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ERRORS IN ARCHITECTURAL DESIGN PROCESS: TOWARDS A COGNITIVE MODEL

S. Safin, P. Leclercq and A. Blavier

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1. Introduction

Preliminary design process in architecture consists in defining all the properties of a building. The sketching phase, one of the first of a project, generally represents about 8% of the budget. Before and during this phase, errors are quite cheap to recover, by changing some elements on the sketches. Also, in case of huge errors, starting back the design "from scratch" could also be possible. As the process goes further, errors become quite more expensive and the recovering is very difficult. It is not possible to change concepts but only to correct it (and sometimes not completely). It is also impossible, given time and resources already spent, to come back to another big solution. Moreover, the status of error is very particular in the context of architectural design process. In fact, the major part of errors occurs not from an initial erroneous action but from the evolution of the design and of the context. This evolution of the context transforms some previous correct actions in errors with (sometimes) considerable expensive or dangerous consequences, if they are not early detected and recovered. The detection of this change from correct action to error has thus to occur as early as possible and to allow to accurately recover the error.
The aim of this paper is to provide some information about the particular status of errors in architectural (preliminary) design and the cognitive mechanisms that allow error detection in the design process. Large amount of literature in cognitive sciences has been dedicated to the mechanism of errors production, detection and recovery. Errors are well-known in the problem resolution that is the information processing paradigm. But no model has been specifically dedicated to the architectural design errors in a situationist point of view. In this paper we try to define a model based on cognitive theories on human errors, that operationalize the concept of errors, applied to architectural design, and taking in account the situatedness of design cognition.

2. Design process in architecture

Architectural project is a long process supported by several different tools (paper/pencil, CAD tools, optimization tools…). It uses several types of representation, from rough sketches to elaborated precise plans. It calls up several cognitive processes, different in nature. The architectural project can be distinguished in two main phases: the *design*, creative and conceptual, mainly individual and still based on paper/pencil sketches; and the *production* phase, consisting in precisely defining the object with a complete geometric and technical resolution, based on precise plans [Leclercq 2005]. In this paper, we are interested in the first step.
Although there exists a lot of Computer Assisted Design tools (CAD), sketches are still widely used in the early phases of design, because the sketch is ambiguous, allows multiple exploration

and a large collection of drawings [mcCall *et al*. 2001]. On the contrary CAD representations allow only one model that has to be changed. The process is destructive. The representation is judged more finite and less creative [Brown 2003]. Sketches are externalization of the though. They represent intermediate states of the design object. But, beyond this presentation and information conservation roles, they really mediate cognitive processes of design. They are cognitive artefacts [Norman 1991] allowing to extend cognitive abilities of the designer: they support reflexive thinking. The architect voluntarily keeps sketches imprecise in order to avoid being to early wrapped in an unique solution.

The design process has been described in many different ways, each integrating one of the two general paradigms describing the design process. The first one sees design as a rational problem solving process (see for example Simon [1999]). In this view, design is a process of ill-structured problem solving. The characteristics are that there's a large problem space and the solution is unknown until it is reached. Although this model is quite interesting, it is reducing the richness of design situation and particularly architectural design situation [Gero 1998, Visser 2006]. The second sees design more as a reflective conversation with the situation (See for example Schön [1983]). In this view, design is not reduced to an intentional problem-solving. The designer reflects-in-action. From this point of view, design is reflective conversation between a designer and its sketches. From the interaction with external representation, the designer makes unexpected discoveries [Verstijnen *et al*. 1998]. The design process is therefore emergent.

Numerous stage models have been defined but recent studies have shown the opportunist character of the design [Visser 2006]. Lebahar [1983] describes the architectural design process as a double movement. As the design object grows in precision, the mental model loses in uncertainty. From a wide range of possibilities, the architect tries solution with external representations. As long as he draws sketches, he defines more and more his object and he "closes doors", i.e. he reduces the uncertainty and the space of possibilities. Succession of sketches has also been studied [Goel 1995]. From one sketch to another, there could be *lateral transformations* (moves from one idea to another) or *vertical transformations* (moves from one idea to a more precise representation of that idea). We can describe architectural design mainly in terms of opportunistic constraints management. There exist many different constraints, being more ore less "heavy". The architect, in the course of the design, has to decide how to resolve some constraints, and how to make compromise between constraints. These constraints are from several types: linked to the client or building's (future) users, to technical issues (stability, acoustics…), to budget, to the building-site… These constraints are external. There are also internal constraints like aesthetics, personal brand or concepts [Heyligen and martin 2004], inherent to the architect. These internal constraints can often weight very heavy in the balance of the constraints. The different constraints are often spatially expressed [Lebahar 1983] in order to help the designer to structure and organize them. The designer can not manage all parts of the object with all constraints. When a designer is sketching, he carries out multiple actions which modify the state of the symbolic objects that he handles on paper. The object is either an element (a part of furniture like a staircase for example) or a concept which occupies a physical place in space (the kitchen for example). The architect can also handle some abstracted concepts, like aesthetic or building accessibility. Those are considered as attributes of the object. The concept of design units refers to a couple object-attribute. In fact, all design recommendations and all spaces cannot be considered at the same time by the architect. This one breaks up the problem by working on a single unit at the same time, in order to reduce his/her cognitive load. Therefore, the architect has to carry out changes in one design unit according to all the design units which (s)he thinks connected without error. A change in a design unit can affect other design units (other objects or other attributes of the same object) or even the whole design [Lee, Estman & Zimring, 2003].

3. Human error

Human error has been largely studied by cognitive sciences from a long time. Within the framework of our study, we adopt the Reason's classification [1993] which distinguishes three main types of error: slips, lapses and mistakes. This error classification is very useful for identifying the detection processes because it points out the individual's role in the occurrence of errors and thus their possibilities for detecting their own errors [Blavier *et al* 2005]. Moreover, this taxonomy allows the attribution of a possible origin to an error and to temporally locate this error in one of the three main stages that range from the conception (*planning*) to the production (*execution*) of an action sequence through a *storage* (retention) of the information. The planning involves processes that identify the goal and the ways to reach it. As an action rarely occurs directly after its planning, a storage phase (retention in memory) is generally essential between the formulation of desired actions and their execution.

- *mistakes* are due to *planning problems* (the action is executed according to the plan and the intention, but the plan is wrong)
- *lapses* result of *retention deficits* (the intention is not retrieved or recalled on time or at all)
- *slips* are the consequences of *execution problems* (the plan is correct but the execution is wrong because the action is not appropriate to the intention).

This classification was significantly improved by a link with the Rasmussen's cognitive stages [1990] which distinguish three levels of the activity control: the automatisms, the rules and the knowledge. Slips and lapses are errors based on automatisms while mistakes are based on misuse of rules or a lack of knowledge (e.g. in unfamiliar context). An example of rule-based mistake is when a designer has to dimension a beam on three supports but uses the formulas for the calculation of two beam supports. An example of knowledge-based mistake is when the designer incorrectly estimates the price of an elevator because he never designed elevator. This jointed classification (called GEMS) is one of the most famous in the literature because its decontextual aspect allows its use in all types of situations [Grant 1997, Kirwan 1998].

Within our framework, we define the design error as: *Any action and/or decision and/or declaration which carries out to a noncompatible result with the data of the problem and with the development of an effective solution from a functional, cultural and technical point of view*. This definition highlights that the error can be an action, a decision (intention) or an observation; the result of an action must be able to answer several criteria at the same time: when a criterion is not filled, then the action, the decision or the declaration becomes an error; this definition does not carry any judgement about the importance of the error.

Figure 1 schematizes the types of errors and the corresponding cognitive stages.

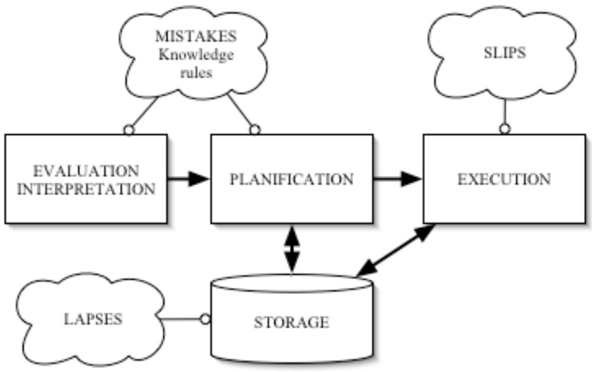

Figure 1. Types of error and levels of control

In this theoretical context, the error detection is the awareness of making an error, independently of the understanding of its nature and its cause. This error detection phase is followed by the "error identification" which is the knowledge of what was wrongly made or of what should have been made, and by the "error recovery" which implies the knowledge to recover the error effect and the means to correct it and to reach the desired state. Sellen [1994] identified three levels of error detection: (1) the detection based on the actions: the error is detected by using information resulting from the erroneous action; (2) the detection based on the results of the actions, the error is detected from the observation of the results of the erroneous action; (3) the detection due to the limitation of later functions, the error is detected thanks to information coming from the environmental constraints processing, reducing or preventing the actions of designer. These detections appear at different levels according to the action evolution. The action-based detection is the first level at which detection may occur. If the individual fails to detect from the action, the error produces some consequences and the error may be detected from these consequences. However, if the consequence-based detection also fails, the individual will be stopped in her/his action by the limiting functions. Usually, the damage from the error increases with the levels of detection: the error detected by the action will not lead to any consequence while the error detected by the consequences and by limiting functions will lead, by definition, to damages in the environment. Later the error is detected, greater are the consequences and the difficulty to recover the error.

4. Study

In order to investigate the nature of errors in architectural design, we conducted a short study by observing the sketching activity of a complex building (a school). In usual circumstances, this exercise takes several weeks of work, but it was impossible, from a practical point of view, to undertake the experiment during more than two half-days, this duration being regarded as a minimum to achieve a whole solution. During the whole experiment, a video camera filmed the documents on which the designer was working while two observers followed the exercise, silently, and noted the errors made by the designer. The definition of the error adopted for this experiment was given to the observers, and designer was asked to compose by thinking aloud.

Our result showed most frequent errors were mistakes (72%), in a more marginal way the slips (22%), then the lapses (6%). These mistakes covered a "wrong intention" or the fact that constraints from the "external world" were not considered. Among those, only 30 % were found by the designer, the remainder being found by the observers. In the majority of cases, the good result or what it should have been done was not known (72%). This was one of the causes of the non-detection of error. When the result may be known in advance, (s)he found his/her errors two times on three. Among the three modes of error detection, the detection by observing the result was mainly used. Moreover, detection was more effective when the perception of the result was outstanding and the expected results belong to a familiar situation. These findings emphasize the importance of the knowledge of the result in the detection process, however, this is impossible in the design process.

Theses results are not surprising. In fact, the majority of actions in the design process are not erroneous at the moment of their execution. But with the evolution of the design process, they are transformed in error. In this context, it is thus impossible to detect an error from the action and the principal ways to detect errors are the consequence-based detection and the limiting functions. Moreover, we showed the error was detected according to external criteria to those on which the error was made. This detection requires a broad and a complete vision of the problem. This detection mode works out if the external criteria have already been considered. Indeed, it appears clearly that the human selectivity of the data processing is an important source of reasoning errors. The mistakes occur because attention focuses on irrelevant characteristics. This cause of non-detection of error is obviously explained by the lack of knowledge, the limited mental load capacity and the lost of control of all the external criteria. All these criteria should be evaluated by a new study with expert in order to understand the process the expert uses for detecting errors

4. The error in the design process

In the light of this study and the questions it raises, we propose a model to understand errors in architecture based on cognitive theories.

As described above, in the design process, an action may be initially correct and thus not considered as an error but with the evolution of the design, this initially correct action may be transformed in a very inconvenient error. In this case, it is really important to detect the moment at which an action that was initially correct becomes an error and to study which factors help to detect this change from correct action to error. The moment of the detection is very important in terms of cost (later the error is detected, more advanced is the project and thus more difficult is to adjust the project with the new data) and in terms of safety (if the construction has already begun). In order to detect as quick as possible the errors that occur during the design process, it is essential to understand which elements are determinant in the detection of this type of error.

To understand errors in architectural design, we propose a model based on the notion of “evolutive context”. In this model, we define the context in design as “the set of elements of a situation that provide resources on which intentionality is grounded”; these elements are :

- The internal or external constraints (see above).
- The internal representation of the architectural object is the “mental model” of this object. It is constantly evolving in relation with external representation i.e. drawings, plans, mock-ups, pictures… of that object.
- The history of the design. In fact designing is managing constraints. As long as trials are made, some ways are abandoned. History of design is very important because it allows designer not to get twice in the same “deadlock”.

We emphasize the context is evolutive. It constantly changes throughout the design process. When a designer is sketching, (s)he carries out multiple actions which modify the state of the symbolic objects that (s)he handles on paper. Each action aims one of these objects and, more precisely, one of the object’s attributes (a design unit) to make it matching to the context and reaching a balance. But this context does not remain fixed. It will evolve according to the actions carried out thereafter on other design units, being able to break the balance previously reached. The designer will then have to create a new balance on this unit. Those changes cause in turn other units to become at fault and the process starts again.

In design process, every action has a main goal and thus direct and expected consequences. Nevertheless, every action also generates a lot of indirect effects on other objects. These indirect consequences, in opposition to direct consequences, are not intentionally required by the action, but are produced by the carried modifications. When the designer is conscious of the influence of his/her action on some other objects which are not directly noted, we consider that (s)he works in "a intentional context" and we call these consequences indirect expected consequences. However, some indirect effects are not necessarily considered by the designer and he discovers them when they appear: these effects are "detected but unanticipated indirect consequences". These three types of consequences (direct, indirect expected and indirect detected) occur in a conscious context. However, some consequences are not detected by the designer; they remain hidden and are considered as "undetected indirect effects". This last type of consequences belongs to the "unconscious context" (cfr. Figure 2). Each of these consequences can be positive or negative for the design.

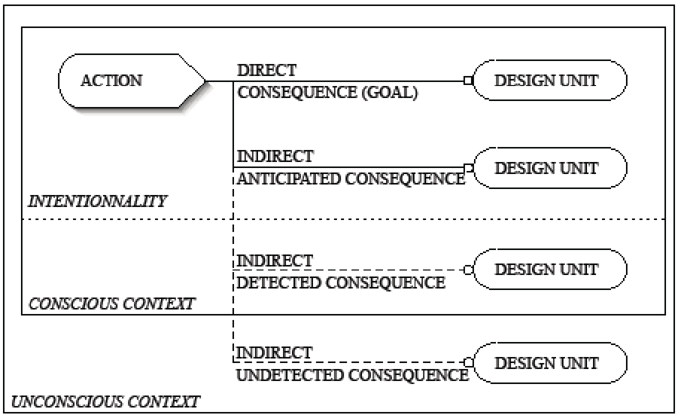

Figure 2. Types of consequences of an action in conscious/unconscious contexts

The following example from our study illustrates this schema: to allow the arrival of an important group of visitors, the airlock of a building is widened. With this intention, the designer pushes back one of the walls delimiting the initial space. (S)he modifies the [airlock] object by focusing on the increase of its [surfaces] attribute. The enlarging of the building airlock is the desired and direct consequence of the designer’s action. But by moving the partition, the designer reduces the surface of the next room. This indirect effect was probably considered by the designer and should form a part of its conscious context. Drawing again the plan with the modification (pushing back a wall of the airlock), (s)he realizes that the initial symmetry of the building is not respected any more. This indirect effect, unconscious at the beginning, becomes visible and creates a new imbalance. In addition, by an unconscious and invisible way, leads the enlarging to an incompatibility with the bearing structure of the subjacent stage. This indirect modification will be the cause of error at the time of its later discovery. A great part of errors in architectural design finds their origin in this unconscious process of indirect effects generation: during the design process, design units are continuously modified without the designer realizing. Moreover, given the state of the context, some errors can not be detectable. Indeed, some actions can have consequences that will only emerge later in the process. Consequences also can be visible (based on graphical traces) or invisible (not based on graphical traces). For example, the size change of a room is visible, directly on the sketch. The acoustic performance, on the contrary, is not directly visible. Nevertheless, it can be estimated by calculation or thanks to the expertise of the designer.

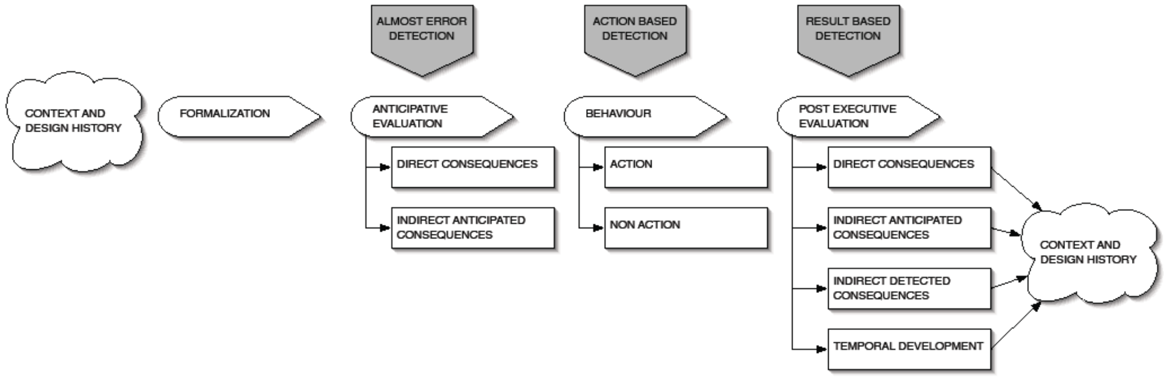

Figure 3. Decision process and error detection model in architecture

The process leading in design decisions in architecture can be described in several stages (Figure 3).

- The formulation of an intention. Based on the current state of the context, the designer tries to resolve a local problem. In this first activity he mentally identifies the "problem" to be resolved, the design unit on which he will act, and a possible action on this design unit to bring a solution. He also formalizes the direct consequence he expects i.e. the goal of the action.
- Then the designer makes an anticipative evaluation, prior to the drawing. He tries to identify the consequences of his potential action. He will seek the direct consequences, linked to his objectives, but will also try to identify the other consequences – called indirect – on this design unit and on the other design units. He identifies a set of expected indirect consequences.
- From this evaluation he will decide to act or not. He could decide to cancel the idea if the direct consequences are not those expected (his solution doesn't work for the problem) or if the negative effects of indirect consequences are more important than the positive effects of direct and indirect consequences.
- Based on this decision the designer will behave. This behaviour can be about acting, i.e. drawing, generating or modifying his ideas on his sketch. The behaviour could also be not to act. This nevertheless constitutes a behaviour and has an impact on the context (see further)
- Then the designer evaluates the results and consequences of his behaviour. If he has decided to act, he will evaluate the direct and indirect consequences of his action. In this situation, he will evaluate the gap existing between anticipated consequences and post execution consequences. As long as there were no problems into the two evaluation processes the direct and expected indirect consequences will be the same. On the other hand, the detected indirect consequences will be found here. At last, other consequences won't be detected

(undetected indirect consequences). All these consequences can be visible (graphically expressed) or not and will inevitably change the context. As a matter of fact, the external representation has changed, and the constraints have been managed (some constraints have been resolved and other may have emerged) and the history of design has changed. This process of evaluation can also lead to new discoveries, by the reinterpretation of the sketches by the designer.

- If he has decided not to act, although the sketch didn't change, the context evolves. In fact, deciding not to change a design unit will lead in a new constraint (temporary or definitive): at this moment the design unit can't be changed (in any case in this way). If this doesn't lead to a precision of the object, it reduces uncertainty of the design by hindering this type of solution. The history of design changes here. Some "doors" are closed and the area of possible actions or solutions is diminished.

This evaluation thus changes the context of the design. The context evolves in each step according to the detected consequences of the decisions and actions. The main elements of the context that evolve are:

- The constraints change according to the decisions. Some constraints are resolved, some constraints can be cancelled, and some new constraints may emerge. All these modifications in the set of constraints can be temporary or definitive. The designer has to deal with a new set of constraints
- The representations are modified. The external representation is of course modified in case of action. But the internal representation (mental model of the design object) is also different.
- The history of the design. As mentioned earlier, the design is a matter of reducing uncertainty while the architectural object grows in precision. Any decision (action or no action) changes the way design will take place, adds some constraints (not changing this design unit for example), and "close ways to the solution".

Therefore, the error can occur from several sources.

- Some errors are slips : they consist principally in a problem of execution (the drawing is different of the intention)
- Some errors are lapses (for example, problem in recovering the history of design)
- Some errors are mistakes based on rules (for example, wrong anticipative evaluation, wrong evaluation of the situation) or on knowledge (wrong intention), or on both rules and knowledge (for example, problem in the management of constraints, formalization of the context).

According to our model of decision and action in design, the different levels of error detection occur at different moments. The error may be detected when the designer formulates her/his intention and evaluates its potential direct and indirect consequences. At this moment, the error has not yet occurred and is not usually considered as an error but as an "almost error". The second moment of detection is when the action occurs. At this moment, the error detection is based on the action and principally concerns the slips. If the error is not detected at this moment, the post evaluation will allow result-based detection. This type of detection principally concerns mistakes. And in the last case, the detection will be highlighted by the limiting functions.

6. Conclusion

The concept of "evolutive context" implies that for each direct action applied to the concerned object, one or more indirect modifications are also reflected on other external objects to the initial action. The difficulties of designing are linked to the fact that the designer does not directly realize all these implications. In these circumstances, errors frequently occur. Indeed, all the concerned objects are not taken into account. If the designer does not quickly realize his/her failure, a negative evolution can remain in an uncontrolled way and can lead to the concretization of an error. The context of the design implies that the most part of errors are mistakes and the most frequent detection processes are based on consequences and limiting functions. However, the experience shows that later an error is detected, more complex and expensive is its recovery. In order to support the error detection and recovery from a computeraided point of view, it is therefore important to take into account not only the action, but also and particularly the consequences on the whole project. The importance is to help the designer to evaluate the consequences of his actions.

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Corresponding author :
Stéphane Safin
Researcher
University of Liège, Lucid Group – Lab for user Cognition and Innovative Design
1, chemin des Chevreuils, Bât B52, 4000 Liège, Belgium
+32.4.366.94.12
stephane.safin@ulg.ac.be
www.arch.ulg.ac.be/Lucid/