of these requirements, producing many changes during construction. The projects that had formal systems to solve design problems such as "design inquiries logs" or "design coordinators" showed reduced response time to solve these problems and reduced relative impact on the project.

The application of the "House of Quality" to evaluate technical responses showed that the application of two technical responses: "work specifications" and "Drawing Delivery Schedule" would be effective to avoid almost 50% of the defects found. The common factor of these technical responses was the determination of the information that must be delivered by the designers, identifying the documents involved, and when this information should be delivered to the project.

The implementation of the proposed solutions has benefits for designers and construction companies contributing to avoid rework and all types of waste in both the designer office and the construction site. One construction company involved in this research has implemented these concepts to formalize its design construction interaction with significant impact on the effectiveness and efficiency of the processes. They have significantly reduced design defects and changes, these improvements have also had significant impacts on project productivity.

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