Schema as an architectural design operator

The case of the transformation of the morphological model

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Theme: **ARCHITECTUROLOGY**

Nowadays, considerable research is being focused on architectural design. As proof of this, we have the quantity and diversity of writings, which have been published on the subject during the past ten or so years —cf. Lebahar (1983), Boudon et al. (1992, 1994, 1997), Conan (1981, 1990), Prost (1992, 1994), etc. The convergence of three major currents of thought seems to have led to the interest raised by this object of study, namely: the design sciences, cognitive psychology, and architecturology. Following a brief description of these three approaches, the article will concentrate on the modelling process in architectural design without attempting to establish an exhaustive appraisal of the present status of our knowledge on the subject. In fact, the focus will be on the much more limited question concerning the descriptiveness of changes of state in the architectural project. Architecturology has already described some transformations thanks to operations where the *scale* acts as operator. The present article would like to suggest that, although the above modelling fits adequately so long as the morphological model remains unchanged, the said approach becomes imperfectly adaptable to the description of changes which alter the very structure of the morphological model. In such a case, it appears necessary to introduce another set of operators—the *schemata*—in order to describe the additional changes of state.

The Design Sciences

Present thinking on architectural design owes considerably to the research on "design" as initiated by Herbert A. Simon (1963). He is responsible for having formulated the idea of a modelling of design, which is common to the architect, the engineer, etc, and for having brought to light certain specific thinking processes shared by designers. Thus, Simon's essay on "The Science of Design" (1963, 1974: 73–103) demonstrates that architectural design is a field involving sub-optimal solutions or *satisficing* (since the designer generally does not have either the time or cognitive resources to reach an optimal solution, should it exist). Simon also shows that architectural design is a field of heuristics (since the designer cannot apply an algorithm or establish an inventory of possible solutions and must therefore usually imagine solution methods).

Christopher Alexander, an architect and mathematician, was one of the first to benefit from the thinking of Simon and collaborators since he considered that mathematical methods could be applied to the processing of architectural programs. His main contribution relates to the breaking down of problems into semi-independent problems. Alexander (1964) starts out with the fact that every architectural object is complex and meets a considerable number of requirements (or variables). The proposed method involves the construction of a graph whose nodes represent the variables and whose arcs represent the relations between variables. Thus, the initial problem is decomposed into semi-independent sub-problems on the basis of a division which minimizes the number of intercepted arcs. The resulting break-down permits solving each sub-problem and then reconstituting the sub-solutions found into a global form. In spite of their limitations, the works undertaken respectively by Simon (1963) and Alexander (1964) have contributed significantly to efforts to explore rationally the design process and their impact is still seen in contemporary research on the subject.

Cognitive Psychology

The second approach that is useful to research on architectural design consists of the work undertaken in experimental and cognitive psychology. Initial research, which aimed at characterizing the phases involved in the design process, was followed by research on the very nature of mental operations and on problem-solving situations. Basically, one can speak of problem-solving whenever the subject "is looking for a means to reach a goal" and the activity is guided by a *single goal* (winning a chess game, solving and equation) or by *multiple goals* (adapting the shape of a building to the implicit or explicit constraints of the project). The activity of design can also fall under the category of "ill-defined problems" (Holyoak, 1995), which necessitates referring to analogy or intuition (Cauzinille-Marmeche et al. 1985; Metcalfe and Wiebe, 1987). Studies on problem-solving came as a reaction to the debate on mental imagery. As a follow-up to the line of thought on the analogical theory as opposed to propositionalism[1] studies by Huttenlocher (1968), Carroll, Thomas and Malhotra (1980), Denis (1989) have retained the hypothesis of a functional role of the mental image for problem-solving. For example, Carroll et al. (1980) have shown that, in the solving of two isomorphic versions of the same problem (a spatial and a temporal version), it is the spatial that gives rise to more visual imagery and results in the best performances (including shorter solving times), as compared to the temporal version. In an overview of research on this question, Denis writes the following:

> When it comes to solving spatial problems, particularly when they involve a high degree of unfamiliarity, subjects will rely very spontaneously on a figurative strategy. (1989: 225)

This idea, applicable to the architect in the process of designing is borne out by independent observations made by Schmeidler (1965) and Hall and MacKinnon (1969) establishing the high propensity among architects to have recourse to imagery. The usefulness of the mental image in design is due to the fact that it allows for the "instantiating of hypotheses", a formula that can be deduced from several fundamental properties:

1. There exists an *isomorphism* between the mental image and the represented object, as shown by experiments on the transformation of the image by rotation (Shepard and Cooper, 1982) or by change of size (Bundensen and Larsen, 1975). The representation of a building is therefore isomorphic to the real building—even if the latter remains a virtual object at the moment of its design.
2. The mental image proceeds from a *selection* of the relevant information. It presents systematic differences with reality, particularly as regards "mental models" in which the information is limited only to those relations deemed useful for the task at hand (Leplat, 1985; de Vega and Rodrigo, 1997).
3. The image has a higher degree of *plasticity* than the real object. It is easier, *ceteris paribus,* to increase the surface of a project than that of a constructed edifice.

The above properties express the economy of figurative strategies. Imagery enables the architect to test constructive hypotheses more quickly and in a significantly cheaper manner than if he/she had to make a choice on the basis of a full-scale test.

Architecturology

The third approach that has given rise and has contributed much more directly to the development of research on architectural design is linked to Philippe Boudon's project (1971) for an "Architecturology". Singling out judiciously that architects often consider "theory of architecture" to be a more or less disordered set of propositions inspired by axiological judgments (on the Beautiful and the Good), Boudon has proposed that architects should concentrate on establishing a body of knowledge on architecture that is distinct from aesthetic doctrines and normative discourse. Although architecturology defends the specificity of the phenomena it analyses, it functions in the general areas of constructivist epistemologies as described by Le Moigne (1995). The preceding is evidenced in Boudon's and Deshayes' foreword (1997) to the MCX Report, where the authors recall the key areas of research on architectural design. Such research should:

1. Focus on *virtual objects* (the edifice to be built as opposed to the finished one);
2. Explore *processes instead of states* (the passage from one sketch to another as opposed to the architectural sketches themselves);
3. Consider the above processes from both the *material as well as a cognitive* point of view, an approach that counters the traditional division between the natural and human sciences;
4. Approach these processes from a "poietic" perspective (Aristotle, Valéry) implying the recognition of *goal-directed human actions*.

It is readily recognizable that here, architecturology adheres to four points which define the minimum programme proposed by the sciences of design. The limited differences that may exist are due to a few variations which affect architecturology's reticence to the linking of architectural design to problem-solving situations as called for by a long research tradition established by Newell and Simon (1972).

Limits of the Article

The three approaches, which we have just described, provide the framework for the ideas we shall be developing. If one agrees with Wittgenstein (1961) that words are more connected to *usage* than to *definitions* then one of the main difficulties of this article is to try to establish linkage between fields which, however related they may be, do not however join together in the regular and uniform usage of concepts. For example, the term "model" is known in cognitive psychology as well as in architecturology, but their use of the word coincides only partially. We have made every effort to clarify the usage of words whenever possible a confusion of this type could arise, either by recalling the accepted meaning of the word or by placing it in a given context while avoiding, if possible, to rely on neologisms.

Architectural design offers a number of characteristics (solving of ill-defined problems with multiple objectives and sub-optimal solutions), which subject it more easily to observation than to experimentation. Observation, however, gives rise to difficulties which should not be underestimated:

1. Source-models and goal-models for a given operation are rarely reflected in systematic material representations (an architect may not draw anything and still have recourse to internal memory: the resulting operations are thus inaccessible to observation);
2. The architect may carry out several elementary design operations simultaneously;
3. A single elementary design operation corresponds rarely to a single relevance. Yet—a further distinction among the three approaches described above—the project for an experimental architecturology (Boudon, 1997) has barely begun its work. It would seem premature therefore to situate the following remarks within that context, even though we should not lose sight of potential experimentation.

The changes of state for the projects presented in this article were reconstructed *ex post facto* on the basis of chronological series of architects' sketches. Let us call the consecutive states of project: e1, e2, e3... it is possible then to ask ourselves what changes intervened in between two states: e1 → e2, e2 → e3... Such an approach assumes the designer calls upon material representations (rough sketches, sketches, plans, etc.) to fix the result of an action affecting the project, although, as was stated before, that is not always the case. Consequently, the series of documents must go through a *selective process* in order to be analyzed. We assume also that such series are complete, something which is uncommon among archived documents. We can estimate, nevertheless, the *completeness* of series of graphic representations in combination with external criteria, such as their number or their chronological distribution. In short, to be useful for analysis, the series of sketches must be selected on the basis of their degree of *traceability*, that is, as regards the possibilities they offer to follow the evolution of the same architectural element (stairs, beam, etc.) through successive representations of the project. The analysis of the changes of state, which have been rendered manifest, proceeds from rational reconstructions such as those practiced in epistemology. In this specific case, the reconstruction will seek the reasons why the designer introduced a change between two successive drawings. We might describe this phase as the interpretative part of the research. We can lay down criteria to avoid arbitrary interpretation because interpretation must also be reinforced by the written or oral comments of the architect. Furthermore, the interpretation cannot contradict general knowledge on design practices. All of the above criteria were integrated into our research.

An example of operator

As regards the activity of design, Architecturology is concerned with the identification of operations expressing changes of state undergone by any edifice in the project phase. Boudon et al. state:

> The process of design is a diachronic process implying a progressive transformation of what is in project and, hence, of repeated models. In such a process the operations are that which regulate the passage from one state to another. (1994: 132)

It is useful to represent a given project through a succession of states (mental or material) spread out between an initial state and a final state for the architectural project. Between the above *extrema*, every design operation transforms a source-state into an goal-state. Both the operand and the operator of these operations can be articulated:

> The model is thus that to which the measurement operations are applied: the model is an *operand*. The operation in which the model acts as operand involves an *operator:* the scale.
>
> (Boudon et al., 1994: 131)

We shall note that in this definition the use of the word operator comes closer to the mathematical rather than the psychological tradition. For the latter the operator corresponds instead to "the one" who brings about the transformation (in the present case, the designer). Formalizing such operations is simple. On the basis of the specifics just given, we can write:

$$o_i(m) = m'$$

Operation where [m] represents the source-model, [m′] the goal-model, [o_i] the operator whose index [i] specifies the architecturological relevance (economic, functional, technical, etc.). A sequence of several design operations can be formulated thus:

$$o_k(o_j(o_i(m))) = m'''$$

Or, if we accept interpreting this more freely:

$$o_{kji}(m) = m'''$$

This symbolic transcription is not imperative but it does emphasize the constant nature of the operations. There remains to define the nature of these architectural design operations.

Definitions of the scale

In the definition mentioned *supra* (Boudon et al., 1994: 131), operator and scale are equivalent to the extent that the notion of scale is central to architecturological research. The bulk of the studies carried out since the 70's have dealt with the scale even before it had been identified as an operator in architectural design (Boudon, 1994). The importance of the scale is due to the fact that a major part of an architect's work consists of defining continuously the measurements of the projected edifice. In this sense, as the author puts it, giving measurements becomes an "irreductible function" for the architect (1992: 102). The question that logically comes to mind is obvious: "How does the architect give measurements to space?" This question calls for a wide range of answers. For example, the height of a door must take into account the height of people. It is therefore designed in relation to a *human scale*. The width of the door—which will vary depending on whether it is a bathroom or a hospital room door—will be designed in relation to a *functional scale* (since the hospital has to leave enough room for the passage of hospital beds, a constraint that does not apply to a bathroom door). The height of the door's lintel will be determined primarily by a constructive necessity; its design will then be established in relation to the *technical scale*. We can see then how the question on "how does…" leads to a compilation of modalities on the basis of which the architect attributes measurements to an architectural object.

The concept of architecturological scale, which meets that concern, requires a formulation "radical + desinence", for, in the same way we can write the latin word *doloris: dolor* (radical) + –*is* (genitive), the functional scale can be defined as: "relevance of the measurement" (radical) + "according to functional usages and constraints" (desinence). By this definition (Boudon, 1992: 171), the radical underscores how design falls within the framework of finalized actions: the *relevance* (economic, functional, technical, etc.) constitutes the teleological aim of the measurement and the criterion on the basis of which one determines whether the designed object meets or not the initial requirements (which does not imply, moreover, a mechanical correspondence between means and ends since the edifice belongs to the category of "sub-optimal solutions"). Some twenty scales have been identified to account for factors guiding the attribution of measurements. An account of these scales will be found in Boudon (1992: 134–163). It goes without saying that this division of architecturological scales is *analytical*, to the extent that the parts of an architectural work often reply simultaneously to several scales (which explains the sub-optimal nature of architectural solutions). Scales thus work in combination among themselves through *juxtaposition*, *overdetermination* or *codetermination* (Boudon et al., 1994: 198–200). For example, measurements for the above-mentioned door will obey the juxtaposition mode (human scale for the height, functional scale for the width, etc.).

If we wish to convert the scale into a modelling tool for architectural design it is necessary to add to our observations a functional definition that applies to the scale as an operator of architectural design. We shall then say that the object of this operator is to transform an operand in such a way as to endow it with greater architecturological relevance, in the sense described *supra*, and that the latter presupposes either a *qualitative* evaluation of the measurement ("a tiny living-room") or a *quantitative* one ("a 32 sq. m. living-room"). On the basis of the above, we can make the following summary: design work can be modelled by operations whose scale is the operator and whose model is the operand; the designer uses such operations to increase the relevance of the virtual object he/she is designing. Recognizing scale-based operations answers many queries concerning the architect's work. Entire facets of that activity fall under this conceptual framework. Some questions arise nevertheless as regards these operators that scales are, and it would be appropriate to examine them now.

Questions on the scale

The main question elicited by the scale arises after a reading of the basic texts. The definitions of the architecturological scale are generally linked to the measurement. The following is a sampling of such definitions:

> The choice of the instrument of *measurement* will depend on a relevance and it is such a definition which shall constitute for us the theoretical unity of the term scale: the relevance of the *measurement*, that which as a result constitutes the source from which shall emanate the diversity of particular scales. (1992: 130)

> Among the diverse meanings that the term scale can cover even outside the realm of architecture, I have chosen to limit myself to a definition of the scale understood as 'relevance of the *measurement*.' (1992: 171, my italics)

Nevertheless, it would appear that the usage of the word scale refers sometimes to phenomena which, although not fully separate from the measurement, no longer relate to it substantially. The examples of architecturological scales found in Boudon et al. (1994) provide us with an excellent case since we can find, in addition to scales applying explicitly to the measurement of the edifice, other scales—visibility scale (1994: 174), model scale (177), extension scale (179), economic scale (180), etc.—which assume a priority or a joint operation applying to *non-measurement*. Such a polysemy which goes beyond that which we find in the basic definitions suggests that architecturology has perceived the existence of operations that it does not deem useful to be defined with precision.

Let us return to the term "model" employed by architecturology. If the model is to be the operand of an operation involving either measurement or non-measurement we have every right to make a distinction between the following two cases:

1. The operation applies to the measurement, in which case the operand is integrated into the measurements of the model;
2. The operation aims at transforming another aspect of the model, in which case the model is understood in a larger sense.

The hesitation to refer to the operand of the scale by the term "measurement" (as a replacement for the word "model")

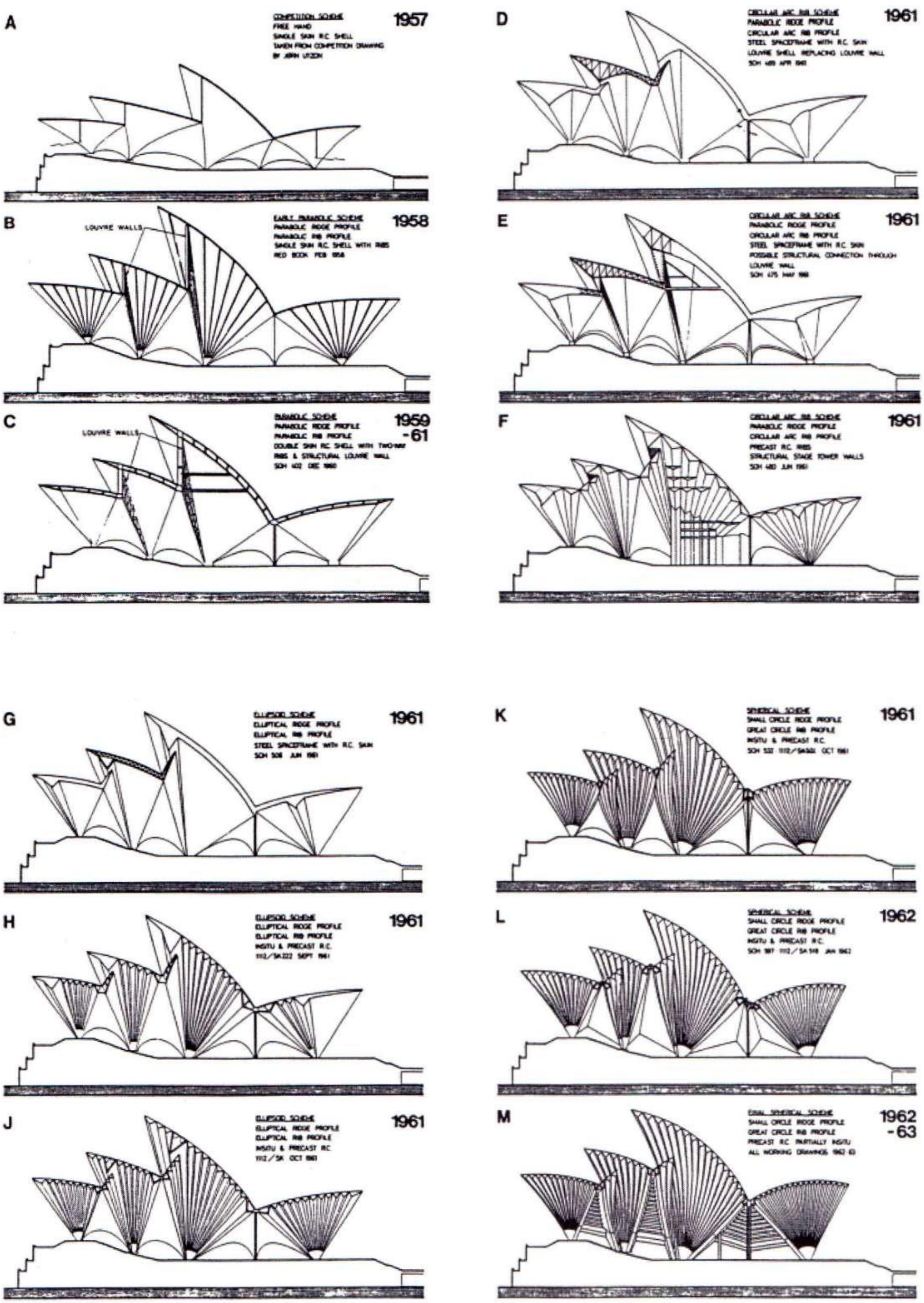

Plate 1: Jørn Utzon, *Opera House*, Sydney (1957–1963). Conservation of the model through the successive versions of the shells.
A: Free-hand curve.
B, C: Parabolic edges and ribs.
D, E, F: Parabolic edges and circular ribs.
G, H, I: Elliptical edges and ribs.
K, L, M: Circular edges and ribs.
From Fromonot (1998).

is a good indication that the non-measurable aspects of the model have also been perceived. In what follows, we shall speak of a *morphological model* to indicate this type of operand that is non reducible to measurement so as to avoid any confusion with the terminology established in architecturology. However, we do note that the term has now come closer to the sense it has in the cognitive sciences, particularly under the form of "spatial mental models" (Johnson-Laird, 1983, Denis, 1997). In this area the model is contrasted with the idea of a propositional representation meaning that there is a structural isomorphism between the characteristics of the model and the spatial properties of the object the model is meant to represent. Consideration of these questions leads us to conclude that we cannot exclude *a priori* the existence of other classes of operators in architectural design. Far from being abstract, such a distinction, in fact, corresponds to distinct design situations. Certain projects can help us perceive the basis for the preceding statements.

Let us consider the various options for the Sydney Opera House, as proposed by the Danish architect Jørn Utzon and Ove Arup and Partners between 1957 and 1963 (Fromonot, 1998). We can count no less than twelve variants for the shells. The choice of profile for the shells accounts for the difference among all the versions *(Plate 1)*. The initial shells, drawn free-style (A), are replaced by a parabolic profile (B-C), then by a circular one (D-F). The latter group was subsequently replaced by ellipsoidal triangles (G-J), and then by spherical ones generated by the same 245-ft. radius theoretical sphere (K-M). The above operations depend on a geometric scale since they aim to endow the building with dimensions based on a geometric order. Utzon himself explains this transformation:

> It is not possible to build such a complex of forms without geometric clarity, without having found some kind of harmony among themselves... I ended up extracting these forms from the same sphere. That means that when the forms are constructed in space their intersection takes place according to given laws. (1965: 87)

Here we have an illustration of a characteristic example of transformation of measurements that is not accompanied by an alteration of the morphological model. From beginning to end of the project, the two auditoriums continued to be covered by four shells: three interlocked into each other and opening up out northward on to Sydney Bay; the fourth leaning against the three others and opening up on to the city. This long reflection on the shells for the opera house did not impact the general morphology of the building and influenced only the measurements of the architectural model. We can observe an analogous fact in Alvar Aalto's sketches for the Göteborg City Hall project (1955). There we can note that the morphology of the Council Hall remained basically unchanged from the beginning to the end of the project *(Plate 2)*.

Let us imagine that Jørn Utzon had not succeeded in coming up with an elegant solution for the shell system of the Sydney Opera House and that he had begun to change the morphological arrangement by *unnesting* the shells from each other. We would then be confronted with a transformation not only of the measurements but also of the building's morphological model. The same would apply, should Jørn Utzon have abandoned the principle of encased shells and designed a parallelepiped of the Boissevain-Osmond type, third prize for the Sydney Opera Contest. The same case would have applied to Alvar Aalto, had he dropped his sketches for the council hall and opted for *joining* it side by side to the City Hall building instead of keeping the hall separate.

So it is important to make a distinction between two cases: 1) The change of state results from an adjustment of the measurements but does not alter the morphological model (the Utzon and Aalto projects); 2) There results a transformation of the morphological model (the experience of reflecting on the Utzon and Aalto projects). Let us note that the above distinction is not in contradiction with the idea there can be no model without scale (Boudon 1992: 103). There exists an obvious asymmetry between the two types of transformation: *the change of measurements does not necessarily distort the morphological model of the edifice; every alteration of the morphological model requires a correlative change of measurements.* For example, it is clear that, had Utzon replaced the Opera shells with a Boissevain-Osmond parallelepiped, he would have had to start his reflection on the relevance of measurements from scratch.

The schema as operator

Since the scale cannot be considered as the only operator in architectural design, the way is now clear for the discovery of new operators. These will probably constitute numerous

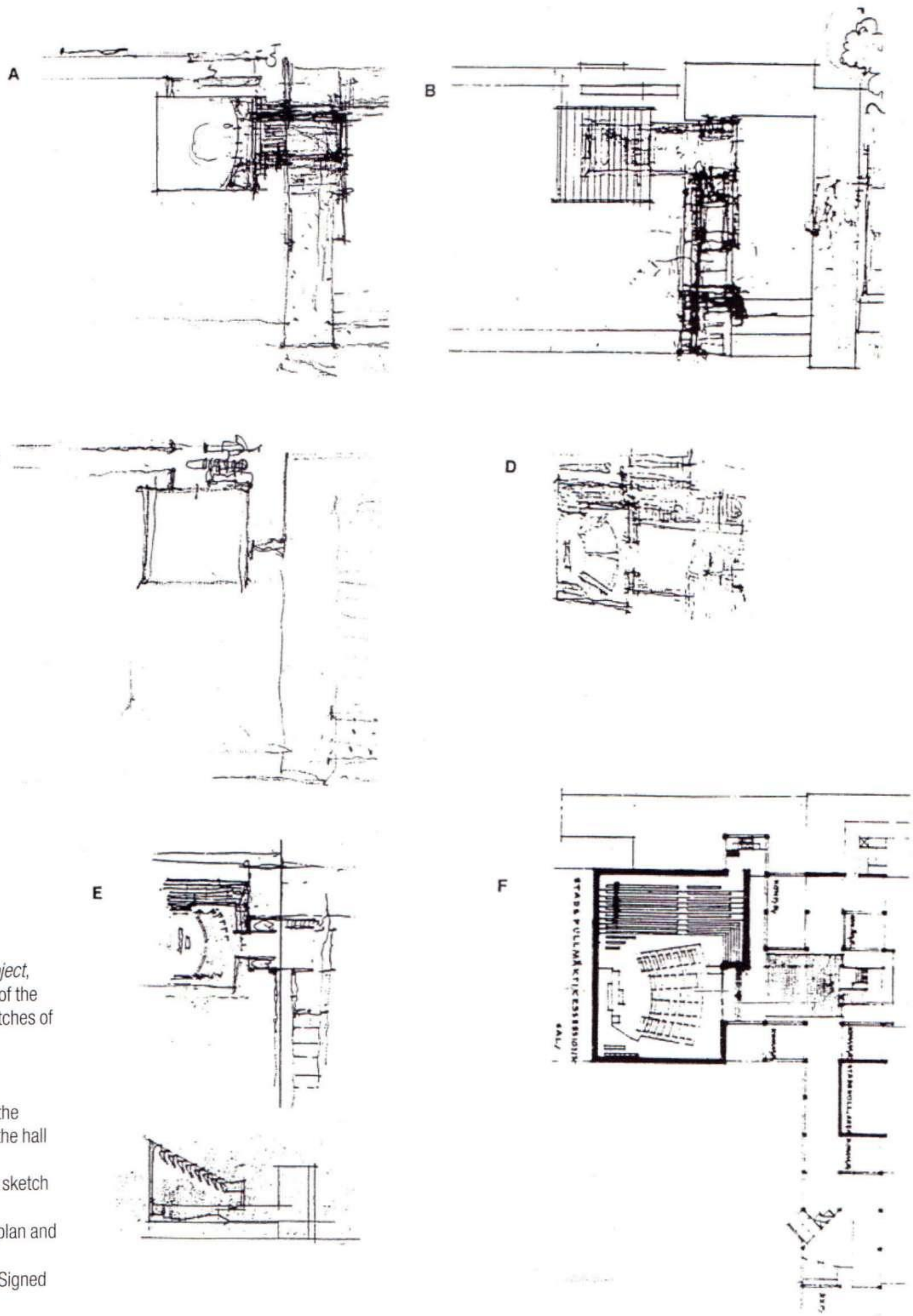

Plate 2: Alvar Aalto, *City Hall Project*, Göteborg (1955). Conservation of the model through the different sketches of the council hall.
A: First rough sketch.
B: Sketch.
C: Rough sketch with details of the components and disposition of the hall (on the same sheet as B).
D: Rough sketch of the hall on a sketch of the restaurant.
E: Proposal for the council hall (plan and section).
F: Design development project. Signed drawings. From Fleig (1974).

classes (geometric operators, topological operators, etc). Here I shall concentrate only on the hypothesis according to which "action schemata" can describe the transformation of morphological models. The notion of schema dates back to a long philosophical and psychological tradition that we cannot retrace in detail here (Kant, 1781[2]; Revault d'Allones, 1921; Piaget, 1936; Cellerier, 1979; Raynaud, 1990, etc.). Let us limit ourselves to recalling the primary characteristics *from the point of view we have been discussing*. *Primo*, as with Revault d'Allones (1921) we can retain the rule calling for a designation of the schema through an action verb. *Secundo*, it is possible to set up a list of schemata starting with a parasynonymic analysis of action verbs. The action verb chosen to qualify the schema assumes then an archilexeme status for the entire family of parasynonyms (Raynaud, 1990: 216–230). For example, the family "ascend, climb, elevate, erect, mount, perch, put up, etc." is indicative of a schema we can designate under the most general verb of the entire family, namely: "ascend". Thus, we can reduce the 8000 some usual verbs in French to around sixty schemata. Tertio, a comparative analysis applied to a sampling of 162 buildings allows one to single out from among them around twenty schemata that make it possible to generate architectural forms. Those schemata are the following, in a decreasing order of frequency: *contain, turn, ascend, radiate, cover, pass through, open, begin, separate, descend, undulate, join, enclose, take out, bind, repeat, finish, surround, diminish, cross, beat, enlarge, enter* (Raynaud, 1998)[3]. Let us now see to what extent such schemata constitute a new class of operators in architectural design.

A Hypothesis by H.A. Simon

The first reference to the hypothesis of the operator schema is to be found in the essay "Thinking by Computers" (Simon, 1966, 1992) where we find the foundations of the General Problem Solver subsequently described by Newell and Simon (1972). The author maintains therein that means-end analysis is a powerful heuristic for problem-solving. The analysis assumes the following:

1. A given situation is compared with the desired situation so as to highlight one or several differences between them (for example, you have a five meter board and you need a three meter board);
2. You carry out a memory search for an *operator* (or several) that can be associated with the difference detected (ie. *saw, plane, drill)*. The operators are linked to the differences through the outcome of experiences having shown said operators are capable of reducing or canceling the differences in question (ie. *sawing* changes length);
3. You then try and apply the operator to the given situation. Sometimes you discover that the operator cannot be used without modifying certain aspects of the situation (ie. a board needs to be held firmly in order to be sawed). In such a case, a new objective of type 1 is defined as a means to reach the desired situation (ie. *hold* board firmly) (Simon, 1992: 67).

In this text, Simon defines the notion of operator in a very general manner: "By operator I mean any process that will change the present situation." (1992: 67). And it is the general nature of the definition which has been retained—justifiably so. One can go even further and suggest that the example given by the author ultimately contributes directly to knowledge of operations in architectural design. Simon points spontaneously to operators such as *saw, plane, drill*... all action verbs which are general enough to integrate the class of schemata. Moreover, the idea that the operator changes a source-model into an goal-model corresponds—with the exception of a terminological difference—to the notion that the operator changes a given situation into a desired situation. The only notable difference between the schemata and Simon's operators is the latter act on the physical world whereas the former affect the virtual framework of design. While bearing such a difference in mind—and it is not insurmountable[4]—we are struck by the similarities. Simon's example of the joiner compels us to seriously examine the hypothesis of the operator schema which is supposed to express the transformation of a source-model into a goal-model:

$$S_i(m) = m'$$

Formally, this formulation is analogous to the one that can be applied to the scale. There remains for us to determine whether such a formulation is meaningless or whether it is apt to qualify actual facts in design. The initial arguments are provided by examples in design drawn from the history of architecture. We shall now analyze three projects, by

Philibert de l'Orme (ca. 1648), by Ludwig Mies van der Rohe (1929), and by Norman Foster (1981).

Bind, by Philibert de l'Orme

I have chosen expressly an initial example drawn from the early history of architecture in order to suggest that the hypothesis of the schema permits the description of design operations independently of the historic context, or of the specific working conditions of the profession of architect. Let us take the *Traité d'Architecture* of Philibert de l'Orme (1648). On several occasions (Books X and XI) the author speaks of an invention we can call, in a nearly neutral fashion, "composite frame", while recognizing in it also the ancestor to the glued laminated. The composite frame results from a transformation of the model for the classical basic structure:

> I want to show how to make a straight beam consisting of several sections of equal length that you wish and have to build.
>
> (*Traité d'Architecture,* XI, 8, 319a)

What is involved here is the assembly of pegs of several short pieces of board so as to reconstitute a normal length board. The resulting assembly of pieces braced together replaces a single solid beam. The reconstitution of the goal-model (conventional frame piece) can then be described by the operator *bind*:

> *Bind* (board, pegs) = beam

The preceding formulation calls for stipulating to what extent the operation it symbolizes embodies an architecturological relevance. The French renaissance architect himself gives us the reason which determined the transformation of the classical model:

> When the boards are assembled together they may be of different length, one two feet the other four. But in this manner, the junctions will be linked and adjacent to each other as is necessary to bind together best; it is also the best method to raise the beam and to add other pieces if one wishes.
>
> (*Traité d'Architecture,* X, 5, 284a)

The primary interest of the composed basic structure is that worn wooden pieces can be easily replaced. First of all, this arrangement corresponds to a technical relevance. But, in Book XI, Philibert de l'Orme also underlines another more fundamental reason as to why we should prefer the composed skeleton as opposed to the conventional model:

> We need only look at the price of the truss used to support the masonry arcs built for bridges... This is something which through this invention we could avoid doing without changing the flow of the water and by not using such a long and thick webs... In short, through this method no wood is lost as is the case with other frameworks, for the large mortise and tenon joints we are used to making on.
>
> (*Traité d'Architecture,* XI, 14, 326b–327a)

This passage is concerned with a different point of view since the architect has to watch over expenditures. The composite frame partakes also of an economic relevance.

We now need to ask ourselves if the above design operation could have been described by bringing into play the architecturological scales (in which case the schema operator would be useless). The following demonstration will provide us with a negative reply to the question. Let us assume that Philibert de l'Orme's composed frame is supposed to be applied to the rebuilding of a simple roof structure whose tie beam measures 1000 cm, the crown post 200 cm and the rafter 538 cm. By assuming the architect gave thought to the economic scale he could have also modified the internal arrangement so as to *reduce* by half the width of the frame. In such a case, the length of the frame pieces would have been reduced by half thereby making it unnecessary to proceed to an assembly of the skeleton's pieces. Such a solution abides by the same economic relevance (it renders long pieces useless), but it presents itself as an alternative solution to the one imagined by the architect. Thus, the scale alone cannot express the choice made by Philibert de l'Orme to transform the morphological model. The above example, drawn from the architecture of the French renaissance does not merit further analysis because the context for the design of the composed frame is poorly known and the documents are too scarce to enable us to draw up a precise diagnosis of this discovery. But the interest of this example is that it is adequate for giving us a general picture of an analysis of design operations, namely: 1) identification of the schema; 2) identification of the relevances to which the schema corresponds; 3) consideration of the potential for reduction of this description to the scale. We shall now apply the analysis to more recent and better documented examples.

Separate, by Mies van der Rohe

The name of Mies van der Rohe (1886–1969), the German architect who emigrated to the United States in 1938, remains identified with the design of the "open plan" which frees walls from their bearing function while transforming them into mere screens. Mies van der Rohe seems to have discovered the structure while working on the project for the German pavilion at the Barcelona World's Fair (1929). Here is how the architect describes the background to his discovery: "One evening, since I was still working on it (the pavilion), I began to draw a self-bearing wall and I had a shock. I had just stumbled into a new principle..." (Mies, 1952: 28). By resorting to the system of the "open plan" he transforms the conventional model of the wall which, until then, was supposed to bear the load of the roof. Such a transformation can be described by an operation expressing the passage from source-model to goal-model. Conventional design of a bearing wall means the wall serves two purposes: 1) as a structural element (bearing the loads of the roof and/or of the floors above), and 2) as an element of spatial separation (isolating one space from another). The "open plan" system involves, on the contrary, a concrete rendering both from the spatial and constructive points of view of the two distinctive functions of a bearing wall. Stricto sensu, one should reserve the term "screen" or "partition" for those walls standing alone in order to avoid any confusion with the conventional idea of a wall; similarly, it would be better to speak of a "pole" or of a "vertical support" to avoid any possible linkage with the column. At the Barcelona pavilion the structural function was assumed by eight cruciform stainless steel poles; the spatial separation function will be handled by onyx partitions freely disposed in space[5]. The above discovery must be placed between drawing I and drawing II, both dated 1928 *(Plate 3,* B-C). The eight cruciform poles appear, in fact, only in the second document. The passage from source-model to goal-model can be described by the operator *separate*:

Separate (bearing wall) = screen, pole

Does the operation, as symbolized by the preceding formulation, have an architecturological relevance? The name "open plan" points us in the right direction since an independent load bearing structure allows for the adjustment of the position of the screen with greater precision as regards the purpose of the spaces (since, strictly speaking, "screen" no longer has a technical role). Here, we can recognize a functional relevance defined on the basis of an architectural space determined in relation to its destination, its utilization, its usage. In other projects, such as the Tugendhat House in Brno (1930) Mies van der Rohe *separates* once again poles and screens while exploring variations which instead of affecting the form as such—he uses the same stainless steel cruciform poles again—have an impact on the nature of the design activity. Jean-Louis Cohen has clearly seen "the play of the dividing walls and the facades with the vertical supports has become more difficult and complex than in Barcelona" (1994: 62). We can also notice that the villa's east gable poles are around 20 cm behind the glass partition. The poles cut from view the bay window's casings since the latter are placed on the axis of the poles. An elegant solution indeed for, had the architect placed these poles on the plane of the bay window, the casings would have had to be fixed on the flanges of the pole, with a resulting reduction of the field of vision. The schema involving a dissociation of screens and poles is accompanied, at the Tugendhat House, by a surprising reflection on the optical relevance and on the relevance of the visibility of the arrangement (showing the landscape instead of the casings; adjusting the position of the cruciform poles in relation to a viewpoint). The schema that consists of separating poles and screens thus complies with several relevances: functional, optical, of visibility.

There remains to determine if the schema is necessary to describe the preceding design operation. We can begin to see the answer thanks to a simple observation. Should Mies have had the same thoughts on the functional scale as he did in Barcelona, he could have opted also for *not separating* the poles and the screens. He would have then freely adapted them to the rooms and would have crossed the distance between the bearing walls and the beams with variable length girders (a common design tactic among architects). Similarly, at the Tugendhat House, the visibility scale could have led Mies not to separating the casings from the cruciform pole but rather to *fixing* the latter against the exterior wings of the pole. The executed operation cannot therefore be articulated in terms of scale. Here, the scale informs us on how and on which basis the architect gives measurements but not on how he/she transforms the morphological model. The schema *separate* is so closely identified with Mies'

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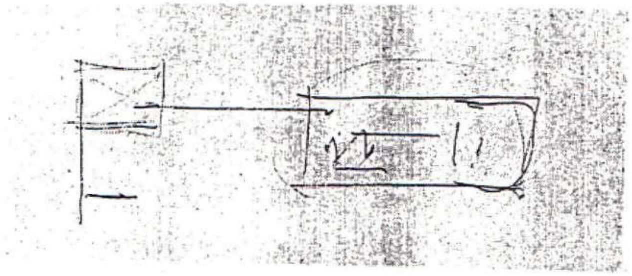

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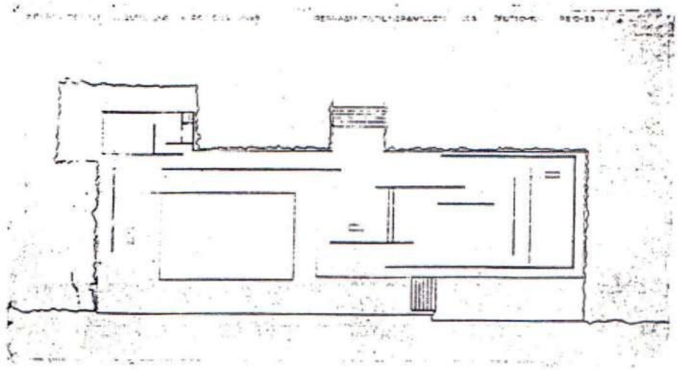

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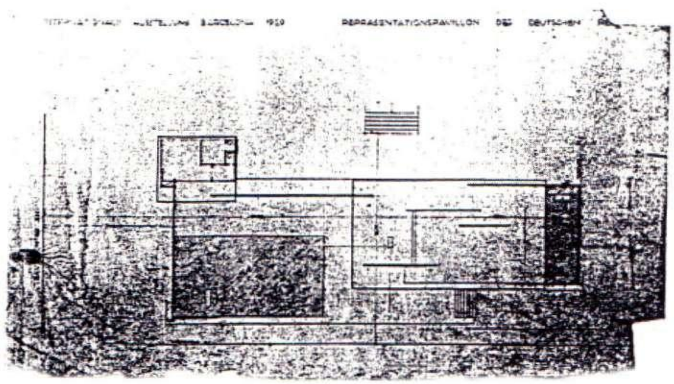

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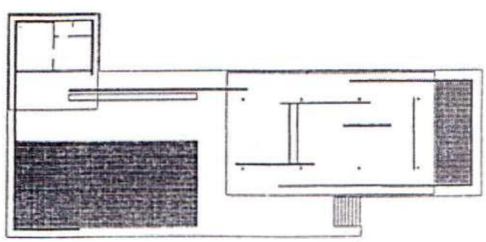

Plate 3: Mies van der Rohe, *German Pavilion*, Barcelona (1928–1929). Genesis of the screens + poles' system.
A: Rough sketch.
B: Plan I, pencil on tracing paper, 1928.
C: Plan II, black and colored pencils on tracing paper, 1928.
D: Final drawing for the German pavilion. Signed drawings, Mies van der Rohe Archives, New York, Museum of Modern Art. From Zukowsky (1987).

projects that some historians have used it as a starting point for commentaries on his projects of the 30's. Frampton, for example, summarizes Mies' edifices by a series of antinomies:

> pillars as opposed to flat surfaces, tectonic as opposed to atectonic, opaque as opposed to translucent, tranquility as opposed to agitation, open as opposed to closed, and even, architecture as opposed to construction.
>
> (in Zukowsky, 1987: 47.)

Take out, by Norman Foster

The Hong Kong Banking Corporation project, whose work site was completed in 1986, is one of the best known productions by the British architect Norman Foster. It constitutes one of the most salient creations in high tech architecture. Design of the project lasted from 1979 to 1981. There were four working hypotheses envisaged successively for this project. In the initial 1979 proposal the designers settled on the idea of four bays linked by concrete pillars in H formation into which the services were introduced *(Plate 4,* A). This version was abandoned in May 1980 in favor of the so-called "chevrons" version. In this hypothesis, comparable to the system of suspended bridges, the platforms for the different floors were suspended by cables attached to lateral steel columns. This second project was also dropped due to the image of downward pointing chevrons which, in the eyes of the bank directors, was incompatible with the rules of *Feng shui*. A new project, called "organ pipes", was designed by the architects in July 1980. As the architect writes, this solution "found itself at the origin of the slender towers effect on the east façade" (Foster 1989: 33). Finally, a last project elaborated in the beginning of August 1980 was approved formally by the governing board in January 1981. Each of the above four versions bears the trace of the famous distinction established by Louis I. Kahn between "servant area" and "served area". From the outset the platforms of the served area were contained to the east and to the west by two "walls of movement" where the servant area was lodged. The elevators, the stairs, the toilets, and the pipe ducts were in contact with the building's envelope.

If we now focus on the placement of the fire-escape stairs in the eastern façade, we can note that they migrated throughout the entire project. In the first proposal, the stairs are set back from the platforms *(Plate 4,* C). In the "chevrons" version, the stairs are at the level of the structural elements with a given degree of uncertainty as to their exact location. In one sketch the stairs are half-encased into the platform *(Plate 4,* D) whereas in the scale drawing, the servant area consists of autonomous cells attached to the building skin *(Plate 4,* E) which the designers team named "pods" (Foster, 1989: 136). Lastly, starting with the "organ pipes" version the stairs will be jutting out from the platforms, a feature that will be further accentuated in the definitive version *(Plate 4,* F-G). The migration[6] of the fire-escape stairs from the interior to the exterior of the outer envelop can be described by the operator *take out*:

> *Take out* (stairs, façade) = exterior stairs

It would be appropriate now to look for the architecturological relevances of this operation. The first explanation for the abandonment of the stairs on the façade resides in the goal of flexibility for the platforms (Foster, 1989: 204). The architect accounts for the positioning of the servant areas on the east and west façades in order to "leave a vast extension of the work area uninterrupted". He adds that "structural towers on each side of the building were seen as containing also the served area of the building, thereby leaving the wide-sized floor boards free from any obstruction" (Foster, 1989: 136). The above functional relevance is supplemented by two other determinations. In the first place, from the beginning of the project the architects had been reflecting on a façade that would offer deep contrasts of shade and light *(Plate 4,* B). In this regard, the "organ pipe" hypothesis is qualified by one of the collaborators—Tony Fitzpatrick—as "an exercise to settle the problem of shade" (in Foster, 1989: 33). Projecting the fire-escape stairs out from the building's façade is a clear example of such efforts. The relevance on the visibility point of view is accompanied in turn by a consideration of the constructive solutions. The concrete or steel pillars of the initial versions were replaced by "structural masts" consisting of a cluster of four vertical elements linked to each other—identifiable on the drawing through four round studs *(Plate 4,* G). In order to avoid any overlapping between the Saint Andrew's crosses which ensure the wind-bracing of the masts and the servant area, two solutions could be envisaged: either relocating the services area inside the structural masts; or else, pushing them further outside the structural masts. The second hypothesis was

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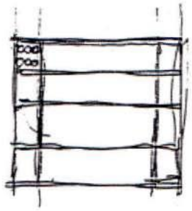

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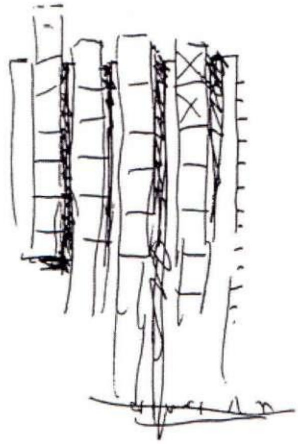

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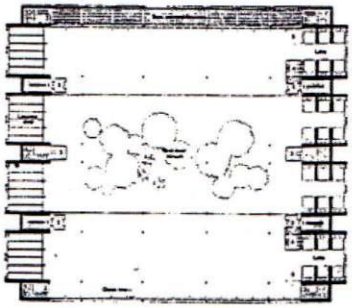

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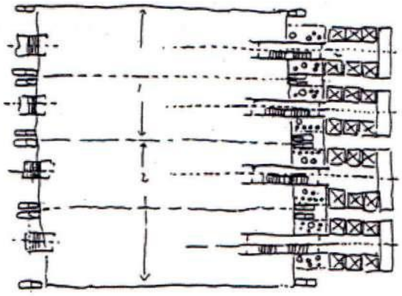

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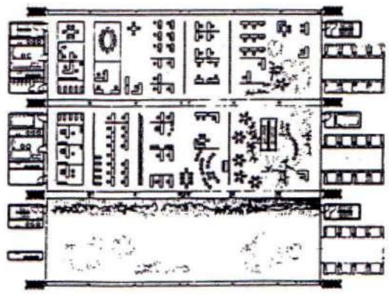

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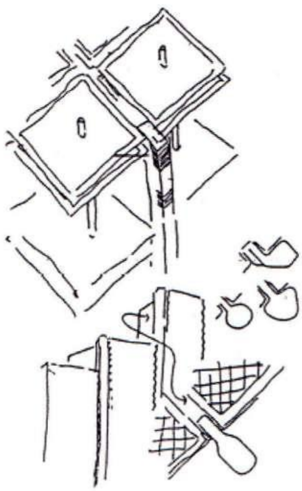

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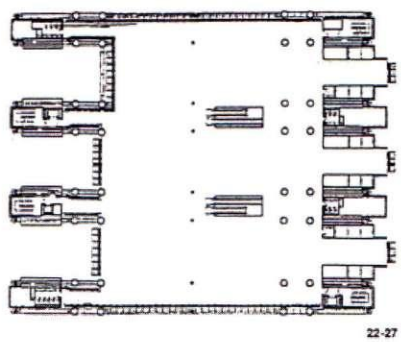


Plate 4: Norman Foster, *Hong Kong Bank Headquarters*, Hong Kong (1979–1981). Changes in fire-escape stairs through the different versions of the project.
A: Initial proposal, 1979.
B: Play of shade on the east façade.
C: Plan for the original proposal.
D: Rough sketch for the "chevrons" solution, 1980.
E: Plan for the "chevrons" solution.
F: Rough sketch for the "organ pipes" proposal, 1980.
G: Floor plan of the final project, 1981.
Foster Associates Archives.
From Foster (1989).

adopted since it was more in harmony with the idea of the flexibility of the platforms and the preference for accentuated shadows. This hypothesis also underscores the protuberance of the fire-escapes on the façade *(Plate 4*, G). Thus, in Foster's Hong Kong Bank project, the schema *take out* corresponds to three relevances: functional, technical, and of visibility.

Let's ask ourselves, nevertheless, if the schema is necessary for undertaking the present analysis. As with the Mies project examined before, the present project seems to provide evidence concerning an aspect of the design process which cannot be described in terms of scale. For example, consideration of the visibility scale by the architect could have just as well led the Foster and Partners Bureau to adopt another hypothesis, namely, *bringing* the fire-escapes *back inside* to be level with the façade, and placing a sun breaker on the façade so as to obtain the expected shadow and light contrasts. Therefore, although the scale can express adequately certain transformations it cannot expect to describe the transformations affecting the morphological model.

Conclusions

In spite of the inherent limitations of any *ex post facto* reconstitution of design operations based on chronological series of sketches, the study of architectural projects shows that the distinction we proposed in II.2 is valid. Thus,

1. There are cases where the morphological model is not adulterated in the course of the process of design. Design operations involve then the measurement (the Jørn Utzon and Alvar Aalto projects) and can probably be interpreted within the conventional framework of architecturology.
2. There are cases where the morphological model undergoes transformations other than a dimensional adjustment (the Philibert de l'Orme, Mies van der Rohe, and Norman Foster projects). In such a case, it becomes necessary to describe the changes of state by other operators in architectural design, namely, the schemata.

Let us observe that it is highly unlikely that the three action schemata identified here *(bind, separate, take out)* would be the only ones able to account for an operation on the models. Archived documents can readily provide us with other examples. Let us quote the case of two Swiss architects, Herzog and Meuron. Recently, they designed a house for a quite narrow lot whose center was occupied by a very old paulownia. Since they wanted to keep the tree, they distorted the façade so as to be able to *avoid* the tree trunk; the distortion called for a reference to the parcellar relevance. The list of examples could be extended so far that it would be more reasonable to admit that the list of such operators can be merged with the list of schemata we have drawn from a parasynonymic analysis of action verbs (cf. *supra* III).

The projects examined in this article suggest the architect calls regularly on design operations that affect the morphological model of the edifice. The apparently regular and general character of such operations—or "virtual objects manipulations"—can be highlighted by the following formula:

$$S_i(m) = m'$$

On the other hand, the symbolic meaning of the formula does not fail to raise certain questions concerning the modelling of design operations. At the beginning of the article we accepted the position whereby scales are *operators* in design (Boudon, 1992: 179–180. Boudon et al., 1994: 131). Subsequently we submitted the idea schemata constitute a second class of operators. Resorting to the concept of operator to express changes of state in the design sequence raises some problems which merit our examination.

The first question raised applies to the usage of the word operation. In the hard sciences having recourse to this notion implies *ipso facto* one is in a position to determine the result of the operation. An equation of the type $y = ax^2 + bx + c$ obviously can meet such a condition. In architectural design the use of operations implies that the knowledge of the source-model, of the operator, and of the relevances should permit the reconstruction of the goal-model. Architecturology has moved apart from such an orientation. It prefers to introduce a degree of flexibility with respect to the notions of operation, operator, and operand so as to avoid reflecting on the determinability of the goal-model. Another reply which could be put forth is based on the fact—admitted by some—that design is a space of finalized actions. A preliminary observation is in order: the *goal*, prior to merging with the *result*, must be taken for what it is, namely, a mental representation anterior to the action. Therefore, the goal is not identical to the result although one must admit that a designer with a minimum amount of experience catches a glimpse, via the goal, of the result of the operation he is about to undertake. Goal and result must be concordant at least in a "good enough" manner, as Herbert A. Simon puts it (1982). To suppose the contrary would amount to pretending that the joiner who planes down, the surgeon who operates, or the architect who designs act half-hazardously within a context of non-finalized actions. The next question would be that of knowing why they act if they know they cannot reach any goal. The fact that architectural design involves the solving of ill-defined problems with sub-optimal solutions—including the introduction of a distance between goal and result—does not mean, however, that one must do away with the idea design is a space of goal-directed actions. This argument incites us to continue speaking of design operations.

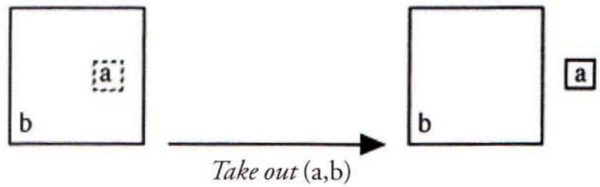
The second difficulty will be found in the meaning attributed to the expression *determination of the result* in the context of these operations. If one interprets such determination *stricto sensu*—that which imposes a complete knowledge of the result—it goes without saying that the operations relative to the scale or to the schema do not belong to such a category. The obstacle can be overcome, however, if we understand the expression in the sense of determination *from a given point of view.*

Primo, it would be useful to recognize that total determination is an utopia. Mathematical operations give us such a feeling of determination of the result because the mathematical point of view is *unimodal*: it establishes a clear demarcation between what must be determined and what is subtracted from the operation. Thus, the mathematician in the process of solving an equation is not in the least concerned with the form of the characters, the color of the ink used, or the potential objects in the real world to which the equation could be applied. Anyone can therefore follow the development $(a+b)^2 = a^2 + b^2 + 2ab$, without imagining for a second that it could serve to calculate the increase of a square's surface. The fact that *a* and *b* can represent measurable quantities in meters is simply indifferent to the mathematical point of view.

Secundo, it is necessary to examine how the idea of determination is applied from a given point of view to architectural design. Contrary to the mathematician, whose point of view is clearly marked out, the architect has to specify the architectural object in reference to several points of view. Not only must the architect give forms and measurements to the edifice, but he/she also has to choose materials having a certain texture, a certain color, etc. The solution of architectural design problems is therefore *multimodal.* Such a characteristic does not impede speaking about determination of the result so long as the point of view is clearly specified. As an illustration, let us transcribe the schema imagined by Norman Foster:

Take out indices (stairs, building) = exterior stairs

For greater clarity, the above schema can be associated with the following representation:



One must admit that the architect who shifts the stairs outside the envelope of the building knows, *by anticipation,* that they will be located in the exterior of the building. Similarly, if we go back to the Mies van der Rohe pavilion, anyone dissociating bearing walls and screens knows, *by anticipation,* that they will be separated. Once the point of view is specified—in the present case, it applies to morphological changes and not those that could be found in a system of geometry, of measurements, of materials, etc.—the goal model can be known on the basis of the source model and the operator. The goal-model is then well *determined* under the specified point of view. The object of the determination here is the position aimed at or the direction of the variation [7].

On the basis of the preceding remarks we can now envisage an articulation of schemata with the architecturological model. For though it is true that there can be a change of measurements without changing the morphological model, the opposite is false. *There can be no change of the morphological model without a correlative change of the measurements.* And that is why the preceding description calls for a corresponding description of the change of measurement. The schema *take out* (stairs, building) asks the following question: "How far must we take out the stairs ?" Similarly, the schema *separate* (bearing wall, screen) asks: "How much must we separate the bearing wall from the screen?" The scale operator provides an answer to those questions. It is up to architecturology to interpret those phenomena before which the model of the schema remains silent. Let us note however that such operations on morphological models and on measurements can be distinguished only through an analytical process. For the architect in the process of designing there exists no chronological distinction between a phase of morphological operations and a phase of attribution of measurements. Those reflections are simultaneous. They open the way to an articulation of the scale and of the schema in design if, indeed, the difference of position on the predictability of the result of design operations can be reduced.

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Footnotes

1. Since the 70's there have been two opposing approaches as regards the nature of internal images. Kosslyn (1980) has defended the hypothesis of a specific format for representation. Pylyshyn (1981) has supported the idea of a reductibility of the image to the propositional format. The difference between the two conceptions can be expressed in several manners. From a syntactic point of view: images are subject to spatial relations (topological or metric) *versus* names belong to classes (entities, properties, logical relations). From a semantic point of view: there exists, in one approach, an iconic ressemblance between the image and the object *versus* there exists, for the opposing approach, an arbitrary relation between the name and the object. The above controversy seems to have now reached a concluding phase which, on a neurological basis, weights against the arguments of propositionalism (cf. Kosslyn's conclusions, 1994, and 1995: 290–293).
2. Kant, who introduced the notion, treats it as "a *monogram* of a priori pure imagination through and according to which images are at first possible" (1944: 153).
3. For the complete list, cf. Raynaud (1990: 273–279). Arguments have been made (1990: 231–252) in favor of describing every schema on the basis of four variables—number of actants (N), proximity (P), dimension (D), and symmetry (S)—an option that would offer an alternative solution to the conventional breakdown into action primitives.
4. There exists considerable experimental data supporting the thesis there is a structural isomorphism between representations and the perceptible events on the basis of which the representations were made. We can refer to the experiments on "mental rotation" undertaken by Shepard and Metzler (1971) and Shepard and Cooper (1982) in which a subject is asked to judge whether two objects presented from different perspectives are identical or not. The linear function existing between the deciding time and the angular difference for the presentation of the objects suggests the subjects undertake a mental rotation isomorphous to the rotation that would be applied to real objects. One can consider that representation offers the designer the possibility of carrying out "symbolic manipulations analogous to real manipulations and which provide the subject with symbolic equivalents of physical states resulting from actual manipulations" (Denis, 1989: 226). There is no reason to opposing the real actions of Simon's joiner to the virtual actions of the architect.
5. Let us note that this discovery was in the making in preceding projects. The text accompanying the 1922 project for the Concrete Administrative building, published in the very first issue of *G [Material zur elementaren Gestaltung]* states the following: "The materials: concrete, steel, glass. Reinforced concrete structures are skeletons by nature... The poles and beams eliminated bearing walls. This construction is composed of a skeleton structure and a skin." (Mies in Zukowsky, ed., 1987: 44). The same preparatory formulas appear for the Weissenhof Housing building (1926), which adopts an independent steel structure. The architect states: "In this case, the skeleton structure construction is the best adapted construction system. It can be produced in a rational manner and leaves full freedom for the division of interior spaces" *[Der Skelettbau ist hierzu das geeingneteste Konstruktionssystem. Er ermöglicht eine rationelle Herstellung und lässt der inneren Raumaufteilung jede Freiheit]* (Mies in Zukowsky, ed., 1987: 65). It is possible—though not proven—that Lilly Reich, Mies' collaborator between 1926 and 1938, might have influenced the above reflection on atectonism by the German architect. She had, in fact, studied under Josef Hoffman at the Wiener Werkstätte in 1902.
6. Two historical remarks are in order as regards the present analysis. Firstly, the Hong Kong Bank takes its inspiration rather directly from the Louis I. Kahn design of the Richards Medical Research Laboratories where we see a façade that comes close to a Norman Foster hand rough sketch *(Plate 4,* B). Secondly, at

the time, the Foster Office designed several buildings utilizing the same distribution system. The Billingsgate Market in London (1981) offers us a case that is similar to the initial bank project *(Plate 4,* C). As for the Louisville Humana Competition project (1982), we can say that it resembles the definitive solution adopted by the bank *(Plate 4,* G) since a cylindrical tower (served area) is flanked by two service blocks (servant area) (Foster, 1989: 81).

7. This does not mean that the word determination has been weakened. If, in relation to the schema *take out*, we take a position around the envelope of the object *b*, we can measure the position p of *a* on a perpendicular axis to the surface of *b*. Let us determine an origin (the interior-exterior limit) and a direction (negative values in the interior). It then becomes possible to define the function: $f(p<0) = -1$, $f(p=0) = 0$, $f(p>0) = +1$. The approached position of *a* will have a value of +1 (that of the operation *enter* has the value −1). Other possibilities exist in order to establish a more general characterization of the schema. Let us consider the smallest convex envelope (SCE) containing all of the objects to which the operation applies. Between the source-state and the goal-state, the operation will affect the volume of the envelope: $E \rightarrow E'$. We can define again a variation domain and a function such as: $f(E'>E) = -1$ (the volume of the SCE increases), $f(E'=E) = 0$ (SCE volume is identical), $f(E'<E) = +1$ (SCE volume decreases). Under such conditions, the schemata *take out, open, radiate, cut, enlarge, separate,* etc. determine the value of symmetry $S = -1$. Such reasoning serves as the basis for a classification of "divergent", "avergent", and "convergent" schemata (Raynaud, 1990: 239–245; 1998: 133–135, 138).

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References

ALEXANDER C. (1964) *De la synthèse de la forme,* Paris, Dunod.

BOUDON Ph. (1971) *Sur l'espace architectural. Essai d'épistémologie*, Paris, Dunod.

BOUDON Ph. (1992) *Introduction à l'architecturologie*, Paris, Dunod.

BOUDON Ph. (1994) Existe-t-il des opérations de conception architecturale? in Prost R. (éd.) *Conception, invention, création*, Paris, L'Harmattan.

BOUDON Ph. (1997) *Sémiotique architecturologique et architecturologie expérimentale*, fasc. 2, Rapport final quadriennal, Paris, LAREA.

BOUDON Ph. et al (1994) *Enseigner la conception architecturale. Cours d'architecturologie*, Paris, éditions de la Villette.

BOUDON PH. ET DESHAYES Ph. (éds.) (1997) *Les sciences de la conception sont-elles enseignables ?* Dossier MCX 12, Aix-en-Provence, Association européenne du Programme Modélisation de la CompleXité.

BUNDESEN C. ET LARSEN A. (1975) Visual transformation of size, *J. of Experimental Psychology*, 1, pp. 214–220.

CARROLL J.M., THOMAS J.C. ET MALHOTRA A. (1980) Presentation and representation in design problem-solving, *British Journal of Psychology,* 71, pp. 143–153.

CAUZINILLE-MARMÈCHE E., MATHIEU J. ET WEIL-BARAIS A. (1985) Raisonnement analogique et résolution de problèmes, *Année psychologique*, 85, pp. 49–72.

CELLERIER G. (1979) Structures cognitives et schèmes d'action, *Archives de psychologie*, 47, pp. 87–122.
CHASE W.G. ET SIMON H.A. (1973) The mind's eye in chess, in Chase W.G. (ed.) *Visual information processing*, New York, Academic Press.
CHI M.T., FELTOVICH P.J. ET GLASER R. (1981) Categorization and representation of physics problems by experts and novice, *Cognitive Science*, 5, pp. 121–152.
COHEN J.L. (1994) *Mies van der Rohe*, Paris, Hazan.
CONAN M. (1981) *Les processus de conception architecturale*, Paris, Plan Construction.
CONAN M. (1990) *Concevoir un projet d'architecture*, Paris, L'Harmattan.
DENIS M. (1989) *Image et cognition*, Paris, PUF.
DENIS M. ed. (1997) *Langage et cognition spatiale*, Paris, Masson.
FLEIG K. (1974) *Alvar Aalto*, Zürich, éditions d'architecture Artémis.
FOSTER N. et al. (1989) *Buildings and projects*, vol. 3 (1978–1985), Hongkong, Watermark.
FROMONOT F. (1998) *Jørn Utzon et l'Opéra de Sydney*, Paris, Gallimard.
HALL W.B. ET MACKINNON D.W. (1969) Personality inventory correlates of creativity among architects, *Journal of Applied Psychology*, 53, pp. 322–326.
HOLYOAK K.J. (1995) Problem solving, in Smith E.E. et Osherson D.N. (eds.) *An invitation to cognitive science*, vol. 3 : *Thinking*, Cambridge, The MIT Press, pp. 267–296.
HUTTENLOCHER J. (1968) Constructing spatial images : A strategy in reasoning, *Psychological Review*, 75, pp. 550–560.
JOHNSON-LAIRD P.N. (1983) *Mental models : Towards a cognitive science of language, inference, and consciousness*, Cambridge, Cambridge University Press.
KANT I. (1944) *Critique de la raison pure*, trad. A. Tremesaygues et B. Pacaud, Paris, PUF [1781].
KOSSLYN S.M. (1980) *Image and mind*, Cambridge, The MIT Press.
KOSSLYN S.M. (1995) Mental imagery, in Kosslyn S.M. et Osherson D.N. (eds.) *An invitation to cognitive science*, vol. 2 : *Visual cognition*, Cambridge, The MIT Press, pp. 267–296.
KOSSLYN S.M., BALL T.M. ET REISER B.J. (1978) Visual images preserve metric spatial information : Evidence from studies of image scaning, *Journal of Experimental Psychology*, 4, pp. 47–60.
LEBAHAR J.C. (1983) *Le dessin d'architecte. Simulation graphique et réduction d'incertitude*, Marseille, Parenthèses.
LE MOIGNE J.L. (1995) *Les épistémologies constructivistes*, Paris, PUF.
LEPLAT J. (1985) Les représentations fonctionnelles dans le travail, *Psychologie française*, 30, 3–4, pp. 269–275.
MANDLER J.M. (1984) *Stories, scripts and scenes : Aspects of schema theory*, Hillsdale, Lawrence Erlbaum.
METCALFE J. ET WIEBE D. (1987) Intuition in insight and noninsight problem solving, *Memory and Cognition*, 15, pp. 238–246.
MIES VAN DES ROHE L. (1952) 6 students talk with Mies, *North Caroline University State College, School of Design Student Publication*, 2, s.p.
NEWELL A. ET SIMON H.A. (1972) *Human problem solving*, Englewood Cliffs, Prentice-Hall.
NEWELL, A. (1990) *Unified theories of cognition*, Cambridge, Harvard University Press.
ORME PH. DE L' (1981) *Traité d'architecture*, Bruxelles, P. Mardaga [1648].
PIAGET J. (1936) *La naissance de l'intelligence chez l'enfant*, Paris, Delachaux et Niestlé.
PROST R. (1992) *Conception architecturale : une investigation méthodologique*, Paris, L'Harmattan.
PROST R. (éd.) (1994) *Conception, invention, création*, Paris, L'Harmattan.
PYLYSHYN Z.W. (1981) The imagery debate : Analogue media versus tacit knowledge, *Psychological Review*, 87, pp. 16–45.
RAYNAUD D. (1990) *L'imagination architecturale*, vol. 1. *Méthodologie et études*, vol. 2. *Essai de schématologie*, thèse de doctorat, Grenoble, Université Pierre-Mendès-France.
RAYNAUD D. (1992) La conception architecturale : un processus séquentiel, analogique et sémantique, *Séminaire sur les processus de conception*, Paris, Ministère de l'Equipement, vol. 3, pp. 224–250.
RAYNAUD D. (1998) *Architectures comparées. Essai sur la dynamique des formes*, Marseille, Parenthèses.
RAYNAUD D. (1999) Forme urbaine. Ph. Boudon, éd., *Langages singuliers et partagés de l'urbain*. Actes du Colloque CNRS UMR 7544, Paris, L'Harmattan, pp. 93–120.

RAYNAUD D. (1999) Le schème: opérateur de la conception architecturale, *Intellectica*, 29 (2), pp. 35–69.

RAYNAUD D. (2002) Le schème, du point de vue nominaliste et pragmatiste, Ph. Boudon, éd., *Langages singuliers et partagés de l'urbain*, 2. Actes du Colloque CNRS UMR 7544, Paris, L'Harmattan (in press).

REVAULT D'ALLONNES M. (1921) Les schèmes présentés par les sens, *Revue philosophique*, 91, 2, pp. 316–343.

RICHARD J.F. (1998) *Les activités mentales. Comprendre, raisonner, trouver des solutions*, Paris, A. Colin.

SCHANK R.C. ET ABELSON R.P. (1977) *Scripts, plans, goals and understanding*, Hillsdale, Lawrence Erlbaum.

SCHMEIDLER G.R. (1965) Visual imagery correlated to a measure of creativity, *Journal of Consultative Psychology*, 29, pp. 169–181.

SHEPARD R.N. ET METZLER J. (1971) Mental rotation of three-dimensional objects, *Science*, 171, pp. 701–703.

SHEPARD R.N. ET COOPER L.A. (1982) *Mental images and their transformations*, Cambridge, The MIT Press.

SIMON H.A. (1974) *Sciences des systèmes. Sciences de l'artificiel*, Paris, Epi [1963].

SIMON H.A. et al. (1992) *Economics, bounded rationality and the cognitive revolution*, Brookfield, Ed. Elgar.

TREIBER D. (1992) *Norman Foster et la tour de la Hongkong Bank. Vers l'espace tertiaire du futur*, Paris, Plan Construction et Architecture.

UTZON J. (1965) The Sydney Opera House, *Zodiac*, 14, p. 49.

VEGA M. DE, ET RODRIGO M.J. (1997) Les représentations topologiques dans le traitement des descriptions spatiales, in Denis M. (ed.) *Langage et cognition spatiale*, Paris, Masson, pp. 51–68.

VOLKEMA R.J. (1988) Problem complexity and the formulation process in planning and design, *Behavioral Science*, 33, pp. 292–300.

WILLIAMS S. (1989) *Hongkong Bank. The building of Norman Foster's masterpiece*, London, Jonnathan Cape.

WITTGENSTEIN L. (1961) *Tractatus logico-philosophicus. Investigations philosophiques*, Paris, Gallimard.

ZUKOWSKY J. ed. (1987) *Mies van der Rohe. Sa carrière, son héritage, ses disciples*, Paris, éditions du Centre Georges Pompidou.