USE AND ADAPTATION OF PRECEDENTS IN ARCHITECTURAL DESIGN

TOWARD AN EVOLUTIONARY DESIGN MODEL

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Proefschrift

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To my grandma Elza, my parents, and Gijs

ABSTRACT

For centuries, architects have re-used design precedents in the conception of new design solutions. Whether explicitly – as in the case of Le Corbusier, James Stirling and Jo Coenen – or implicitly – as with J.J.P. Oud, Aldo van Eyk, and Santiago Calatrava – this practice has led to very advantageous efficient, effective, and innovative results. The goal of this research project is to contribute to the construction of computational tools to facilitate this practice by developing a model that grasps significant characteristics of the design process as it employs precedents. The model is built drawing an analogy from the natural evolution. The intention is not to represent the processes that take place in the architects' minds but rather their behavior as this is manifested in their design products.

The project draws from the multidisciplinary methodology of design tool development of the Design Knowledge Systems Research Center. It employs an analogy with Darwinian evolutionary theory in combination with recent theories of genetics and embryology. The criteria of usefulness in picturing the phenomenon in architecture determines the focus on particular aspects of the analogy. The research also uses three case studies from the architectural domain: J.J.P. Oud, to identify adequacy criteria for the model; Le Corbusier, to illustrate the components and conduct of the model under development; and Santiago Calatrava, to test the model. The research develops a pre-computational qualitative model that provides insights into the process of re-use and adequacy criteria for an analytical model to succeed in architectural practice.

Given the notorious history of misuse of analogies from the Darwinian model and biological models in general to other fields, special attention was paid to circumscribe the limits of the analogy. There are basic differences between design and evolutionary models, the most important being the process of selection, natural versus artificial. As "breeders", designers recall from memory and/or from archives through "artificial selection" – this is not the case in natural selection. In natural evolution, mutations are "random", and natural selection gives the direction. In the human design process, mutations and selection are mostly intentional. Many analogies suffer from confusion between the natural science notion of evolution and the cultural notion of progress; they are also highly reductive in their representation of cognitive processes of design, misrepresenting the design process.

The evolutionary and genetics analogy serve as heuristic devices to represent the mechanisms in the process of use and adaptation of design precedents and the elements of such precedents accumulated over the years that are adapted and recombined during the design process often leading to design innovations. The model employs the notion of "design feature", a precedent component, as the most important unit of selection. Drawing from developmental genetics, and the idea of regulatory genes, each feature is derived from two interlinked kind of instructions where the "regulatory d-gene" deals with the configurational instructions and the "structural d-gene" deals with the technique and materials used. In the design model, just as in evolution, the notion of fitting environmental constraints in the generation of form is essential. Fitness relates to both internal and external constraints; it is multi-dimensional in a multi-criteria ecological environment.

PREFACE AND ACKNOWLEDGEMENTS

Nowadays it has become popular to refer to biological theories in developing models and theories about design history, design marketing and product design. In this study, my task is to study these references in order to see how far this type of modeling of design can be stretched to gain insight into the process of use and adaptation of design precedents in architectural design and the phenomenon of change involved this activity.

Unequivocally, typical pragmatic criteria of usefulness determined the focus on particular aspects of the analogy between the re-use of design precedents and biological evolutionary models, that is to say, those that could be fruitful in describing the use and adaptation of precedents in architecture. By modeling the architectural phenomenon, we reduced and described the process to a level of abstraction that gave insights into this strategy in designing.

Parallel to the use of the analogy between the re-use of design precedents and biological evolutionary models, I used three case studies: the first case on a series of designs from the Dutch architect J.J.P. Oud; the second on the phylogeny of the Unité d'Habitation of the Swiss-French architect Le Corbusier; and the third on a series of projects of the Spanish engineer and architect Santiago Calatrava. These cases are respectively used to find adequacy criteria for a model to perform well in architectural practice, to illustrate the proposed model, and to test the potential of the model to the phenomenon in a different oeuvre; i.e. whether it is possible to generalize the model to provide insights into the process of re-use of numerous architects.

One develops a model in order to theorize about a subject or to develop computer simulations. A model does not truthfully represent the data or phenomenon under study. Its success depends on its usefulness. The analogy with the biological theory of evolution is fruitful and this qualitative model proposed here gave me better insights into the process of the use of design precedents, and it allowed me to discuss what is being re-used and to compare the processes carried out by different architects. Therefore, and above all, the research product is an analytical device that can be used in design education; and in this sense, we can say that the model proposed here is successful. I believe that these and future insights developed through further testing of the model may contribute to the development of future computer simulations that may assist architects in making creative use of their design precedents when designing with a computer.

This qualitative model was developed with my thesis adviser Prof. A. Tzonis. I am deeply indebted to him for his assistance and his theoretical and creative insights. I want to thank Prof. Doorman for his interest and commitment to my thesis. Where my research reaches precision in the use of a clear research method, it is due his guidance; where it does not, the shortcoming is my own. I would like to thank Prof. dr. H. Galjaard, Prof. dr. W.L. Porter, Prof. J. Coenen and Dr. A. Romeijn for being in my committee and for their extensive and helpful comments. I am also indebted to Dr. R. Sierksma and Prof. Habraken who read my drafts and gave me precious and challenging comments.

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CONTENTS

CHAPTER 1

INTRODUCTION

Toward an Evolutionary Model for Use of Design Precedents in Architectural Practice

It has been popular over time to draw analogies from biological evolution theories in developing models and theories about the design process. In this research, our main task is to investigate the possibilities this kind of model can offer in enhancing the understanding of the process of use and adaptation of precedents in the generation of new designs. Pragmatic criteria of usefulness and originality determined our focus on particular aspects of this analogy.

In architectural practice, the use of design precedents as a source of knowledge is often considered to be a more efficient strategy in developing designs than initiating a project from tabula rasa. Architects often explicitly make use of design precedents, such as Le Corbusier, James Stirling and Jo Coenen; and others less explicitly, such as J.J.P. Oud, Santiago Calatrava and Aldo van Eyk; both ways frequently lead to efficient, effective, and/or innovative results. This research refers to strategies employed for the use and adaptation of design precedents. In particular, it refers to conceptual and structural changes of design precedents which, with reoccurrence through time, occasionally give rise to new building types.

The motivation to start this research was to develop a computational tool to facilitate the use of design precedents to assist architects in the creation of innovative designs. The rationale behind the idea of the designer being assisted by a computer-based system in the process of use and adaptation of design precedents could be summarized by: providing reflectivity on the process; providing efficiency in dealing with large amounts of data; and effectiveness of controlling the process. This research should be seen as just an initial step toward this ultimate objective.

According to the influential work of D. Marr, there are three levels of development of an information-processing device: first, development of a computational theory; second, algorithm development; and third hardware implementation. Marr claimed: “At one extreme, the top level, is the abstract computational theory of the device, in which the performance of the device is characterised as a mapping from one kind of information to another, the abstract properties of this mapping are defined precisely, and its appropriateness and adequacy for the task at hand are demonstrated. In the centre is the choice of representation for the input and output and the algorithm to be used to transform one into the other. And at the other extreme are the details of how the algorithm and representation are realised physically - the detailed computer architecture, so to speak. These three levels are coupled, but only loosely” (Marr 1982, pp. 24-25). The present research on use and adaptation of precedents in architecture deals with the highest level of Marr’s classification and provides a model towards the development of a computational theory.

In her “Models and the limits of theory: quantum Hamiltonians and the BCS model of superconductivity”, Nancy Cartwright asserted: “Models mediate between theory and the world” (Cartwright 2000, p. 242). Thus in the case of our research, we develop a model to theorize about the frequently observed phenomenon of innovation in designing to the extent to which it is using design precedents.

The research refers to Evolutionary Biology, Computation, Design, Theory and Methodology and indirectly to Cognitive Science. This multidisciplinary approach was made necessary because although the literature on design precedents is extensive (sub-section 1.1), we found no architectural theory that could systematically assist us in modeling the phenomenon of change in the generation of designs to the extent in which it is based on the reoccurrence of design precedents. We claim that the changes in the precedents by modifying and recombining them are often one of the forces towards innovation.

Frequently, theories about innovation and creativity are criticized for claiming too much about a most complex and hard to understand phenomenon. For this reason, we thought that it was necessary, before moving forward in this introduction to our research, to make it clear that this research is not claiming:

1. The use of design precedents is the only factor contributing to changes in design.
2. Design relies only on the use of precedents.
3. The model explains architects' mind processes. A model account of the world is given with abstractions and approximations, and therefore one can say that a model is never true; it is only fruitful or not. We are modeling or picturing the phenomenon of change in designing to the extent to which it

is based on the reoccurrence of design precedents in the generation of designs. Our intention is to get insights into the process, in particular in relation to the parts that are recalled, modified and recombined that together result in the production of innovative designs.

Finally, this research does not refer to the changeability of the built environment[1] created by the architect, but to the phenomenon of change in design thinking. It does not refer to how an architect should design to give the most flexibility to people, but to how architects change their concepts and structures based on design precedents. It refers to changes that architects accumulate during their professional lives, which support, but do not dictate, the creation of innovative designs.

The next sections present what is the nature of design precedents, and summarizes the problems, objectives, and scope of this research, as well as the general strategy of the research and its product. It deals chiefly with the "what" and "why" questions, while Chapter 2 will deal with "how" exactly we will apply the method. This chapter also provides a dissertation overview.

1.1. The Nature of Design Precedents

The use of design precedents has been the subject of much research (Tzonis 1992; Tzonis and White 1994; Schmitt 1994; Fang 1993; Anderson 1995; Oxman and Oxman 1994; Bay 2001; Kolodner 1993; Maher, Balachandam et al. 1995; Heylighen 2000).

Tzonis and White assert: "Existing knowledge in any field may of course take a variety of forms: it may be embodied in rules and principles as well as in cases. Reasoning with cases, in its widest sense, includes reasoning with future and hypothetical examples, as well as with actual past and present ones. The area of overlap between reasoning with established knowledge and reasoning with cases is the use of precedents" (Tzonis and White 1994). A precedent is thus a project (case), a feature of this project, or principles (established knowledge).

According to G. Schmitt, a precedent case represents knowledge in design in a holistic way without being exhaustive which, unlike general rules or principles,

[1] This was widely studied by Prof. J. Habraken and his associates and resulted in a decision-making process that could sustain changes in the built environment and subsequently in a design methodology based on a hierarchy of domains and elements. In this design method, the citizens, the community, the family and the individual (domains) respectively control the urban tissue, the block, the house unit and the room (element levels). Each domain has one element level that is considered "fixed" – or controlled by a higher domain – and another that is "variable", i.e. it is under its own decision-making process. For example, the community decides on changes in the building block, but it must respect the urban tissue; the family decides on the plan layout and changes within the house unit, but must accept decisions at the community level of the building block.

provides us with some assurance of the success of a design in its entirety (Tzonis and White 1994; Schmitt 1994). In this research, we shall see that some components of precedent cases seem to be recalled, adapted and recombined over the years becoming independent from the original precedent case. Some of these precedent-components will even become a concept or a principle such as the case of Le Corbusier's five points for a modern architecture, which were once recalled from a precedent case and later applied by a multitude of architects without referring to its roots.

Why is the use of precedents in architecture necessary? According to Bay, precedents are used to overcome difficulties in design. Bay asserts that precedents are in particular necessary for solving design problems in practice because "it avoids combinational explosion in thinking, and saves time and mental resources, to cope with the problem in practice". By saving time and mental resources in things that architects already know, they may be more attentive to innovation and creativity (Bay 2001). In this research we argue that the process of use and adaptation of design precedents can be a creative process in itself that may contribute to the creation of innovative designs.

In a very general way, a design precedent can be an artifact or a drawing and it may be represented by sketches, final drawings, details and specifications, structural, infra-structural drawings and sometimes principles. In a computational system, the needs of the designer will dictate whether he/she will use all categories, and if so, which sub-categories are indeed necessary or not. All in all, efficiency may be gained if the information is less complex and if it has a standardized format in the design space. Since we are heading to a pre-computational model we are not going to constrain our study to any of these categories.

This section will first describe the use of the term "design precedent" and its numerous categories, building particularly on the work of Joo-Hwa Bay (Bay 2001), Nan Fang (Fang 1993) and Alexander Tzonis (Tzonis 1992). Secondly it will present the way it is used in this research.

1.1.1. A Brief Review of Design Precedents

Design precedents have been classified in different ways supporting creative as well as routine design, and the use of precedents has been positively as well as negatively approached.

In his thesis *Architectural Precedent Analysis*, Fang argued that most design types, such as those described by G. Broadbent (Broadbent 1988, pp. 25-54)[2],

[2] Pragmatic design, iconic design, analogic design and canonic design – (Broadbent 1988, pp. 25-54)

those identified by John Gero (Gero 1990, pp. 27-36),[3] and those described by R.D. Coyne in his *Knowledge-based design systems* (Coyne 1990)[4], are involved in two ways of using precedents: *precedent-constrained design* and *design by analogy* (Fang 1993, p. 98).

Referring to J.E. Hancock's "Between history and tradition: notes toward a theory of precedent" (Hancock 1986, pp. 65-77), Fang suggested that *precedent constrained design* might be grounded in one or more of three realm types: place-grounded, type-grounded and principle-rooted precedents. The method of using a precedent was limited to refining, adapting or repeating the precedent. If precedent constrained design is more related to *routine design*, asserted Fang, then design by analogy is more related to the so-called *creative design* or *prototype creation*.

Not fitting completely in the above terminology, Fang asserted that Prof. Wu's creation of a *new courtyard house*, a prototype creation, made use of both types of precedents. For example, by using the traditional urban fabric of the old courtyard house, he used a place-grounded precedent, which is related to precedent constrained design, and subsequently to *routine design.* By using the *southern large mansion*, he used analogic precedents, which are related to *creative design.*

This description is not likely to bring any clarity to the process of using a precedent. For example, it is not clear why the urban fabric of the old courtyard house is then a place-grounded or type-grounded precedent, while the southern large mansion is considered analogic and not a type-grounded precedent. Besides, some analogies are worked out in the designer's former designs in such a way that they become either a type-grounded or a principle-rooted precedent.

In fact, in the creation of the Unité d'Habitation, Le Corbusier probably used all the aforesaid precedents. Obviously, one could say that in the same design there are routine and non-routine uses of precedents, but this classification does not seem to provide insights into the creation of the Unité. Besides the capability to recognize precedents everywhere, his creativity seems to be highly dependent on the way he re-organized precedents in an innovative manner independently of the aforementioned theoretical classification.

A feature worth noting is that when designers are not copying the whole precedent (project or precedent-scheme), they must either isolate part of it for use or abstract some of its features (precedent-component) to transfer to their designs. For example, the piloti and roof garden of Le Corbusier's Unité d'Habitation were allegedly drawn from analogies with the hut and the ocean liner (Tzonis 1992). In other words, Le Corbusier seemed to have recalled the savage hut and transferred the piloti to his villas and afterwards to the Unité d'Habitation. In a similar way, he recalled the ocean liner and transferred the deck to the roof of the Unité, transforming this roof into a public terrace.

[3] Routine design and non-routine design – (Gero 1990, pp. 27-36)

Though acknowledging the use of other artifacts in analogies, Fang excluded any kind of precedent that was not architectural from his research, presumably to reduce the scope of his research. Fang developed a representation of design precedents in the creation of a new design, while our research intends to model the use and adaptation of design precedents over the years, showing their adaptations and recombinations and how they contributed to the creation of an innovative design. For this reason, we will not exclude precedents drawn from or inspired by analogies with artifacts from other fields.

In his *Cognitive Biases in Design, the case of tropical architecture,* Joo-Hwa Bay asserted: "Incomplete information, limited time, and human mental resources make design thinking in practice difficult and impossible to solve. It is not possible to analyze all possible alternative solutions, multiple contingencies, and multiple conflicting demands, as doing so will lead to combinatorial explosion. One of the ways to cope with the difficult design problem is to use precedents as heuristic devices, as shortcuts in design thinking, and at the risk of errors" (Bay 2001, pp. vii-viii). Bay dealt with the problem of biases or illusions that may lead the architect, who uses design precedents, to errors, and he developed a design tool to overcome these types of errors. By contrast, we are interested in the case that the use of design precedents leads to innovations.

1.1.2. Design Precedents in this Research

The use and adaptation of design precedents involve several processes such as analysis, storage, recollection, use and adaptation. In other words, designers often analyze the value of a structure and/or configuration in a certain artifact in relation to particular questions that are bothering their minds and therefore store them in their memory and archives (sketches, photos, drawings, and literature)[5]. Afterwards, they will heuristically invoke this precedent as design knowledge to help them in the creation of designs, which present some similarities with the former. They may have to adapt and/or modify it to fit the new situation. Sinan Inanç's thesis, *Retrieving Architectural Information Objects by the Heuristics of Laziness*, deals with the problem of storage and recollection (Inanç 2003), while this research focuses on this use and adaptation.

[4] Prototype refinement, prototype adaptation and prototype creation – (Coyne 1990)

[5] It is necessary to remark here that analogies recognised by, for example Le Corbusier, might be totally alien to another architect or not totally assimilated (Broadbent 1988, 343) which seems to make the use of precedents very individual.

In describing J.J.P. Oud's (Chapter 3), Le Corbusier's (Chapter 7), and Santiago Calatrava's (Chapter 8) processes of use and adaptation of design precedents, the researcher recognized five overall characteristics:

1. Architects often recall a few elements (a feature or precedent-component), of a certain past experience and these elements are sometimes either configurational or structural. The features may originate from the aforementioned type-grounded, place-grounded, principle-rooted precedents and, in particular, from analogies.
2. Architectural precedents can be described by their performance, operation and morphology.
3. Design precedents may belong to the architect's oeuvre, or may be imported into it.
4. Architects may use numerous design precedents in one project if the precedents do not contradict each other.
5. Precedents are often modified over the course of an architect's career by the process of use and adaptation to new contexts.
6. The process of use and adaptation of design precedents can be fruitfully modeled with the help of our analogy with Evolutionary Biology.

In this research, precedents are mainly features (and at times principles) that are often transferred together in clusters to a new design, and sometimes independently, rather than whole projects or "types"[6]. However, some features may indeed come from well-known types. In fact, we claim that by "breaking the type" and combining some of its features with alien ones, innovations may come into view.

Why "Re-Use" and not "Use" of Precedents?

In a general way, the term "re-use" seems to be somewhat superfluous or, even worse, bad English. People "use" precedents. So why do we employ the term "re-use" rather than simply "use" of precedents?

The term "use" does not carry the meaning of change and adaptation within it. In this research, the word "re-use" refers to the use and adaptation of the design precedent rather than the mere repetition of it. Re-use also refers more specifically to a precedent that is put to different uses such as in the concept of "re-design" in

[6] This decision refers only to the study of precedents in relation to innovations. We are not claiming that the notion of type should be banned from design: architects such as Le Corbusier make use of types and prototypes all the time. As Donald A. Schön asserted: "Types can function as references. By invoking a type, a designer can see how a possible design move might be matched or mismatched to a situation, even when the designer cannot say with respect to what features there is a match or mismatch" (Schön 1988, p. 183). The notion of "type", according to Schön, embodies design knowledge and in certain ways "they can generate sequences of moves and guide

engineering or the use of a precedent by analogy. The term re-use refers to an evolutionary chain of changes. It emphasizes the re-occurrence of a design precedent through time and its transformation through "generations" of designs.

For these reasons, this research employs the notion of re-use.

1.2. The Evolutionary Model: Research Project

Intending to get insights into the process of use and adaptation of design precedents carried out by an architect over the years, we drew an analogy with the biological Darwinian theory of evolution and genetics. The borrowed evolutionary models were reduced and abstracted in a pragmatic way aiming to model the specific architectural phenomenon.

The objective of the proposed model is to move towards a theory to extend our understanding of the phenomenon of change through the use of design precedents. This theory should firstly describe what architects recall; secondly, it should explain the process of adaptation and recombination of design precedents in new situations; and thirdly, it should provide insights into how changes accumulate through generations of designs. Within this realm, we hope to get insights that may contribute in future to the development of a computational tool to assist designers in the re-use of precedents in architectural practice, which was the motivation for this research.

1.2.1. Understanding the Phenomenon of Change: Research Objective

The objective of this research is to model the phenomenon of change in designing to the extent to which it is based on the reoccurrence of design precedents in the generation of designs.

We are not trying to model the phenomenon of change merely in the work of the architects studied in this research. We are looking for a model that can be applied to the work of architects in general to understand the phenomenon of change in the design process to the extent to which they are based on the re-use of design precedents. We want to know what was re-used, how it was re-used, as well as which features (precedent-component) were modified and recombined through time and how.

designing." Schön, Donald A. 1988. "Designing: rules, types and worlds". *Design Studies*. Vol. 9. no. 3. pp. 181-190.

1.2.2. General Approach: Research Method

To date, many approaches have been employed in an attempt to solve the problem of using design precedents such as case-based and knowledge-based systems. Often such research has been conducted ignoring the architect (design by computer), thus creating systems that provide a variation of a theme but no innovation. The process of adapting and integrating the parts of the design is often left so that the architect has to handle the design precedents traditionally, i.e. by manually copying and adjusting them, or by trying to "imitate the architects' methods" (Timmermans, N.M. Seger et al. 2001).

As already mentioned, this research not only focuses on how architects use precedents, but also on how these precedents are modified and their changes are accumulated from generation to generation of designs, often leading to the production of innovative designs. This section presents the general approach of the research and some reasons why we decided to follow this path.

Why Move toward a Model?

A model is a way to represent either an object or a process. The merit of developing such a model is that it reduces the amount of variants working in the real word and, as a result, it makes the data easier to control. We think that if the research is clearly constrained and systematically developed, then new tools can be programmed, either to assist architects or to teach designers in the studio. Therefore, departing from Nancy Cartwright's simulacrum account of explanation (Cartwright 1983), which is further described in the chapter on the research method, we develop a qualitative model.

Coping with the Phenomenon of Change in the Re-use of Design Precedents

The research method is two-fold and based on two kinds of heuristics[7]: analogy between design and biological theories of evolution and genetics and the use of case studies from the architectural domain.

On the one hand, it uses an analogy between the process of re-use in design and biological theories of evolution and genetics in order to identify concepts and theories that may help us in modeling the phenomenon of change within the use and adaptation of precedents. Essential in the development of this model is the use of the Darwinian evolutionary model in combination with recent models of genetics and embryology.

On the other hand, it employs three case studies from the architectural domain, each being in its own way relevant for the development of the model.

[7] For an understanding of the term "heurictics", we refer to A. Tzonis' *hermes and the Golden Thinking Machine* (Tzonis 1990b, pp. 70-80)

The case examining J.J.P. Oud's conception of social housing projects in Rotterdam provided a series of adequacy criteria for the model; i.e. criteria that the model should satisfy if it is to serve architects in practice and designers-in-training. It also suggests the use of the evolutionary analogy as a method to develop a model for the re-use of design precedents. The second case illustrates how the qualitative model can describe the re-use of design precedents in the conception of Le Corbusier's Unité d'Habitation of Marseilles and models the great changes carried out by this architect. Case three, Santiago Calatrava's bridges and buildings, evaluates the potential of the model in representing the phenomenon of change in designing to the extent to in which it is based on the reoccurrence of design precedents in the generation of designs, i.e. it tests the generalization of the model.

Why the Use of an Analogy?

Analogies, claim Diego Fernandez-Duque and Mark L. Johnson in their "Attention Metaphors: How Metaphors Guide the Cognitive Psychology of Attention"[8], "circumscribe the phenomena, define the basic concepts, guide the research program, and determine the inferences drawn about the phenomena" (Fernandez-Duque and Johnson 1999). Fernandez-Duque and Johnson presented evidence to demonstrate that analogies are central to scientific knowledge; they argued that analogical reasoning is a primary basis for our shared knowledge in science, and that it gives rise to and guides our research programs. In contrast to the claim that when science matures, it will replace analogies with "a monolithic, literal, univocal conceptual system for the phenomena being studied", they asserted that science, like all our thinking with abstract concepts, is irreducibly analogic (Fernandez-Duque and Johnson 1999).

According to John Holland et al. in their *Induction, Processes of Inference, Learning, and Discovery*, "analogy is a device for integrating diverse knowledge sources to model a novel situation." They argued that an analogy must be understood pragmatically rather than purely syntactically and that "in the case of problem solving, analogy is used to generate rules applicable to a novel target problem by transferring knowledge from a source domain that is better

[8] Here Fernandes-Duque and Johnson consistently use the word metaphor meaning analogy. One thing is an analogue of the other if they are similar in some ways. The words metaphor and analogy are sometimes used interchangeably. Therefore, we must first clarify the meaning of both words and show why we opt for "analogy" rather than "metaphor." If you draw an analogy between two things, you show that they are alike in some way. A metaphor is described in the Collins Cobuild dictionary as an imaginative way of describing something by referring to something else that has the qualities that you want to express (Cobuild 1995). In this way, analogy and metaphor can be understood as synonymous. However, a metaphor can be used in the restrictive sense of a symbol. For example, "white-collar" workers are people who work in offices rather than in industry doing manual work (in which case they would be blue-collar workers). In this sense, a characteristic becomes the symbol of the people who work in a certain environment. You commit a white-collar crime if you commit fraud in the business world, even if you never wear a white collar.
To avoid any misunderstanding, we will prefer the use of the word "analogy" when referring to our evolutionary analogy.

understood." According to Holland et al., "The usefulness of an analogy depends on the recognition and exploitation of some significant similarity between the target and the source." They claimed: "the model of the source problem is used as a model of the target problem generating a new model that can be applied to the novel situation." However, they stressed the fact that not even in the ideal case all elements of the source situation need be mapped, only those relevant to the achieved solution (Holland et al. 1986, pp. 287-319).

As Holland et al. assert, "Analogy involves second-order modeling – a model of the target problem is constructed by 'modeling the model' after that used in the source problem." Following Holland's argumentation, in our research, the analogy is our method of structuring our model and it is used due to the lack of an architectural theory that could represent the phenomenon of change in the process of re-using design precedents over the years in the generation of (innovative) designs.

This analogy between re-use of design precedents and the theories of evolution is used as a strategy of this research (see Chapter 2: Research Method, for an explanation of how we use the analogy); and it is our first heuristics (the second is the use of case studies from the architectural domain) to develop our model and it is used due to the lack of an architectural theory that could systematically represent the phenomenon of change as specified previously in this chapter. It helped us in a bottom up approach to construct our qualitative model.

To highlight the use of analogies in science, we may recall Charles Darwin's research on evolution. One of the applied analogies was drawn from breeding. By analyzing change in breeding and its relation to processes of selection - known then as "Artificial Selection" - he questioned by analogy how selection occurred in nature. He drew a subsequent analogy from his reading of Malthus' *Essay on Population*. Darwin borrowed from Malthus the notion of the "struggle for survival", which led him to the idea of the mechanisms of selection in nature, which he called "Natural Selection". The merit of developing a model by analogy will not be further discussed here, since the literature on developing new models by analogy is vast.

Why the Use of the Analogy between Re-Use of Precedents and Biological Theories of Evolution and Genetics?

It is claimed in this research that, presently in the basis of this analogy between re-use of design precedents and biological theories of evolution and genetics, criteria can be specified which should be satisfied by a model to picture the phenomenon of change through the re-use of design precedents in architecture. This analogy is used as a strategy of this research and it is not to be confused with analogies employed by the architects who use them in the process of analysis and recollection of a particular feature. Architects' analogies between features of their current project and features of other artifacts are seen in this research as their heuristics in the search for solutions.

This analogy of design with the biological evolutionary model faces two major risks. Firstly, there is a risk of misrepresenting biology by using pseudo-concepts which are either very reductionist or false. Secondly, there is a risk of blindly applying biological theories to architecture, forgetting the distinct characteristics of both fields and thus not satisfying the conditions of a tool to serve architects in practice. Therefore, we borrowed biological evolutionary models developed from evolutionary theories (Darwinian and neo-Darwinian), but only to the extent that they can help us to model architectural phenomena (Fig. 1).

Why the Use of Case Studies?

We used cases because we do not have precedent architectural theories to support the development of our model and because the phenomenon is very complex. So, instead of enumerating all possible situations, which would make us run out of resources, we made use of representative cases. The case as well as the use of analogy is part of our heuristics, they are both our research strategies. Case studies are holistic, and therefore, let us observe the phenomenon in its entirety in its natural context. We carry out three case studies in the architectural domain. In a general way, the use of cases helped us: first, to understand how far we can stretch the analogy; and second, to set up a pragmatic approach to the analogy (applying the analogy according to its usefulness). By choosing representative cases, i.e. cases that present clear differences among themselves and could therefore highlight different approaches to the process of re-use of design precedents in architecture, we hope to avoid the exhaustive study of all possible situations.

Each of the three case studies is used in its own way relevant for the development of the model: the first to develop some adequacy criteria to the proposed model; the second, to illustrate it; and the third, to test the possibility to generalize it.

1.2.3. Toward an Evolutionary Design Model: Research Product

The research product is a qualitative model providing insights into the process of re-use of design precedents that might contribute to the future development of a computational design tool to support the creation of innovative designs in architectural practice. More immediately, this model can be a useful resource in design teaching functioning as an educational analytical (non-computational) device. Students in the design studio can use the model to analyze the phenomenon by comparing the processes carried out by different architects. In this sense, we model to theorize about the process of re-use of design precedents.

This educational role of the model refers to Donald Schön in his *The Reflective Practitioner.* Schön called *seeing-as* the process of perceiving similarities that guide the inquirer to further investigation. He asserted that "The perception of similarity before one can say *similar with respect to what,* and the subsequent reflection to it are essential both to the art of engineering design and to the art of scientific investigation"; through examples, he illustrated that in some cases they played "a critical role in invention and design" (Schön 1983, 182-4).

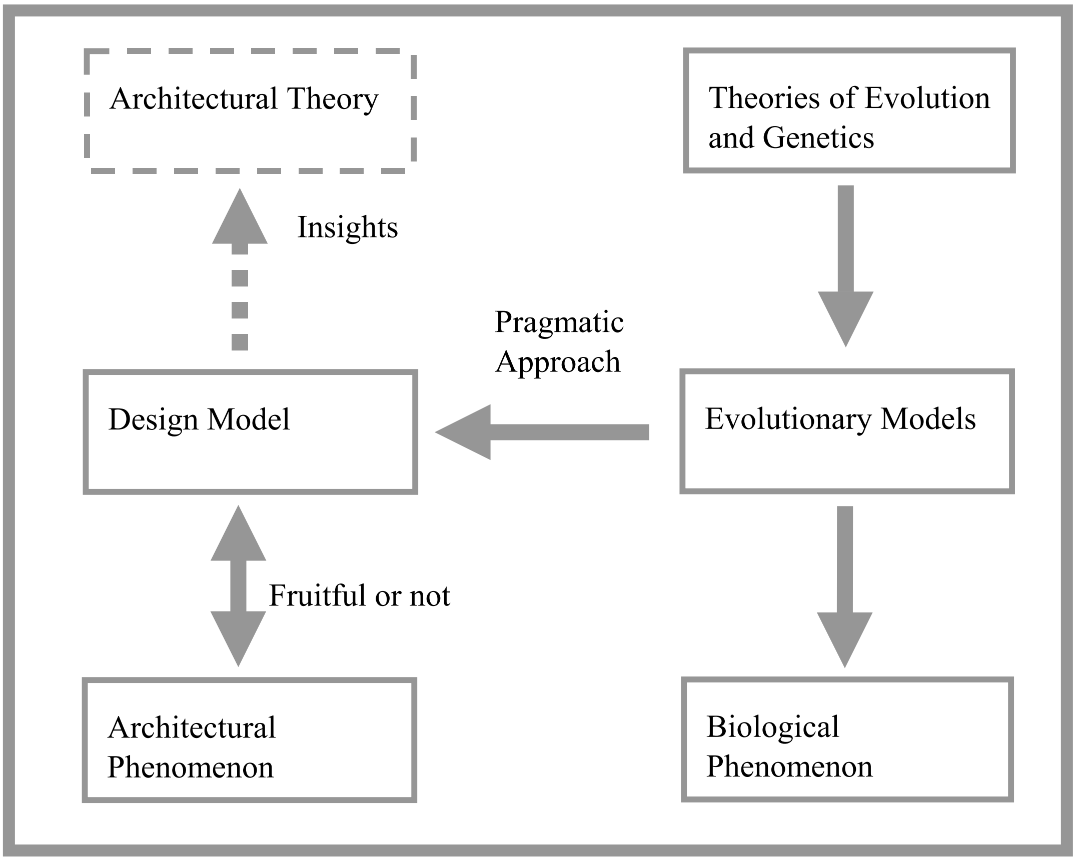

Figure 1: Developing our Qualitative Model.

It is the belief of this researcher that training students to perceive similarities between the design and its precedents as well as to reflect on each precedent on its own are likely to help them when facing problems of their own in practice. Finally the model is also a descriptive didactic device. It enables design researchers and teachers to describe how particular features were used and adapted in different projects. The proposed model does not predict how the architect must proceed to re-use design precedents. It gives an account of how features coming from diverse designs might have supported the creation of unprecedented designs.

1.2.4. “Users” of the Evolutionary Design Model: Target Group

Architects and designers-in-training form our target group. The research shows that the use of precedents can be a source of innovation for creative architects in practice and that the didactic power of the model can contribute to an understanding of the phenomenon of change when produced by design precedents. Therefore it may assist architects and designers-in-training in making satisfactory use of this strategy.

1.2.5. Means-Ends Analysis: Research Questions

Patrick Henry Winston (Winston 1992) in his *Artificial Intelligence*, and Herbert A. Simon (Simon 1996, 210) in his *The Sciences of the Artificial*, use the Means-Ends Analysis in similar ways. According to Winston, “the purpose of means-ends analysis is to identify a procedure that causes a transition from the current state to the goal state, or at least to an intermediate state that is closer to the goal state. Thus, the identified procedure reduces the observed difference between the current state and the goal state” (Winston 1992, 50). In the same way, we use the method to guide us from our main question, through sub questions, to our representations.

Proceeding from the idea of developing a representation(s) for a model of re-use of design precedents, our main question is: “how can we describe the phenomenon of change when based on the re-use design precedents?” To answer it, we must first answer the following questions:

1. What is a design precedent? What is transferred from previous designs into a new design?
2. Does this transference occur several times?
3. If so, does the transferred feature(s) change in the process of adaptation to the new designs?
4. How does change accumulate during the production of a series of designs that leads to the emergence of a unique design?
    a. How do the recollected parts related to each other?
    b. Are they also recollected as a set of combined precedents?

The answers to these questions will be sought in the architectural projects of our case studies and not in cognitive models. In the meantime, a qualitative design model will be developed with the support of our analogy between the phenomenon of change based on re-use in design precedents and evolutionary biology. In evolutionary biology, we will look for similarities and differences between, for example, the processes involved in copying and transferring genes and those of using design precedents. The main questions, then, are:

5. How can the biological evolutionary model help us to represent systematically the re-use of design precedents?
6. Can we find processes or mechanisms in evolutionary biology that may help us in representing the transference encountered in the case studies of design features from one design to another?
7. Finally, how can we test the representation?
    a. Would our model give insights to the phenomenon of change to the extent that it is based on the re-use of design precedents?
    b. What could be the next steps towards a model for the re-use of design precedents?

In relation to the testing of the proposed model, we will limit ourselves to questions related to the model's potential in providing new insights into the study of the re-use of design precedents and to the possible generalization of the model in interpreting the use of precedents of diverse architects.

1.3. Dissertation Overview

After this introduction, Chapter 2 describes the research method; in particular, it refers to the roles of: the model, the analogy between architectural processes and biological theories of evolution and genetics, and the three case studies. Chapter 3 sets out our first case study. This case study showed us certain patterns of re-use that guided us to an analogy between architecture and biological theories, and to criteria that the model should satisfy if it is to be used by designers in architectural practice.

Chapter 4 presents our review of evolutionary analogies as they have been in use; however, the numerous interpretations and many pseudo-uses of the evolutionary model did not show potential in solving our research problem. First, we reviewed traditional analogies between architecture and biological theories employed by several architects of the nineteenth century; second, we briefly described the use of the analogy between evolutionary computation and biological theories; and third, we described some design models developed by design researchers that use evolutionary computation as schemata to develop their evolutionary design models. The chapter shows that probably no answer can be found to our specific problem of representation in these extant analogies.

In the search for a good representation of the re-use of design precedents, we turned to the sources of Darwinian Evolution, as well as the subsequent sciences of Genetics and Embryology. Without trying to use the biological evolutionary model to describe all design processes or strategies, we use it pragmatically with the intention of structuring our particular architectural process, and therefore guiding our search with particular architectural questions. Chapter 5 confronts the process of re-use in design with concepts and mechanisms of the Darwinian evolutionary model, genetics and embryology, always endeavoring to point out the differences wherever they were found. This chapter provides a set of assumptions that were taken into consideration in developing our qualitative design model.

Chapter 6 shows that a gene for architecture needs to have its own domain-specific structure. Therefore, it introduces the P.O.M. reasoning system developed by Alexander Tzonis to our model. The P.O.M. system describes the instruction contained in the conceptual and structural precedents (the architectural genes). The structure of design precedents refers, on the one hand, to molecular genetics and its regulatory genes, and on the other hand to the P.O.M. reasoning system.

Chapter **7** provides an illustration of the application of the proposed model using Le Corbusier's Unité d'Habitation of Marseilles. The chapter presents the phylogeny and ontogeny of the Unité. It presents in the phylogeny the changes that occurred to certain features through time before they were applied to the Unité d'Habitation, and it presents the re-organization in the development of the building itself. By applying this model, we attempt to determine whether it can describe the re-use of precedents and that we can get useful insights in this process.

Chapter 8 presents the results of our third case. The case is employed to test the model and to expose problems concerning the generalization of the approach. By applying the model to another oeuvre, we can see whether it can still give insights into the way design precedents are used.

Chapter 9 provides the research conclusions and indicates directions for future research in the field.

CHAPTER 2

RESEARCH METHOD

This chapter presents the research method. It presents the way the evolutionary analogy was applied and in particular, the method used in the case studies of this research with their distinctive objectives as well as their criteria for selection.

The introductory chapter presented the research method and explained why we have chosen it. This chapter presents how the research method is applied. This research is conducted in order to understand the re-use of design precedents considering the particular phenomenon of change that occurs in designing over the years and it is carried out by developing a model. The model does not represent architects' mind processes since it presents abstractions and approximations about the process of re-use. As previously mentioned, the research method is two-fold; on the one hand, we employed three case studies, and on the other hand, we applied an analogy between the re-use of design precedents, and the biological Darwinian evolutionary model and genetics.

Accordingly, this chapter will clarify what is a model in this research, the role of the analogy in developing this model, and the role of the case studies from the architectural domain. Section 1 describes Nancy Cartwright's Simulacrum Account of Explanation, it shows how our argument is linked to it and to what degree a model is developed in this research. Section 2 shows the way in which the analogy is applied; it will raise the question of similarities and dissimilarities between the two processes and the pragmatism of the analogy. Section 3 describes the specific methods of the three case studies.

2.1. The Role of the Model in this Research: Cartwright's Simulacrum Account of Explanation

As was stated in the introduction, we want to model the re-use of design precedents considering the phenomenon of change in designing that occurs over the years. In modeling this process, we follow the simulacrum account of explanation proposed by Nancy Cartwright (Cartwright 1983) in her *How the Laws of Physics Lie*. However, it is not within the scope of this research to set out all her arguments against the other accounts of explanation.

Likewise, the "simulacrum account" refers to theories and models of physics and though we can learn from it, we cannot completely apply to architecture. By following her rationale, we have to be aware of the difference between theories in sciences as exact as physics, which is the source of Cartwright's examples, and theories in the domain of architecture, which seems more susceptible to personal interpretations.

2.1.1. Developing a Model

Drawing on cases from physics, Cartwright asserted that the fundamental laws patently do not get the facts right, and that the "appearance of truth comes from bad models of explanation, a model that ties laws direct to reality." She therefore proposed the simulacrum account of explanation as an alternative, where the fundamental laws of the theory are true of the objects in the model, and they are used to derive a specific account of how these objects behave. But the objects of the model have only 'the form or appearance of things' and, in a very strong sense, not their *substance or proper qualities*" (Cartwright 1983, p.17)[1].

In the simulacrum account, a model is an intermediate point between theory and the phenomenon in the world. A model pictures the phenomenon, but with the use of abstractions, approximations and even distortions, and hence it is not true. A model is fruitful or adequate (or not) according to its purpose. In other words, the success of a model depends on how well it suits its purposes.

In fact, there are two ways to develop a model. On the one hand, there is a top-down approach in which we have a theory and we construct the model according to the axioms, concepts and theorems of this theory. On the other hand, we have a bottom-up approach. That is to say, we do not have a satisfactory theory that can explain the phenomenon; therefore, we construct a model to theorize about the phenomenon. In this case, an analogy between the field under study and another

[1] According to the second definition in the Oxford English Dictionary cited by Cartwright (Cartwright 1983, p. 17).

field is often used. In other words, one borrows a model from other theories. This borrowing of a model happens in a pragmatic way; i.e. one only borrows structures to the extent that it can help in picturing the phenomenon in a better way.

We shall use the bottom-up approach. We do not have a theory which systematically explains how the mind of architects work, and we thus build a qualitative model to get insights into the process of use and adaptation and to provide some adequacy criteria toward the development of future computational tools to be used by designers in architectural practice.

This model can be used as an analytical tool to be applied in education for instructing students by illustrating how the process of re-use (hypothetically) works in various contexts; it does not dictate how architects should proceed to get what they want from a design precedent.

2.1.2. Developing a Theory

The theory explains the phenomenon and is true or false in relation to the objects of the model.

According to Cartwright, theory entry proceeds in two stages; she imagined that we begin by writing down everything we know about the phenomenon to make the point. This is what she called *unprepared description* or a rough description of the phenomenon. She asserted: "The unprepared description may well use the language and the concepts of the theory, but it is not constrained by any of the mathematical needs of the theory" (Cartwright 1983, p. 133).

At the first stage of theory entry, claimed Cartwright, we prepare the description; she asserted: "we present the phenomenon in a way that will bring it into the theory. The most apparent need is to write down a description to which the theory matches an equation. But to solve the equations we will have to know what boundary conditions can be used, what approximation procedures are valid, and the like. So the prepared descriptions must give information that specifies these as well" (Cartwright 1983, p. 133). At the first stage of theory entry, the check on correctness "is not how well we have represented in the theory the facts we know outside the theory, but only how successful the ultimate mathematical treatment will be." There may be better and worse attempts if we refer to the purpose of the model and, as she asserted, "no principles of the theory tell us how we are to prepare the description." At the second stage of theory entry, "principles of the theory look at the prepared description and dictate equations, boundary conditions and approximations" (Cartwright 1983, p. 134).

Drawing from our first case study, we provide an *unprepared description*[2] of the process of use and adaptation and enter slightly into the realms of the first stage of theory entry with the help of our second and third cases. The proposed model presents insights into the realms of theory making and adequacy criteria toward the development of computer simulations.

2.2. The Role of the Analogy in Developing the Model

One may use an analogy in three distinctive ways: as a heuristic device, as a justification of a claim, or as a didactic device. This typology of possible uses of an analogy is not exclusive; i.e. an analogy can simultaneously be a heuristic device and serve didactic purposes to explain certain mechanisms in a domain such as design. In fact, this is the case in this research. We do not use the analogy to justify our claim.

Heuristic device. Some aspects of the Theory of Evolution and genetics seemed to be similar to the process of re-use and adaptation in design. These aspects made us think of using this reference among others as a heuristic device. We used the analogy hoping that some concepts of natural evolution could help us in picturing some aspects of the use and adaptation of design precedents in architecture capturing the phenomenon of change that occurs through generations of design. We claim that, when used pragmatically, mechanisms of evolutionary biology could describe mechanisms and processes from the design domain. This could be possible by structuring the description of the architectural phenomenon with the same kind of arguments and framework as some of the mechanisms found in Darwinian evolution and genetics. We claim by no means that the similarities between the biological evolutionary models and architecture cover all details. The purpose of our modeling determines the nature of the similarity.

Didactic device. The proposed model seems valuable in explaining the phenomenon to others by naming and describing the objects in the model (the design precedents) and the actions that occurred over the years, such as how a given precedent was recalled, whether it has been recombined or modified.

To constrain the use of the analogy, we focused, on the one hand, on the kinds of similarities and differences which could be found between the mechanisms of use and adaptation in evolutionary biology and in architecture. On the other hand, we made an attempt to describe the phenomenon of change through the re-use of design precedents in architecture relying on architectural cases. From this two-fold approach, a qualitative model was developed, which is applied to our second case study and tested to determine whether it is a fruitful approach and whether it is

[2] We are aware that our *unprepared description* is not carried out by enumerating all cases available, but by the heuristic use of cases and therefore, it has the risk that it is influenced by the selection of the cases used in this research.

possible to generalize it with our third and final case. This test does not constitute a final approval of this model. It is the first step towards the generalization of its concepts in such a way that it could be applied to describe and compare the use and adaptation of precedents in architectural practice.

As mentioned previously (Chapter 1), this analogy between the use and adaptation of design precedents and the biological Darwinian and genetics models pertains to the level of design thinking; it is a strategy to find out how we can possibly represent the process of re-use of design precedents over the years through generations of designs. Though we are not trying to explain architects' mind processes, it involves designers and objects (design precedents). The analogy between the use and adaptation of design precedents and the biological Darwinian and genetics models is not to be confused with designers' analogies mentioned in this research, which are made between two artifacts and used as heuristics in finding a particular design solution.

Due to the use of the evolutionary analogy, this research also becomes part of that conducted by an extensive worldwide group of researchers from diverse backgrounds working with evolutionary design, resulting in numerous evolutionary models for design developed during the last decade. These models are mostly developed in combination with evolutionary computational methods. This research greatly differs from these efforts as explained later in Chapter 4, which presents a review of the evolutionary analogies and their applications.

The following subsections will deal with questions on the similarities and differences between the use and adaptation of design precedents and the biological Darwinian and genetics models, as well as on the pragmatics of the use of the analogy.

2.2.1. Similarities and Differences: In what Sense are the Process of Re-Using Precedents and the Evolutionary Model Comparable?

In searching for heuristics with our first case (J.J.P. Oud) for the projected model, we came upon our first glimpse of an analogy between the evolutionary models. It seemed that the idea of the **re-use of design precedents** bore some similarity to **speciation and development**. In other words, there are reoccurrences of design elements, their recombination, constraints related to the correlation of the parts, and possible modification due to adaptation. In nature, there are reoccurrences of phenotypic characteristics from generation to generation by duplication, recombination, mutations and the manifold constraints under which the embryo develops. The similarity refers to the reoccurrence and modification of certain features in both fields.

Obviously there are dissimilarities between the two processes. At this juncture we will just mention the three major and most evident dissimilarities, leaving aside a more detailed discussion of them to Chapter 5.

First, the production of designs is not randomly carried out and tested only when construction is started. The concept of “get it right first time” is frequently used and the building is then tested in simulative environments. Second, the design process may be ill-defined, but it is certainly not blind: there is a designer (among other players), whose intentions guide the process. Third, time clearly has different dimensions in what concerns the phenomenon of change in design and evolution in nature. These similarities and differences and others are examined further in Chapter 5.

2.2.2. Pragmatism of the Analogy: Is the Analogy Fruitful Despite its Limitations? If So, Why?

We claim that the analogy presents a sufficient number of similarities to make the use of this particular analogy fruitful (see Chapter 5). The analogy is fruitful because:

1. The resultant qualitative model presents a methodological ordering that enables comparison of the process of re-use of precedents among designers.
2. Its concepts have the didactic potential to be communicated among designers in training.
3. The phenomenon of change fits better in this analogical model than in other existing design theories.

2.3. The Role of the Case Studies

Cases are generally used when the problem or phenomenon that one is facing is complex and /or we do not have satisfactory precedent theories to help in solving a specific problem. It is a heuristic procedure. That is to say, rather than describing a phenomenon by enumerating all possible situations, the researcher selects a representative case that may help him/her to grasp the problem in (hopefully) a shorter time. The selection of the case is therefore a critical moment in the research. If the selection of the cases is not carried out following a series of pre-selected criteria, then it might drastically influence the results of the research as a whole.

In our research, it was necessary to describe the re-use of design precedents during a series of designs by a specific designer to model significant aspects of the process. We selected three cases, each with a separate objective in structuring our model. Case One shows the heuristics and approach to the problem; Case Two shows how the proposed model can be applied to describe the process of re-use of design precedents; and Case Three tests its potential in the sense of generalization. The concepts of this model are not tested according to their computational power, but according to their fruitfulness in providing insights into the process by describing changes over the years that, when accumulated, guided architects in the production of innovative designs.

According to Robert K. Yin in his *Case Study Research, Design and Methods*, five components of a research design are especially important for case studies:

1. A study's question;
2. Its propositions, if any;
3. Its unit(s) of analysis;
4. The logic linking the data to the propositions; and
5. The criteria for interpreting the findings (Yin 1994, p. 20).

The main question is the same for all three cases: how change is accumulated and how to represent change in the process of re-use of design precedents. The proposition of each case was respectively: gaining heuristics, and criteria for the model to work adequately in architectural practice; illustrating the structure of the proposed model; and testing the structure on other oeuvres.

The following sub-sections describe the particularities of these three case studies.

2.3.1. Social Housing Projects of J.J.P. Oud: a Case to Search for Adequacy Criteria for the Model

This case was used to extract adequacy criteria for the yet to be developed design model. During the study of this series of projects, the phenomena of change and re-use of elements from project to project were observed and described. These descriptions and analyses drove us to pursue an evolutionary analogy.

Elements of design projects, which were re-used and adapted, were the units of analysis that guided us to the idea of an analogy between the re-use of design precedents and the biological Darwinian model and genetics.

In searching for an instructive case, we have followed five criteria. First, and since we could not explain the designer's cognitive processes and say a priori how designers collect and adapt design precedents, we chose one designer rather than a group of projects. We traced and described the recollection and adaptation of design precedents carried out by a designer (and his team) and we tried to reconstruct a hypothetical path. We assume that the actions carried out by the designer through generations of projects reflect the designer's cognitive processes. The same would not happen if we were to choose several projects from different architects. Generalizing from these actions, we derived some adequacy criteria for the development of the model.

Second, we selected projects of one specific kind: in this case, housing and in particular, public housing. It is not asserted here that there is no cross-influence and no re-use of elements among different kinds. However, given the scope of this case study within the research, this constrained environment was sufficient and more suitable for control.

Third, we selected a series of projects that showed a clear change of pattern over generations of designs. The motive here is two-fold. On the one hand, the model is meant to aid architects in producing innovative designs while being supported by recollection and adaptation of precedents instead of producing designs within a fixed and unchangeable style. On the other hand, we want to know what is hypothetically recalled and which precedents are adapted and how. A clear and systematic description of the change of pattern can show how the designs evolved.

Fourth, we selected a series of projects that have been carried out within a relatively short period. We stipulate this criterion for two reasons: on the one hand, because only then can the designs freshly influence one another; and, on the other hand, because in this way, external influences (contemporary ideas) are constrained.

Fifth, we selected an architect whose archives are accessible. This is a practical criterion. It is necessary because the data collected is based on the observation of different stages of the selected projects, and not just on reading the designer's texts and texts about the designer's projects.

J.J.P. Oud's social housing projects satisfied these criteria and relied on a series of designs for social housing realized in Rotterdam, Hoek van Holland, and Stuttgart by J.J.P. Oud and built between 1918 and 1930. In 1914, Oud designed a residential area in Leiderdorp in conjunction with W.M. Dudok, but it is between 1918 and 1933 that he worked in housing most actively; this coincides with the period in which Oud worked as an architect of the Social Housing Department (Bouwpolitie en Woondienst) of the municipality of Rotterdam.

The designs selected for the analysis are:

1. Spangen Housing Scheme: blocks I and V; Spaanse Bocht, Rotterdam, 1918
2. Spangen Housing Scheme: blocks VIII and IX; Spaanse Bocht, Rotterdam, 1919-1920
3. Tusschendijken Housing: block I, II, III, IV and VI; Rotterdam, 1920-1923

4. Emergency Housing: Oud-Mathenesse (Het Witte Dorp) standard houses, Rotterdam, 1922-1923
5. Row Houses, 2de Scheepvaartstraat 91-113, Hoek van Holland, Rotterdam, 1924-1927
6. Workers' Housing, Kiefhoek, Groene Hilledijk, 1925-1929
7. Row Houses, Weissenhofsiedlung, Stuttgart, 1927

The selected series of social housing projects show a very clear change of design pattern, and they were designed in a relatively short period of time. In this period, the worldwide changes in architectural expression clearly reflect on Oud's designs. This fact made the selection even more interesting. Last but not least, Oud's public archive is at the Nederlandse Architecteninstituut (NAi) in Rotterdam, which contains the majority of his drawings, letters and texts, facilitating the collection of data.

The selected designs were all commissioned for social housing, and they were all designed and built in and around Rotterdam with the exception of the experimental projects and the Row Houses of Stuttgart.[3] This constrained environment as well as the economic and cultural constraints limit the number of viable solutions that one could achieve, thereby revealing the connection between the projects. They therefore allow us to control the aspects of the case that interest us the most: the re-use of design precedents. However, we maintain a broad scope for the recollection of design precedents; i.e. when there is some indication, we include other designs as precedents.

Methodologically, we derived adequacy criteria by observing how design precedents were recalled as well as by analyzing how the design precedents were modified through the selected period of time.

2.3.2. The Unité d'Habitation of Marseilles: a Case to Illustrate the Proposed Evolutionary Design Model

The second case was used to illustrate the concepts of this qualitative model using the assumptions raised in Chapter 5 and our gene structure of Chapter 6. This case was used to illustrate the power of the model in representing change during the re-use of design precedents. The ultimate goal is to shed light on the way in which design precedents were recollected and adapted without hindering the creativity of the designer.

We selected Le Corbusier's Unité d'Habitation based on three criteria. The first criterion was that the selected project should be **clearly based on precedents**. Not

[3] Built in the Weissenhofsiedlung, Stuttgart, 1927

only is the Unité d'Habitation purportedly based on design precedents, but it seems that the re-use of precedents is part of Le Corbusier's design technique.[4]

Secondly, the project should be **innovative.** In other words, we are not interested in mere repetition of design precedents. As Alexander Tzonis[5] and Liane Lefaivre (Tzonis and Lefaivre 1988) asserted, Le Corbusier's Unité d'Habitation, the Residential Block of Marseilles, France, developed from 1946 to 1952, is, within the technologic, urban context of the moment, a new solution for a new problem of provision of shelter for a great number of people. Departing from this innovative design, we want to explore the use of design precedents and the influence that these precedents had in the making of new projects.

Thirdly, the designs should be of uncomplicated access.

Methodologically, our approach is to first describe the Unité d'Habitation and afterwards the lineage of buildings that preceded and (hypothetically) supported the design of the Unité; i.e. we trace the spoors of re-use and adaptations of design precedents through Corbusier's former projects. We also described the modification and recombination of precedents during the development of the Unité. In this case, one can find elements that evolved from a set of analogies, such as those mentioned by Tzonis (Tzonis 1992) in his article "Huts, Ships and Bottleracks". The majority of the precedents refer to morphology, i.e. they refer to configuration.

2.3.3. The Work of Santiago Calatrava: a Case Study to Test the Proposed Model

The objective of this case study is to test whether this qualitative model is able to describe and explain the phenomenon of change through the re-use of design precedents happening in another oeuvre.

The selection of the architect and designs observed the following four criteria:

1. The selected designer should be considered innovative;
2. The designs to be selected for a deeper analysis ought to be representative of a set of projects of the selected architect;

[4] In her "The Chapel of Ronchamp," Danièle Pauly, who studied Le Corbusier's method and his use of references with a case study on the Chapel of Ronchamp, claimed that these precedents were to some extent subconsciously used. In her words, "The 'incubation period referred to by Le Corbusier encompassed more than just the phase between the assigning of the commission and the moment when the first idea was born. This gestation stage in fact implicitly integrated (often in a subconscious manner) a wide range of references generated long before the start of the project: a repertoire lodged in the architect's memory comprising forms and solutions – his own referencing system upon which he drew during the design process" (Pauly 1997, p. 93).

[5] A co-general editor of the most complete publication of Le Corbusier's designs: *The Le Corbusier Archive,* a thirty-two-volume set of the architect's drawings, belonging to the Garland Architectural Archives.

3. The selected series of designs should present a certain amount of similarity to the earlier studied projects (criterion 2) as well as a pattern of differentiation accumulated from generation to generation;
4. This third case should focus on the development and differentiation of a few elements showing their adaptation into new contexts;
5. The designs should have been either published or in accessible archives.

Using these criteria, we initially chose two projects of the architect-engineer Santiago Calatrava. As Tzonis asserted in his *Santiago Calatrava, The Poetics of Movement,* Santiago Calatrava[6], Calatrava's work presents a unique style marked by innovative solutions (Tzonis and Calatrava 1999, p. 9); in this sense, the first criterion is thus satisfied.

The selected projects were:

1. Lusitania Bridge of 1988-1991 in Mérida, Spain;
2. Puerto Bridge of 1989-1995 in Ondarroa, Spain.

Most projects designed by Calatrava show holistic and embedded variations, and a clear gradual change of pattern; these two bridges can be deemed representative of part of his oeuvre, thus satisfying the second criterion. Based on them, we may find "similar" structures in his oeuvre.

To test the potential of the proposed model to generalize, we focus on the development and re-use of the main supports of these bridges, which present similarities and a pattern of differentiation that satisfy the third and fourth criteria. The fifth criterion is also satisfied since Calatrava's projects have been widely published.

Methodologically, the case used biological concepts as revealed in Chapter 5, and the architectural genetic framework as well as the P.O.M. reasoning system of Chapter 6, both illustrated in Chapter 7.

The case method is as follows:

1. General description of the main supports of the aforesaid bridges, and how they are linked to the other elements of the project.
2. The earlier description of the bridges will be structured to see whether they could fit in our model; and therefore, to check whether the representation can be generalized to represent the work of another architect.

[6] Calatrava was born in Valencia, Spain in 1951. He graduated in architecture at the Escuela Tecnica Superior de Arquitectura of Valencia in 1974 and in Structural Engineering at ETH of Zurich, Switzerland in 1979. At the latter, he completed his doctorate in Technical Sciences in 1981. The subject of his dissertation was foldable structures. He now has one studio in Zurich and another in Paris.

3. A series of designs is presented showing how a selected feature, arches and hangers, of the Lusitania and Puerto bridges was re-used and recombined into new contexts.
4. The representation is tested against the adequacy criteria produced in Chapter 3 and on general research criteria.

CHAPTER 3

SOCIAL HOUSING PROJECTS OF J.J.P. OUD

A Case to Search for Adequacy Criteria for the Model

Chapter 2 presented our research method. It showed the role of the model, of the analogy and of the case studies in this research. Chapter 3 presents our first step in the development of the model. The objective of this chapter is to produce some adequacy criteria, which should be satisfied if the model is to be used by architects working in architectural practice, in order to have some direction in the development of our model. To reach our objective we carried out our first case study. These adequacy criteria indicate more precisely the pragmatic approach that is necessary in applying the analogy between design and the biological Darwinian and genetic models.

This first case is applied to the social housing projects of the Dutch architect J.J.P. OUD (mainly) in Rotterdam from circa 1918 to 1930. According to Robert Yin's terminology in his *Case Study Research, Design and Methods,* this case is descriptive (Yin 1994). By observing drawings and reading texts, we describe the phenomenon of change through the re-use of design precedents carried out during the production of a series of designs. Based on our observation and extant literature, we claim that Oud recollected precedents and adapted them to fit new situations. From these observations, the chapter will provide a series of adequacy criteria.

Reflecting on the adequacy criteria, this case led us to a first line of approach in our analogy between the re-use of design precedents and firstly the Darwinian theory of evolution, in the sense that evolution is not progress but the survival of the (relative to the present situation) fittest; and secondly Genetics in the sense that parts of the precedents are re-used in the design of new solutions like the way in which genes are copied/re-used from generation to generation, albeit expressed within innumerous variations.

The designs selected for the analysis are:

- Spangen Municipal Housing Scheme: Blocks I and V; Spaanse Bocht, Rotterdam, 1918-1920
- Spangen Municipal Housing Scheme: Blocks VIII and IX; Spaanse Bocht, Rotterdam, 1919-1920
- Tusschendijken Municipal Housing Scheme: Blocks I, II, III, IV and VI; Rotterdam, 1920-1924
- Oud-Mathenesse Municipal Housing Scheme: (Het Witte Dorp), Rotterdam, 1922-1924
- Hoek van Holland Housing Scheme, 2de Scheepvaartstraat 91-113, Rotterdam, 1924-1927
- Kiefhoek Workers' Housing, Groene Hilledijk, Rotterdam, 1925-1930
- Five Row Houses in the Weissenhofsiedlung, Stuttgart, 1927

The first three building projects are four-story buildings and the other four designs are low-rise buildings (two floors). The Row Houses of Hoek van Holland is the only project that is composed of independent ground floor[1] or first floor houses; the other low-rise projects are composed of row houses. Further, we focus on the house unit level, considering the urban plan only when it has direct influence on the design of the units.

Just before the chosen period, Oud designed three experimental housing projects[2]: the Row Houses, Strandboulevard, 1917; the Double Workers' Housing in Reinforced Concrete, 1918; and the Standard Housing for Workers, 1918[3]. These designs were published in the journal *De Stijl*. Oud developed several concepts and principles in these experimental designs that would be frequently re-used in Oud's further involvement with social housing. These experimental housing projects will therefore also be approached and described in this chapter.

This chapter will proceed as follows: first, we will highlight some aspects of the historical moment in which Oud was working, which was concurrent with the

[1] The first floor in The United States is called the ground floor in The Netherlands.

[2] Illustrations on the descriptive section

[3] The project names follow the translation of Ed Taverne et al. in the book *Oud, Poetic Functionalist 1890-1963, The Complete Works.* Nai Publishers.(Taverne 2001).

period of emergence of modern architecture. Second, we will briefly describe several principles and needs that were relevant to Oud. Third, we will describe the experimental projects. Fourth, we will describe the social housing projects for Rotterdam and Stuttgart, and in particular, the elements of the projects that were presumably re-used and adapted. From this description, we will look for adequacy criteria for our model. Fifth, we will interpret the process of use and adaptation revealing the possible similarities in the process of re-using parts of the projects. Finally, we will show a set of propositions that will serve as adequacy criteria for the model. Readers who are not interested in the historical account of Oud's projects may wish to skip the descriptive section and go directly to the interpretation of the process of recollection and adaptation.

3.1. Oud's Conceptual Ideas

Before we describe Oud's designs, we need to know which conceptual ideas came into being during these projects and were modified through his experience, and how. The documents used in this section do not exhaust the material found in Oud's archives or the bibliography concerning *De Stijl* or Oud. They were selected according to their contents related to the re-use of precedents, and the description of principles and projects.

In this section, we briefly approach the period from the turn of the century to the 1920s. Due to the scope of this case, we are not concerned with describing the origins of functionalism (Collins 1965; Wright 1972; De Zurko 1957), or the discrepancies between functionalism in the United States and the European formalistic or ideological functionalism (Tzonis 1972, p. 88), although both are important for an understanding of the period of the emergence of modern architecture. Rather, we are concerned with how Oud interpreted and used the concepts of his contemporaries. The views of Oud's contemporaries such as Theo van Doesburg and Piet Mondrian are only described because they were, at a crucial moment, Oud's point of departure. In the course of the section, we show Oud's divergence from the initial principles and his reasons for such divergence.

Without doubt, the change of expression in Oud's designs was reinforced by the need for mechanization of construction in Europe[4]; the use of geometric forms and the abandonment of historical forms proclaimed by Berlage[5], Wright (Wright 1972, p. 107), and later Van Doesburg (Doesburg 1924); the political position of

[4] In 1910, Gropius proclaimed the need to industrialize housing construction in Germany, and in 1911 he propagated his idea in his Faguswerken – De 8 en Opbouw, no. 17, 1935, p. 76.

[5] Hanno-Walter Kruft says that Berlage's three "demands of the architecture of the future" were: "a. The foundation of an architectural composition shall once again be based on a geometric scheme; b. The characteristic forms of earlier styles shall not be used; c. Architectural forms shall be developed in an objective direction." Berlage stated: "Ornament too must be governed by geometric laws, for this is the only way in which a new style can develop." (Kruft 1994, p. 378)

Berlage[6]; and the Neo-Plasticism of Mondrian. Oud follows the developments in Europe and the United States, interprets the events, evaluates their concepts and conducts experiments testing their validity, as we shall describe in the next two sections. One of Oud's turning points took place when he engaged in the activities of *De Stijl*[7], so we shall spend some time describing the environment around this movement.

De Stijl was a journal edited by Van Doesburg that had painters, sculptors and architects as regular contributors. In the formative years of *De Stijl*[8], the most regular contributors were Van Doesburg himself, Mondrian, Huszar, Kok, Van der Leck, Oud, Wils, as well as (a little later) Van 't Hoff, Vantogeloo and Rietveld (Blotkamp 1986, VIII).

Hanno-Walter Kruft (Kruft 1994, p. 378) wrote that *De Stijl's* fundamental roots lay in the theosophical ideas of M.H.J. Schoenmaekers, a former priest and theosopher who was a friend of Mondrian. This influence of Schoenmaekers would be then felt through the articles of Mondrian. There is, however, some evidence indicating that this influence was not extensive. According to Els Hoek, "Mondrian's article 'Neo-Plasticism in painting' appears to be based largely on Schoenmakers' theories. However, on closer scrutiny it appears that Schoenmaekers' influence is mostly limited to Mondrian's terminology. Mondrian copied the names Schoenmaekers had used for certain phenomena in the books *The New Image of the World* and *Plastic Mathematics* but ignored ideas Schoenmaekers had taken from physics. The ideas that Mondrian put forward in his articles were his own, and they pre-dated his meeting Schoenmaekers. His Paris sketchbooks and other evidence make it clear that he had developed these ideas long before he met Schoenmaekers (Hoek 1986, p. 49)."

One can say that although *De Stijl* was not formed by a cohesive group[9], it was a movement which had as a departure point some (mostly esthetical) principles

[6] "In Berlage's view," says Kruft, "the subjective concept of art, to him the product of capitalism had to make way for a communal art based on the working-class movement: a rational architecture is the expression of a new feeling towards the world, the social equality of all mankind." (Kruft 1994, p. 378)

[7] The members of *De Stijl* such as J.J.P. Oud, Van Doesburg, Mondrian, Gerrit Rietveld together with Hendrik Petrus Berlage, Frank Lloyd Wright, Adolf Loos, Le Corbusier, as well as many others behind Bauhaus, Cubism, Futurism, and the CIAM were main players in the changing of the architectural expression of the 20th century.

[8] According to Blotkamp et al., the formative years of *De Stijl* were from 1917 to 1920.

[9] Controversies are found in the literature over considering *De Stijl* as a group and not just a journal. "In general reviews of twentieth-century art," claims Carel Blotkamp (Blotkamp 1982, VIII), "and also in the literature pertaining to De Stijl, it is almost invariably remarked that De Stijl was the name of a periodical, not of a group. Nevertheless, the regular contributors are often pictured as a cohesive body." Further, "De Stijl was not such an artists' collective; at least, it was not like the other avant-garde movements of the first half of the century." "During the years when De Stijl was published," continued Blotkamp, "there was not one single exhibition in which all the collaborators participated. As far as is known, there was never a meeting where more than three or four of the men involved were preset simultaneously - not even in the beginning when there was

from the fine arts and led its members to interpret, transfer and develop them for their own fields. A. Elzas mentioned in his article "Theo van Doesburg 1883-1931" of 1935 for *De 8 en Opbouw* that Van Doesburg wrote about the collective requirement of *De Stijl*[10] and that he claimed that the work of architects and sculptors was to discover the right elements of creation in their own field. These elements were the following: color for painters; volume for sculptors; and space and materials for architects. Specifically in relation to architecture, Van Doesburg claimed that the challenge "was to transfer the principles of fine art to architecture" (Elzas 1935, p. 78). Oud was one of the architects engaged in this activity of transferring the principles mainly developed by Piet Mondrian's theoretical work on Neo-Plasticism. However, as we will see later in this section, Oud did not totally agree with the rigid principles that disregarded social and economic issues related to his field.

Some of the general design principles were to:

- Find a scientific precision free of subjectiveness, emotion and nature; i.e. objectiveness as opposed to subjectiveness;
- Accept the phenomenon of the metropolis instead of nature;
- Concentrate on the universal instead of the individual;
- Use straight lines, right angles, and simple forms to create space and light;
- Use primary colors as well as the use of black, white and gray;
- Use new materials in architecture such as iron, glass and concrete;
- Accept new technologies, implying regularity and standardization, therefore industrialization of the building sector.

Looking at this set of principles, one must link some of them to European Cubism and some to Frank Lloyd Wright, or both. In the article "The Influence of Frank Lloyd Wright on the Architecture of Europe" in Wendingen (1926), Oud compared Wright's architecture with European Cubism and presented several similarities. Oud wrote: "The shifting of the planes; the projecting penthouse roofs; the repeatedly interrupted and again continued masses and predominantly horizontal development of the building characterize Wright's designs (Oud 1926)". However, he wrote that it was "a mistake to ascribe the arising of these features exclusively to him [Wright]."

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sufficient reason to discuss their collaboration and the principles they would manifest collectively." However, continues Blotkamp, "there existed a common ground; otherwise the journal would never come into being. Apparently, Van Doesburg's initiative was a response to the need of a number of artists, working in different fields, to manifest themselves outside the existing journals and associations.

[10] This **collective** requirement was founded on the absolute refutation of the tradition

He mentioned that the following principles belonged to Wright as well as Cubism:

- The use of the right angle;
- The tendency to a third dimension;
- The breaking up of bodies and re-combination of their parts;
- The striving to gather many small parts – previously obtained through analysis – into a whole which, in its appearance, still betrays the elements of the original dissection;
- The application of new materials, new methods, and new constructions;
- The conforming to new demands.

Oud concentrated mainly on formalistic similarities between the principles followed on the one hand by *De Stijl* and on the other hand by Frank Lloyd Wright; i.e. principles that could be used in a straightforward manner in designing. The influence of Wright on the architecture of Europe is, according to this article, limited to a reading of his designs as products. The ideological process behind these similarities is disregarded. It seems that most members of *De Stijl* ignored Frank Lloyd Wright's concept of organic architecture as opposed to the "escape from nature" of *De Stijl*.

The differences pointed out by Oud between Wright and the European Cubists, though, seem to be less formalistic; i.e. they seem to be of a more general order. According to Oud, "the plastic exuberance, the sensuous abundance and luxurious growth which could only suit American 'high-life' are typical from Wright. While the puritanical asceticism, the mental abstinence and the humble level of abstraction are typical from the European Cubism (Oud 1926)."

With this article, Oud showed direct links between European Cubism, Wright and the Neo-Plasticism of *De Stijl*, all making use of features such as straight lines, right angles and applications of new materials. The use of principles asks for consideration in developing our list of adequacy criteria.

Van Doesburg, meanwhile, saw more differences than similarities between *De Stijl* and Cubism to the point that he called the new [*De Stijl*] architecture anti-cubic and claimed that *De Stijl* only defended Cubism in the second instance, as a movement that preceded it (Doesburg 1922, pp. 141-142). For Van Doesburg, the differences between Cubism and Neo-Plasticism were that "instead of seeking to assemble the different functional room-cells in one single enclosed cube, it [the Neo-Plasticism] projects these cells, together with areas such as porches and enclosed balconies, outwards from the centre of the cube, as a result of which height, breadth and depth, plus time, combine to produce a completely new pictorial expression in the open rooms (Doesburg 1924, p. 81)."

In the first issue of this journal (1917), Oud published the article "Het Monumentale Stadsbeeld" [The Monumental Image of the City], in which he set out some of his ideas on urbanism and architecture. In this article, Oud wrote that the city layout is dominated by two factors: the street – as composed of rows of houses – and the square – as the center of streets. The image of the street mainly determines the image of the city; thus, to determine the characteristics of the modern street, one should take the image of the street in its totality. On an idealistic level, the image of the street should be universal and monumental[11] following the evolution in architecture, i.e. allying itself to some of the ideas of Berlage. On a practical level, there should be a consideration of the building block because, according to his belief, in modern city planning, private initiative would tend to disappear and therefore the building block would largely replace the building of individual houses (Oud 1917, pp. 15-16).

However, many of the characteristics of the modern building block are in line with neither those of Berlage, nor those of most members of *De Stijl*, who treated architecture as an applied fine art. According to Mondrian's article in *De Stijl* (Mondrian 1917, I: p. 132): "The really modern artist regards the city as an embodiment of abstract life. It is closer to him than Nature and is more likely to convey to him a feeling of beauty, for in the city Nature is ordered, regulated by the human mind. The proportions and the rhythm of lines and surfaces mean more to him than do the whims of Nature. In the city beauty expresses itself mathematically; the city is therefore the place from which the mathematical-artistic temperament of the future must be evolved, the place from which the new style must begin its advance." In *De Stijl*, "architecture was a problem of artistic form: functionalism, construction and materials were subsidiary matters (Kruft 1994, p. 379)."

Esthetically, the new architecture shows a distinct rhythm for Oud. He accepts modern materials as well as the flat roof, with its consequences: the solution of horizontal spans by iron and concrete and the treatment of surfaces with modern materials. In his article, De Nieuwe Bouwkunst-Beweging in Europa (Oud 1935), Oud named other characteristics that were peculiar to the new architecture at that time, such as the interplay between mass and space, and between interior and exterior, the use of flat surfaces, openness, and pure proportions (Oud 1981, pp. 20-21). Moreover, the creed "maximal requirements in minimal spaces" is, according to Esser, a slogan that "would return again and again in the following years (Esser 1986, p. 136)."

However, Oud did not totally agree that the principles of *De Stijl* could be so rigidly used in architecture as they could be applied to the other arts. He never signed *De Stijl*'s manifesto (see Table 1: *De Stijl's* Manifesto I of 1918) and it was

[11] Van Doesburg wrote in De Stijl (Doesburg 1918, 2: pp. 10-12) that a monumental style means a balanced labor distribution of the diverse arts. By balanced labor distribution it is meant that artist

during his time with the group that he designed the housing blocks at Spangen (1918-1919) and the eight blocks at Tusschendijken (1921-1923), which hardly resemble any of the principles of *De Stijl*. Nevertheless, *De Stijl* seems to have helped Oud to form his own ideas on Neo-Plasticism.

Other differences in approach appear with regard to cooperation. Appealing, like Berlage, for a joining of forces with other arts, Oud did not, however, agree with the role that the painters in *De Stijl* would like to have in architecture. "Oud looked at collaboration," commented Esser, "in a traditional way, from the viewpoint of his own field of specialization: the architect should make room for the painter and the sculptor. Van Doesburg, on the other hand, took modern painting as his starting point (Esser 1986, p.126)."

Manifesto I of "De Stijl," 1918	
1.	There are an old and a new consciousness of time.
	The old is connected with the individual.
	The new is connected with the universal.
	The struggle of the individual against the universal is revealing itself in the world war as well as in the art of the present day.
2.	The war is destroying the old world with its contents: individual domination in every state.
3.	The new art has brought forth what the new consciousness of time contains: a balance between the universal and the individual.
4.	The new consciousness is prepared to realize internal life as well as external life.
5.	Tradition, dogmas and domination of the individual are opposed to this realization.
6.	The founders of the new plastic art therefore call upon all who believe in the reformation of art and culture to annihilate these obstacles of development, as they have annihilated in the new plastic art (by abolishing natural form) that, which prevents the clear expression of art, the utmost consequence of all art notion.
7.	The artists of today have been driven the whole world over by the same consciousness, and therefore have taken part from an intellectual point of view in this war against the domination of individual despotism. They therefore sympathize with all who work for the formation of an international unity in Life, Art, and Culture, either intellectually or materially.
8.	The monthly editions of "The Style", founded for that purpose, try to attain the new wisdom of Life in an exact manner.
9.	Co-operation is possible by: I - Sending, with entire approval, name, address, and profession to the editor of "The Style". II - Sending critical, philosophical, architectural, scientific, literary, and musical articles or reproductions. III - Translating articles in different languages or distributing thoughts published in "The Style".
This manifesto was signed by: Van Doesburg (painter), Van 't Hoff (architect), Huszar (painter), Kok (poet), Mondrian (painter), Vantongerloo (sculptor), Wils (architect). Published in De Stijl 2, no. 1.	

Table 1: Manifesto I of `De Stijl 1918

Els Hoek wrote in her essay "Piet Mondrian" that "for Van Doesburg, just as for Mondrian, the greatest objection to Oud's ideas was that Oud let utility prevail

limits themselves to their own fields.

over the aesthetic principles of Neo-Plasticism (Hoek 1986, p. 71).” Hoek mentioned two articles published in the *Bouwkundig weekblad* in which Van Doesburg showed the importance of these principles for the new architecture. The difference in their architectural approaches comes to the surface in a passionate discussion between Oud and Van Doesburg published in *Bouwwereld*, in which the latter questions the validity of Oud's Cubist Architecture (Doesburg 1922, p. 54).

Besides this formalistic divergence, there were also the social and economic aspects of public housing. Oud designed housing projects for the working class and he claimed that the indifference of *De Stijl* towards social questions was such that he had to withdraw his support for the movement. He broke with *De Stijl* in 1922.

In 1925, Oud designed the two connected housing blocks at Hoek van Holland where he made use of the curve. In the article “10 Jaren Stijl 1917-1927”, Van Doesburg maintained his formalistic attack and wrote that Oud, in designing this project, was influenced by Van de Velde and wanted to move to the side of the Jugend-stil. Oud claimed that Van Doesburg would have taken a better approach if he had looked at it as an artist with fewer principles and more open-mindedness (Oud 1963, p. 54). However, Oud also knew that from this moment on he was moving from “zakelijk functionalism” to his “poëtische functionalism” (Oud 1963, pp. 54-55).

Oud did not sign manifestos or permanently join a group or movement. It is remarkable that he did not participate in any of the CIAM (Congrès Internationaux d’Architecture Moderne, formed in 1928) meetings of that time. Oud claimed in his article “Le Corbusier” (1958) that he tried to convince S. Giedion, the secretary of the CIAM, that “elk object van bouwactiviteit bezien moet worden, in een geestelijke sfeer die alles bindt. Men was daartegen en meende probleem voor probleem op te moeten lossen. Op zichzelf. Omdat dit me principieel onjuist lijkt, heb ik me buiten deze congressen gehouden (Oud 1958, p. 130).” That is to say that each object of building activity should be considered under an all-binding mental/spiritual atmosphere. The group opposed this and advocated solving problems individually, one by one. Oud did not agree with this approach, and hence stayed away from the conferences.

In 1958, Oud claimed that he appreciated Le Corbusier as an architect when he built in the model-village Weissenhof, Stuttgart, in 1927 more than in his later period. Oud remarked that at that time all participants – including Oud himself – had equal principles and the village became a milestone for the new architecture. He wrote that Le Corbusier had more to show later, although he provided more to think about in earlier times, and that those thoughts were still of value. Oud also argued that Le Corbusier’s “Ville Radieuse” was too abstract and called it “vervelend principieel”, i.e. annoyingly dogmatic. Oud felt that building required a simpler approach (Oud 1958, pp. 128-132).

"Principle before precedent" is what Wright (Wright 1972, p. 107), and also the Modernists, seem to proclaim; however, they also want mass production and mechanization in the building industry, which consequently guides them to the question of standardization and development of house prototypes. In this way, they negate the forms of the past, but not the re-use of their current plans. Oud seems to have been collecting principles and information from several sources as well as conducting experiments that would form his own path.

The emergent concepts and those somewhat converging streams formed the background against which Oud produced the series of projects that we shall now describe. In the next section, we are going to describe three early experimental housing projects by Oud and describe how he translated those principles into designs.

3.2. Description of Three Early Experimental Housing Projects

According to Hans Oud (1984) in his book *J.J.P. Oud, Architekt 1890-1963*[12], very little attention has been paid to Oud's projects of the early years (1906-1917), which would seem to give the impression that projects like the Seafront Terrace House (Strandboulevard) in Scheveningen (1917) and the Factory and Bonded Warehouse at Purmerend (1919) are a result of a **sudden mutation** in his design process (Hans-Oud 1984, pp. 19-20). Hans Oud thus recalls several projects in which he claims there is a clear influence of Berlage, such as the facade of Oud's "Volksbadhuis" (Public Swimming Pool) of 1915, which shows similarities with the façade of the "Beurs van Berlage" in Amsterdam. Also, there is Oud's first house (1906)[13], in which it is possible to identify patterns of the English country houses that Oud highly appreciated at that time (Hans Oud 1984, pp. 19-20). In this research, we turn our attention to the early projects in search of possible design precedents. Three experimental housing projects published in *De Stijl* are interesting because they seem to show how Oud translated many of his concepts into practice.

3.2.1. Seafront Terrace Housing (Strandboulevard), Scheveningen, 1917

In an article published in the first issue of *De Stijl* (1917), Van Doesburg wrote that the task of the architect is to use space and in esthetic proportion to express it from the inside to the outside. The exterior expresses the interior and both

[12] Hans Oud is the son of J.J.P. Oud. To avoid confusion, we will always refer to Hans Oud by his full name. In references we will place (b) after his name thus: (Oud(b) 1984).
[13] Residence of A. Oud-Hartog, J.J.P. Oud's Aunt.

comprise a unit: the building. In his opinion, the Row Houses for the Strandboulevard constitute an outstanding example in The Netherlands that expresses the possibilities of monumental mass construction relying on harmonious plastic fundamentals. The relation between horizontal and vertical motives controls the total composition, and has remarkable similarities with good modern painting (Doesburg 1917, pp. 11-12).

In this design, Oud showed his interpretation of *De Stijl*'s and Cubist principles, as well as mechanized building production. The Row Houses of the Strandboulevard were meant to show what the new architecture would look like (Colenbrander 1981, p. 31; Hans-Oud 1984, p. 44).

Hans Oud suggested that this design is a Cubist experience almost certainly deriving from Villa Allegona (Hans Oud 1984, p. 44). If this claim is proven true, the Row Houses have North African precedents. Allegona was a renovation project designed by Oud and Kamerlingh Onnes in conjunction with Van Doesburg. However, Oud thought that Kamerlingh Onnes' contribution was so extensive that later he would not present the design as his own (Esser 1986, pp. 127-128). Kamerlingh Onnes was inspired by the block-shaped houses of North Africa.

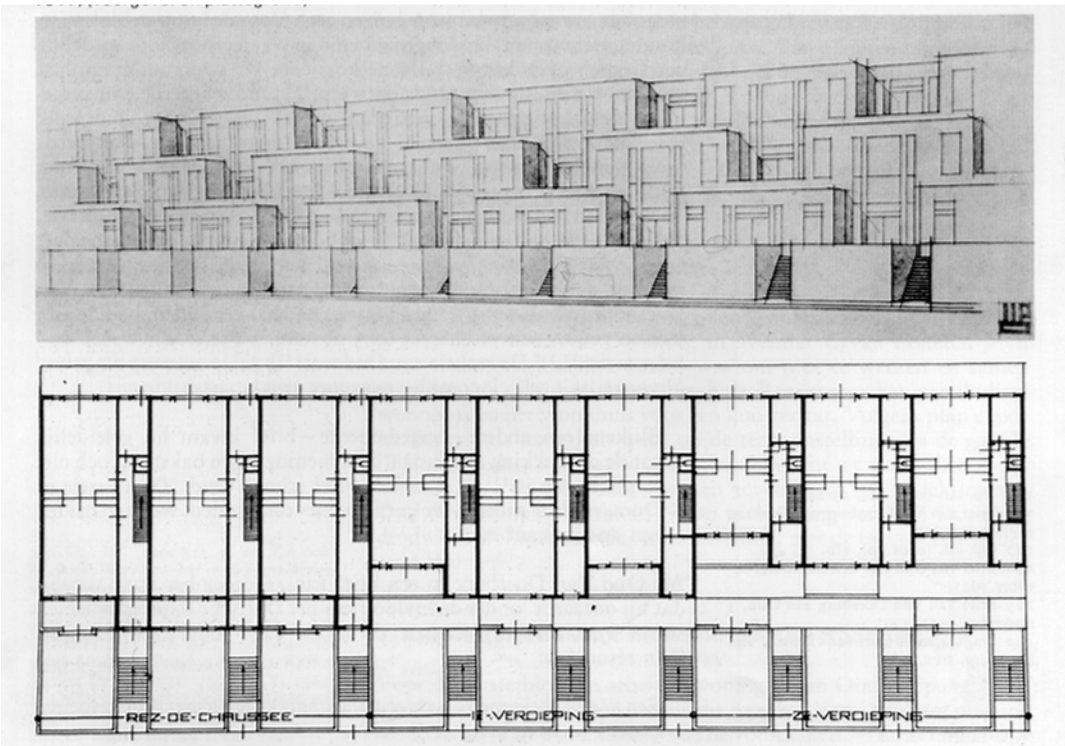

Figure 1: Row Houses, Strandboulevard, Scheveningen, 1917, perspective & plan layout

Examining its layout plan, K. Wiekart (Wiekart 1965, pp. 17-18) had the impression that each house could be recognized as a unit from the street by an outsider, although a further study (Figure 1) of the plan shows that the units belong to more than one volume (Hans Oud 1984, p. 45). In the Row Houses of the Strandboulevard, it seems that neither the plan layout nor the rear façade were a priority; this emphasizes the notion that the objective of such a project was a search for architectural expression.

3.2.2. Double Worker's Dwelling in Reinforced Concrete, 1918

There are two alternative designs, of which one was published in *De Stijl*. In this alternative (Figure 2), one can see morphological similarities such as the entrance, the continuous window that separates the roof from the rest of the building, and the basement that raises the volume from the ground (Barbieri 1986, p. 44) similar to Wright's Winslow House (1893).

In the second alternative (Figure 3), Oud seems to give more attention to the plan layout of the first floor than in the Wrightian version, where the position of the staircase disturbs the layout of the first floor (Hans Oud 1984).

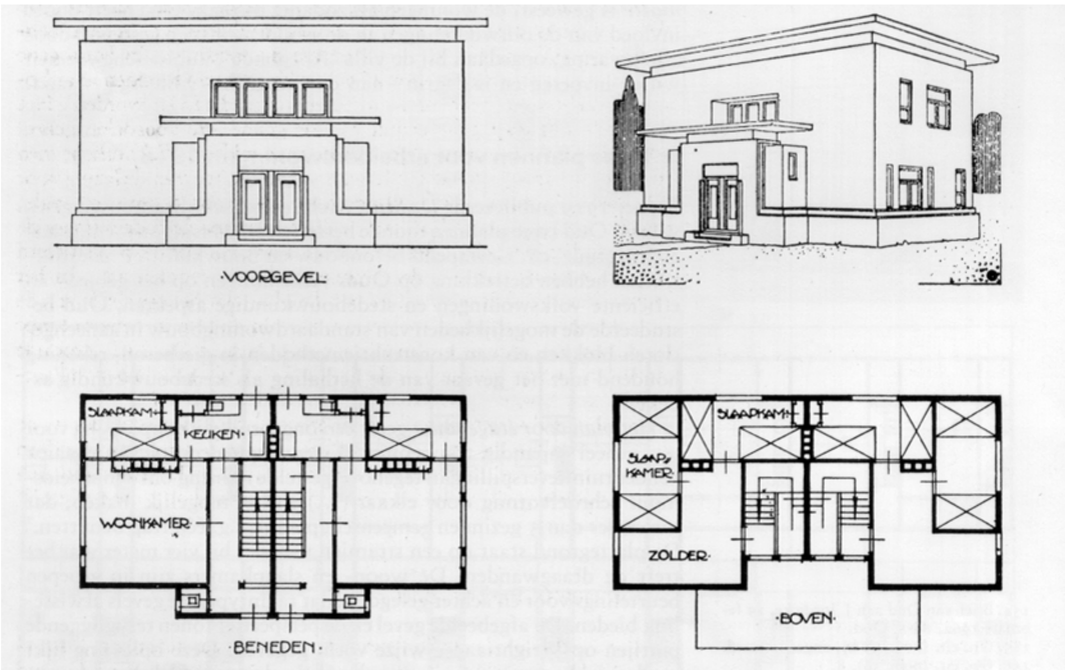

Figure 2: Double Workers' Housing in Reinforced Concrete, 1918, façade, persp. & plan layout

With the exception of one bedroom on the ground floor, all the rooms of both alternatives can be accessed independently via the hall. This independent circulation is common to the villas that he designed; however, this is not seen in his Leiderdorp social houses (1914).

Both alternatives show a play in symmetry. The "Wrightian" alternative gives the idea that you are in front of a villa rather than two semi-detached houses. This effect is given by the proximity of the two doors and reinforced by the composition within a projecting volume.

The project is a plan made with reinforced concrete. Hans Oud claimed, however, that Oud does not take much advantage of the quality of this material to open, for example, large windows, and thus it could have been built with traditional materials. In their *J.J.P. Oud, Poetic Functionalist 1890-1963, The Complete Works*, Ed Taverne et al. assert that the text of Oud's article 'Reinforced Concrete and Architecture' is "symptomatic of the somewhat exalted tone of the debate among Dutch architects on the significance of reinforced concrete for a *modern monumental architecture*." They are also surprised that "The verbal euphoria is in strange contrast to the accompanying illustration of a design for a *double worker's dwelling in reinforced concrete* which displays a far from spectacular use of concrete's much-vaunted structural possibilities" (Taverne et al. 2001, p. 212).

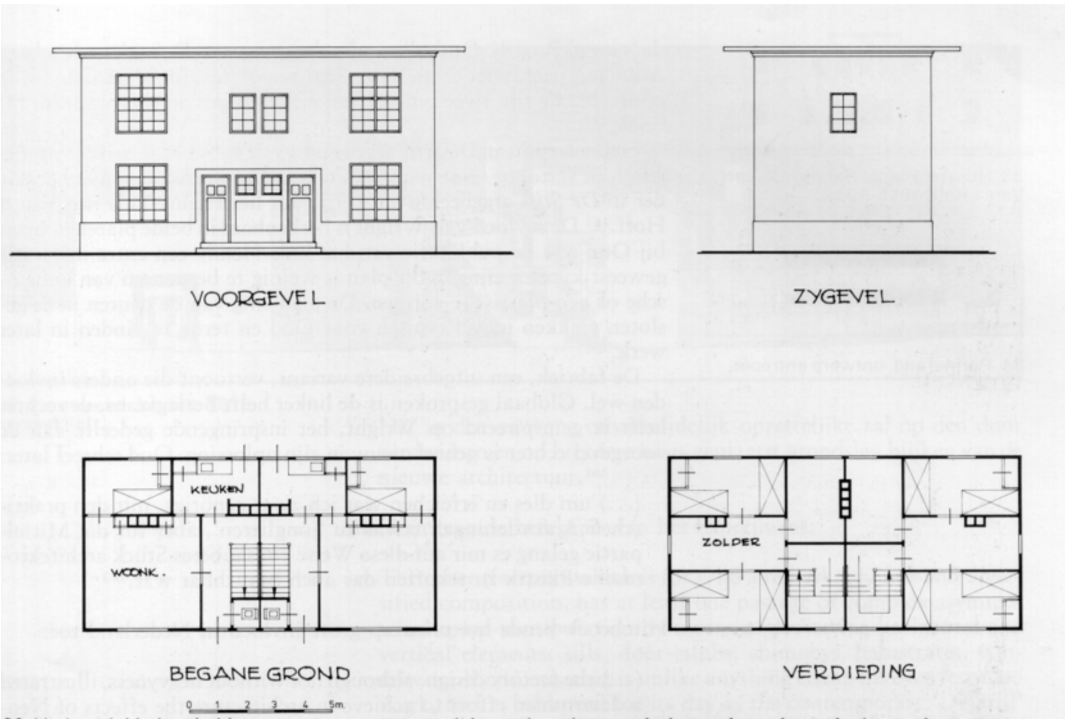

Figure 3: Second Double Workers' Housing in Reinforced Concrete, 1918, façades & plan layout

3.2.3. Standard Housing Types and Street Composition, 1918

The standard house units constitute a main step toward the design of the building block. In Oud's 1919 article "Architectonische Beschouwingen" [Architectural Critique] for *De Stijl* (Oud 1919, pp. 79-84), he described his project.

First, Oud showed his preoccupation with the building industry[14]. He developed a plan within a systematic/constructive layout by means of improving the productivity of the building industry. On the one hand, Oud subdivided the building into structural elements, i.e. the façades (Figure 4) and the structural walls between the house units, and on the other hand into non-structural elements, i.e. the partition walls within a unit. The structural elements stand regularly on a 4m grid.

Second, he placed importance on light. Despite the minimal length of the façades to meet economic requirements, the façades of the units bring natural light into the most important parts of the house; i.e. the living rooms and the bedrooms. For the same reason, Oud locates the staircases in the center of the block between each group of six-house units; the light of the staircase should come from the roof.

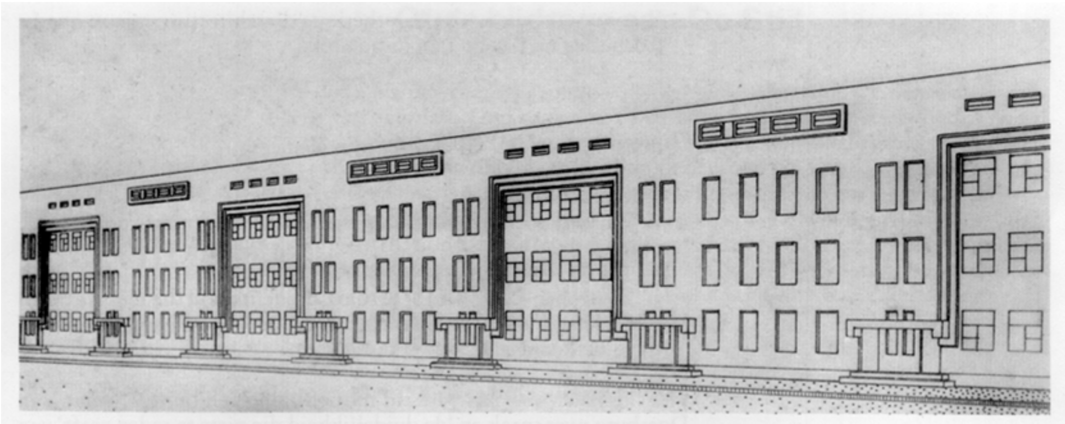

Figure 4: Standardized Housing for Workers, 1918, perspective of the main façade

Third, he designed scissor stairs[15], i.e. a pair of two individual staircases rotating around each other, each giving access to three flats. The stairs have individual entrances that are grouped at façade level. Such a solution seems to give the privacy of sharing common access with few neighbors. The disadvantage of this solution is on the level of readability, because one must take the left door to reach an apartment on the first floor to the right side, since the apartments connected by one staircase are not positioned one upon another.

Fourth, the divided-in-two staircase imposes an arrangement with alternate house-unit doors, which has consequences for the layout of the house units (Figure 5). This is probably the reason why Oud alternates the position of the living rooms

[14] Standardization in mass construction for Oud means a cost-cutting, efficient construction method, based on standard elements and less specialized labor, and a means towards a new esthetics related to modern painting. (Oud 1919, pp. 79-84)

[15] "Two staircases rotate, without any waste of space, in opposite directions, around the dividing wall, in a double helix, so that the stairwell actually contains two individual staircases that are completely separated from one another and which make it possible for no more than three families to share one stair." - Oud, J.J.P. 1919. "Architectural Critique." De Stijl

in groups of two. One may detect that these mirrored flats are not completely similar; the kitchens, for example, remain in the same place directly linked to balconies that, in this way, are always facing the "backyard[16]" of the building.

In his article, Oud does not show any corner solution for his housing block or courtyard layout. The façade and the perspective show, according to Hans Oud, a Wrightian style and he noted that the presented façade is probably a later addition because it does not completely match the plan layout (Hans Oud 1984, p. 45).

According to Taverne et al., "the principal innovation of this design, compared with Oud's own Strandboulevard design and with housing blocks by Berlage and De Bazel in Amsterdam, is the organization of the staircase (Taverne 2001, 207)." Every structural unit has two porch entrances each giving access to one staircase that gives access to 3 apartments.

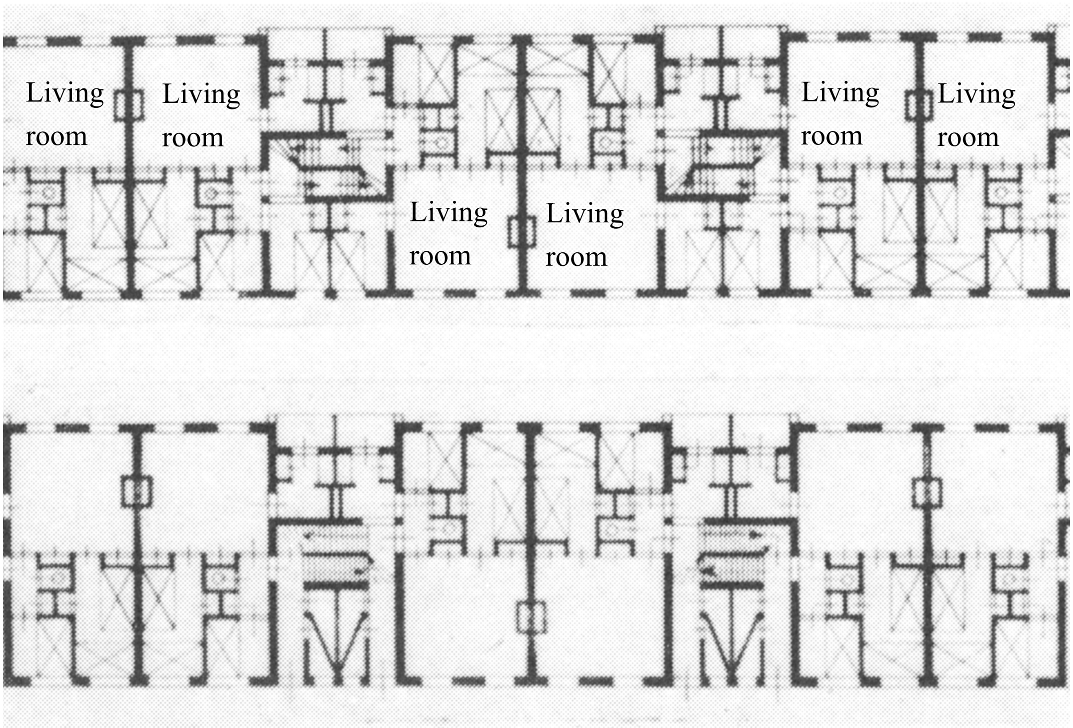

Figure 5: Standardized Housing for Workers, 1918, plan layout

3.3. The Re-Use of Precedents in Oud's Projects

We shall now describe a series of projects based on the observation of numerous authors including Oud himself. We consider anything that is re-used from past experience a precedent; it may be, for example, a concept, a structure, a layout, or

[16] We use the word backyard merely to indicate a direction, meaning not facing the represented street. Oud did not define what was at the back of the building.

a detail. In this section, as in the last one, we shall avoid giving our own interpretation to the phenomenon of change in the process of the re-use of design precedents.

3.3.1. Spangen Municipal Housing Scheme: Blocks I and V; Spaanse Bocht, Rotterdam, 1918-1920

This is the first worker's housing project that Oud designed after his appointment to work as an architect by the municipality of Rotterdam. Oud designed blocks 1 and 5 (Figure 6), apart from the buildings facing Bilderdijk Street, which were already contracted to the Onze Woning [Our Home] housing association. Meischke and Schmidt designed these buildings. In order to integrate the designs, these architects and Oud agreed on: a) the same floor height; b) the use of three horizontal bands on the plinth of the street façade, which Oud had already used in his project "De Vonk"; and c) a continuous roof gutter (gootlijst) at the same height. One given requirement was that the building alignment (rooilijn) should be defined by the street edge. And according to Esser, Oud adjusted the corner solutions to those of Meischke and Schmidt (Esser 1986). Esser claimed that "Oud had to come up with a completely detailed design within a very short time. The lot was ready for development in the beginning of 1918 (Esser 1986, p. 133)."

A main recollection of a design precedent in this design seems to be the layout plan (Figure 7). According to Esser, Oud was urged by the municipal authorities to use the plan layout of C.N. van Goor as a standard or starting point (Esser 1986, p. 134). Taverne et al. (2001) claimed that Oud availed himself of a standard type for the floor plan; this standard type was "previously used by, among others, J.E. van der Pek in The Hague, and C.N. van Goor in Rotterdam: a relatively small dwelling comprising one 'big' living room, two to four small bedrooms, a kitchen and toilet (Oud, Taverne et al. 2001, p. 219)." Whether he was urged to use it or he used it of his own free choice, and whether the project was indeed from Van Goor or only used by him, the fact is that this layout is a design precedent borrowed by Oud and adapted to fit the rest of his design. For example, in a search for greater regularity, Oud changed the placement of some closets, the chimney, and windows (Hans Oud 1984, p. 20[17]; Oud 1920, pp. 219-222[18]). This layout also bears similarities to what Dudok and Oud developed in the public housing complex in Leiderdorp (1916).

[17] Oud, Hans. 1984. "Ouds opgang als architekt van het Nieuwe Bouwen 1918-1933." *J.J.P. Oud, Architekt 1890-1963 - Feiten en herinnering gerangschikt*. The Hague: Nijgh & Van Ditmar. pp. 63-64

[18] Oud, J.J.P.: 1920, *Gemeentelijke volkswoningen, Polder 'Spangen' te Rotterdam,* Bouwkundige weekblad, 41, 37, pp. 219-222

Figure 6: Spangen Housing State: Block I and V, Rotterdam, 1918

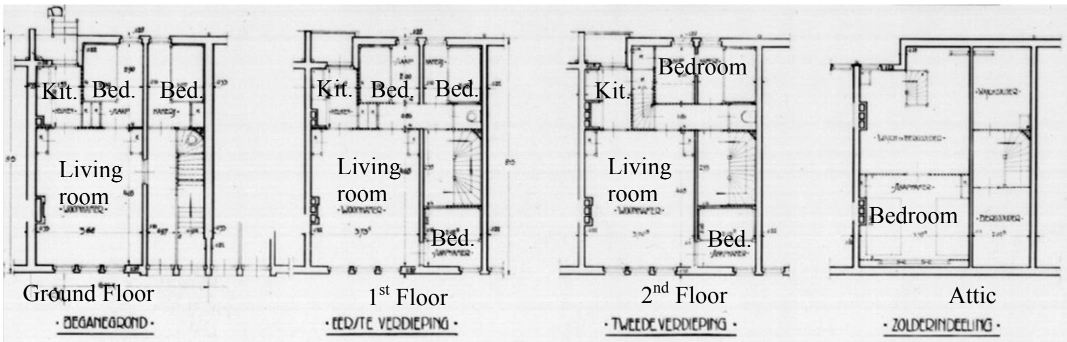

Figure 7: Spangen Housing State: Block I and V, Rotterdam, 1918, plan layout

In Blocks I and V, each group of 6-stacked units is accessed by a group of four doors; the two ground-floor units have individual entrances. Between the ground-floor front doors, there are two entrances with stairs for the units above. Each stairway gives access to one unit on the first floor and to another unit on the second floor. Each unit on the second floor has internal stairs that give access to an attic.

According to Esser (Esser 1986, p. 134), Oud collaborated with Van Doesburg during this design. The latter designed two types of glass windows to be installed above the doors, and he also designated the colors for the exterior woodwork of the dwelling as well as for its interior. Esser emphasized that “By this manner of applying colors to the façades, Van Doesburg tried to cancel out the 'Material heaviness' of architecture. He himself attributed a 'destructive' effect to it.” Esser claimed, though, that “the interior color solution for the Spangen Housing was circumscribed somewhat by Oud.”

All in all, using only part of a project as a precedent, in this case the plan layout; using precedents simultaneously from diverse projects; and the need to adapt it to the current design are facts that ask for the formation of **adequacy criteria**.

3.3.2. Spangen Municipal Housing Scheme: Blocks VIII and IX; Spaanse Bocht, Rotterdam, 1919-1920

Potgieter Street, Langedijk Street, Van Lennep and Van Haren Street surround Block VIII (Figure 8). With the exception of the building at Van Lennep Street[19], which was built by a private company with ground ownership, this block was designed by Oud. Due to the twin ownership of the ground, the courtyard could not be planned for the use of all inhabitants. As a result, fences subdivided the courtyard into private gardens that belonged to the inhabitants of the ground floor.

Oud developed two kinds of standard units for this block (Figure 9), which are stacked upon each other. Each set of four units is grouped and stacked, and their access is provided via a single entrance. Each entrance hall gives access to one unit on the ground floor, one similar unit on the first floor, and two maisonettes on the second floor, which are similar to each other. The maisonettes have a living room on the second floor of the building block and the bedrooms on the third, which are reached by internal stairs. This arrangement keeps stair-climbing to a minimum (Oud 1923, pp. 15-20)[20].

Except for storage rooms, the courtyard of Block VIII contains no buildings (Oud 1923, pp. 15-20) such as the schools of Blocks I and V, and since the street side is much smaller than the width of the courtyard, Oud oriented the living room of both standard units to the courtyard side. Kitchens, stairs and most of the bedrooms are on the street side, with the exception of the units on the corner of the block. This idea linking some characteristic of a feature (in this case from the individual domain) with the characteristics of another feature (in this case from the collective domain) seem to ask for the formation of an adequacy criterion considering the fact that some features pass from one generation to another linked with others.

[19] Taverne claimed that only Langedijk Street was designed by Oud. However, besides a drawing in the archives of the NAi with the notes of Oud, Hans Oud confirmed that the opposite is true; i.e. only Van Lennep Street was not designed by Oud (Hans Oud 1984, pp. 64-65).

[20] Oud, J.J.P. 1923. “Gemeentelijk Woningbouw Spangen te Rotterdam” Bouwkundig Weekblad 44, 2; pp. 15-20

Figure 8: Spangen Housing State: Block VIII, Rotterdam, 1919

Searching for a solution in the design of the corners of the block, Oud faced the problem of integrating his design with the pre-existing building at Van Lennep Street. The pitched roof of Potgieter Street is probably the result of Oud's attempt to integrate the project of Van Lennep Street into his design as well as to cope with imposed economic and cultural constraints.

Block IX (Figure 10) is surrounded by Langedijk Street, Luyken Street, Van Haren Street and the Spanse Bocht. For the first time, Oud designed the whole block. In this project, Oud re-used the standard house type that he developed for Block VIII, stacking four units around a staircase accessed by a single front door. Oud designed the courtyard with private gardens for the inhabitants of the ground floor, accessed via terraces; and in the center, he created a recreation space for the block community. This common space around the courtyard is accessed via two porticoes on the smaller sides of the block. In contrast to previous blocks, this housing block solely has a flat roof.

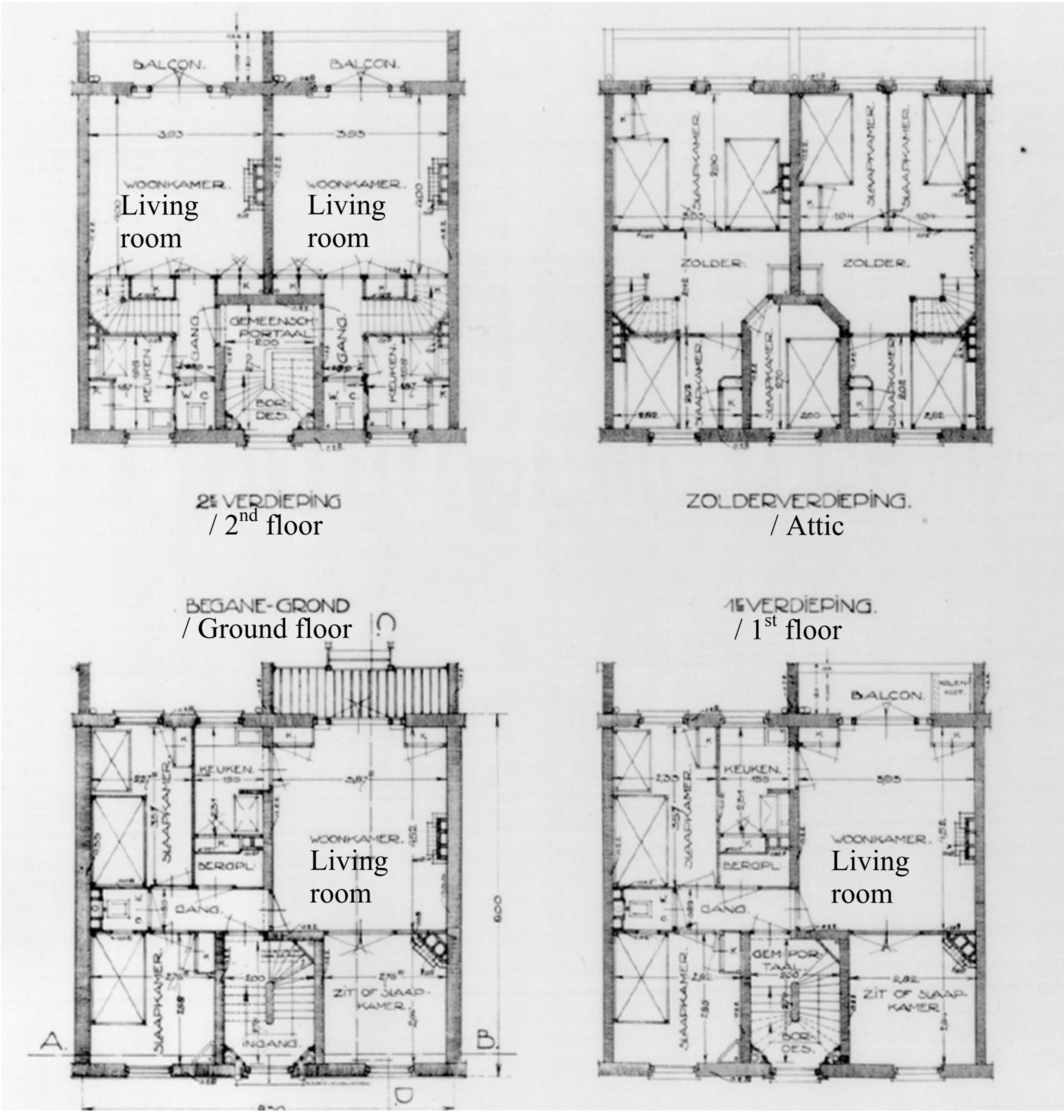

Figure 9: Spangen Housing State: Block VIII and IX, Rotterdam, 1919, plan layout

According to Taverne et al., the idea of a courtyard for the use of the building community was not new, and had already been fully applied in Amsterdam. The innovation was "to link the inner court to the layout of the dwelling and composition of the housing block (Taverne et al. 2001, p. 230)", i.e. by placing most living rooms on the courtyard side and improving the access and layout plan of it, Oud turned the court into the focus of domestic life. "Primary studies show," wrote Esser (Esser 1986, p. 144), "that Oud originally planned for the inner court of Block IX to have galleries around the building at the level of the second floor above the ground level. Perhaps he got this idea from the architect C. Brinkman, who implemented it in another housing block in Spangen. In the courtyard Oud had originally planned collective facilities such as a laundry. These were, however, not realized." Without the constraints of having other designers' projects to cope with, Oud had more freedom to design the whole block, its form and layout, as he pleased. The Neo-Plastic details of the block corners resemble, claimed Hans Oud, those that Oud had used in the same year for the Purmerend factory (1919) and the use of *kannelures* leads us to recall the School of Amsterdam (Hans-Oud 1984, p. 66)[21]. Searching for special effects, Oud designed the balconies of the corner house units on the upper levels that atypically face the street. The building corners house stores.

Figure 10: Spangen Housing State: Block IX, Rotterdam, 1919

Oud and Van Doesburg tried to collaborate once more during this project. However, Oud did not accept many of Van Doesburg's solutions[22], and their different approaches thus rendered any further collaboration in the future impossible. These blocks served as a prototype for the Tusschendijken Housing Scheme.

3.3.3. Tusschendijken Municipal Housing Scheme: Blocks I, II, III, IV and VI; Rotterdam, 1920-1924

Originally, the plan included eight residential blocks (Figure 11) to house approximately 1,000 families, a bathhouse and stores (Hans Oud 1984, p. 68)[23].

[21] Oud, Hans: 1984, p.66

[22] Soon after the occupants moved into the Spangen Housing Scheme, Oud discovered that they were not very pleased with the mural painting that had been forced upon them; shortly thereafter, the walls in most of the apartments were covered with wallpaper. (Esser 1986, p. 134)

[23] Oud, Hans. 1984. "Ouds opgang als architekt van het Nieuwe Bouwen 1918-1933." *J.J.P.Oud, Architekt 1890-1963 - Feiten en herinnering gerangschikt*. The Hague: Nijgh & Van Ditmar. p. 68.

The standard units and the plan layout of the courtyards (Figure 12) of the Tusschendijken Municipal Housing Scheme are improved versions of Block IX of Spangen.

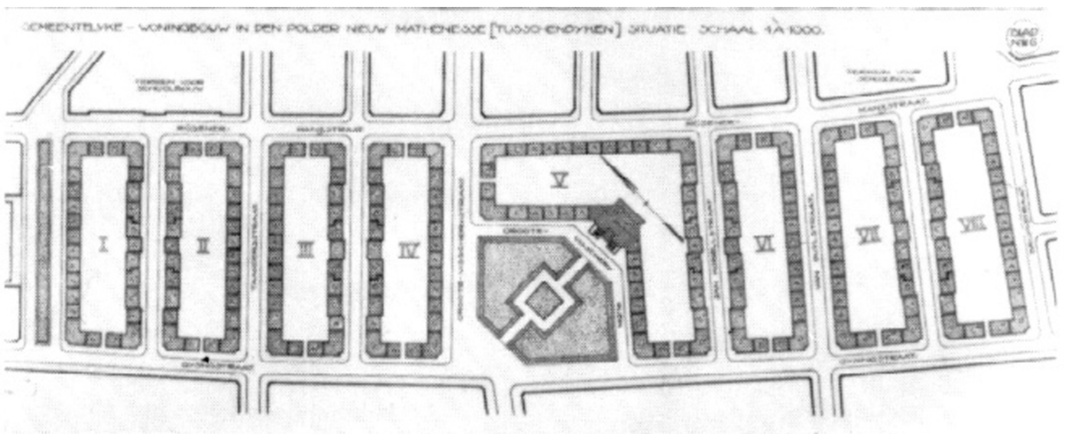

Figure 11: Tusschendijken Housing: Blocks I, II, III, IV and VI, Rotterdam, 1920, urban planning

In some house units, a module with the width of a bedroom was introduced between adjacent units to provide an extended bedroom area. In this way, a unit could have three to five bedrooms without excessive interference in the building structure. Further, a balcony was placed adjacent to the kitchens of the ground and first-floor units. The access to the house units has the same layout as Blocks VIII and IX of Spangen, but now including access to the basement, where storage rooms are located. In this way, the courtyard layout plan is freed of obstacles.

The access to the courtyard for the standard block is the same as in Block IX of Spangen, i.e. via two porticoes at the shorter sides of the blocks, above which the extra bedrooms of the large units are built.

The block corners (Figure 13) are simplified versions of those in Spangen and have balconies facing the street. Pitched roofs are partially applied on the long side of some blocks and balconies are applied on some façades on the street side. As Taverne claimed, “they would not have won any prizes for structural or typological innovation,” but, he continued, “they did succeed in elaborating and perfecting earlier innovations, in particular the inner courtyard (Taverne et al. 2001, p. 241).”

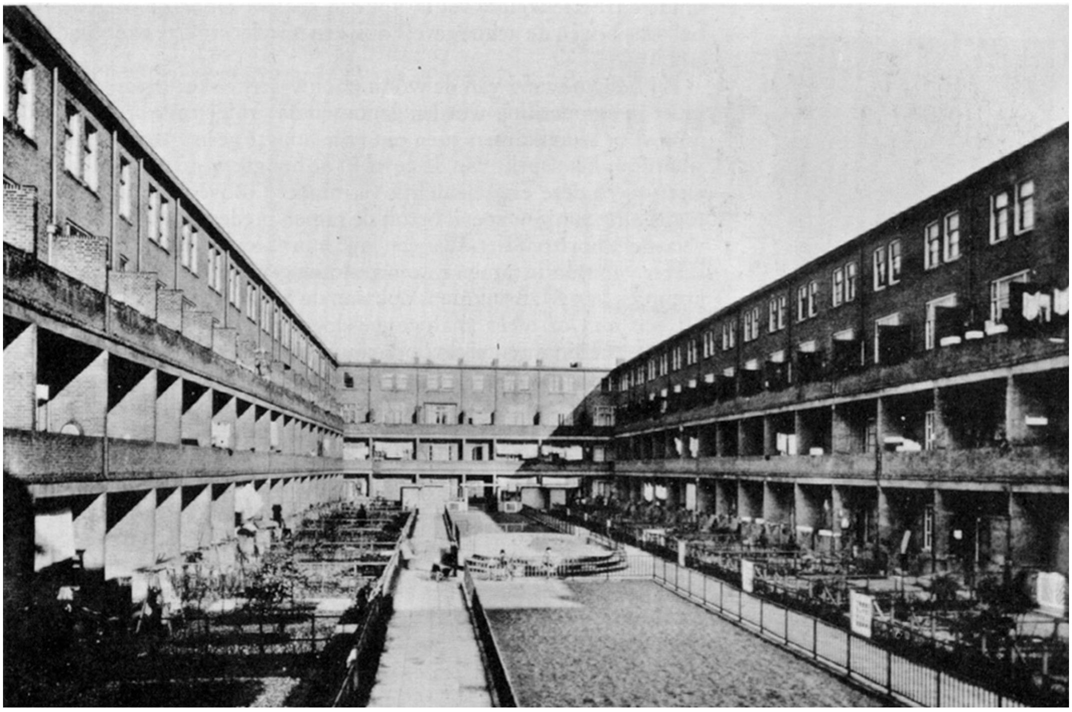

Figure 12: Tusschendijken Housing: Block I, II, III, IV and VI, Rotterdam, 1920, courtyard

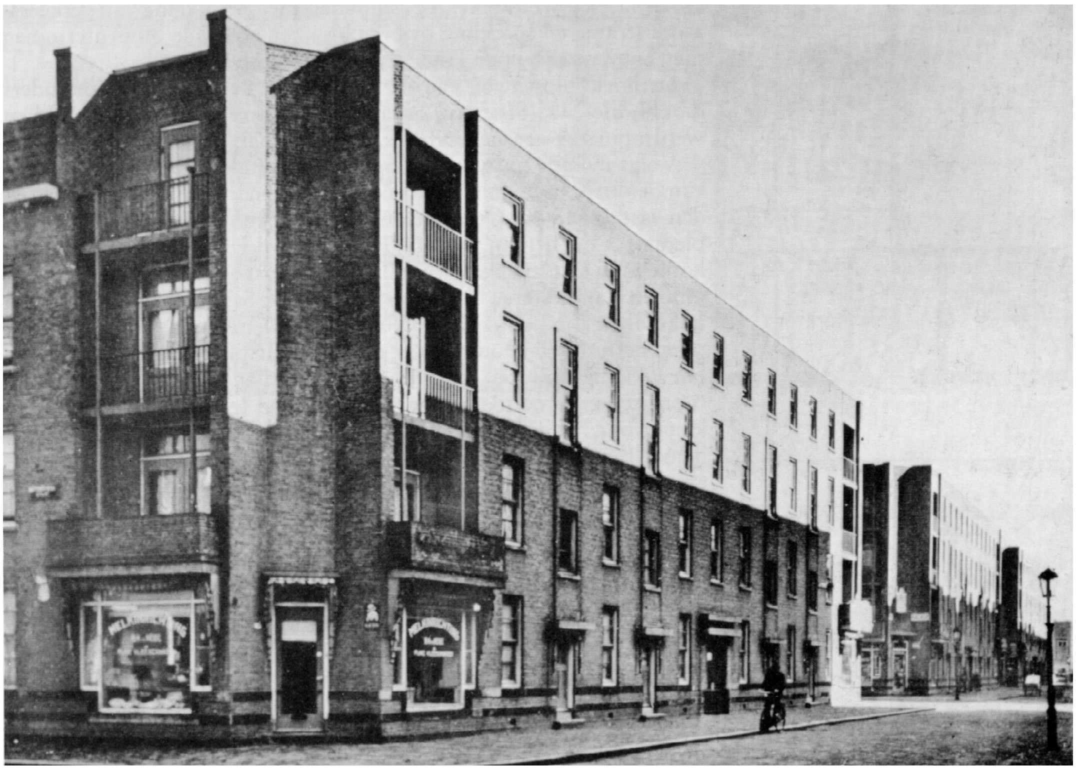

FIGURE 13: Tusschendijken Housing, Rotterdam, 1920

3.3.4. Oud-Mathenesse Municipal Emergency Housing Scheme (Het Witte Dorp), Rotterdam, 1922-1924

Initially, this housing project was planned to be a village for 30,000 inhabitants with a very extensive program. However, between 1922 and 1923, Oud designed Oud-Mathenesse to provide only 342 semi-permanent housing units (Figure 14), eight shop-dwellings, one building for administration and a fire engine shed. The housing complex was projected to stand for 25 years; afterwards a park would replace it. According to Colenbrander, this housing project, a small-scale low-rise and village-like plan, solved some utilitarian and economic requirements (Colenbrander 1981, p. 32).

Figure 14: Emergency Housing, Oud-Mathenesse (Het Witte Dorp), Rotterdam, 1922-23

Oud had more freedom in applying some of his concepts than in Spangen and Tusschendijken. However, new materials and techniques such as reinforced concrete were avoided and he faced the constraint of a pitched roof imposed by the public housing commission. To fulfill this constraint is to satisfy a required performance, and following this criterion, the use of pitched roof is adequate.

He developed a standard layout for houses with shops, and a standard layout for the single-family housing units for the rest of the village. According to Hans Oud, the layout plan (Figure 15) seems to bear many similarities to layouts of the same period, such as that of Jan Wils for public housing in The Hague and the layout of Grampré-Molière and P. Verhagen (1916) for the Vreewijk Garden

Village (Figure 16). Comparing it with the layout plan designed by Grampré-Molière, it seems that Oud used it as a precedent, reducing the depth of the house in one-meter. Hans Oud suggested that he only moved some closets and the toilet slightly and shifted some doors, thus minimizing any waste of space with unnecessary circulation (Hans Oud 1984, pp. 75-76).

Oud's standard layout bears many similarities to his own plan layout for Leiderdorp (1914) that he designed in cooperation with Dudok. *De Stijl* concepts are visible in the design of the façades of the village in the use of color, plastered walls, straight lines and right angles.

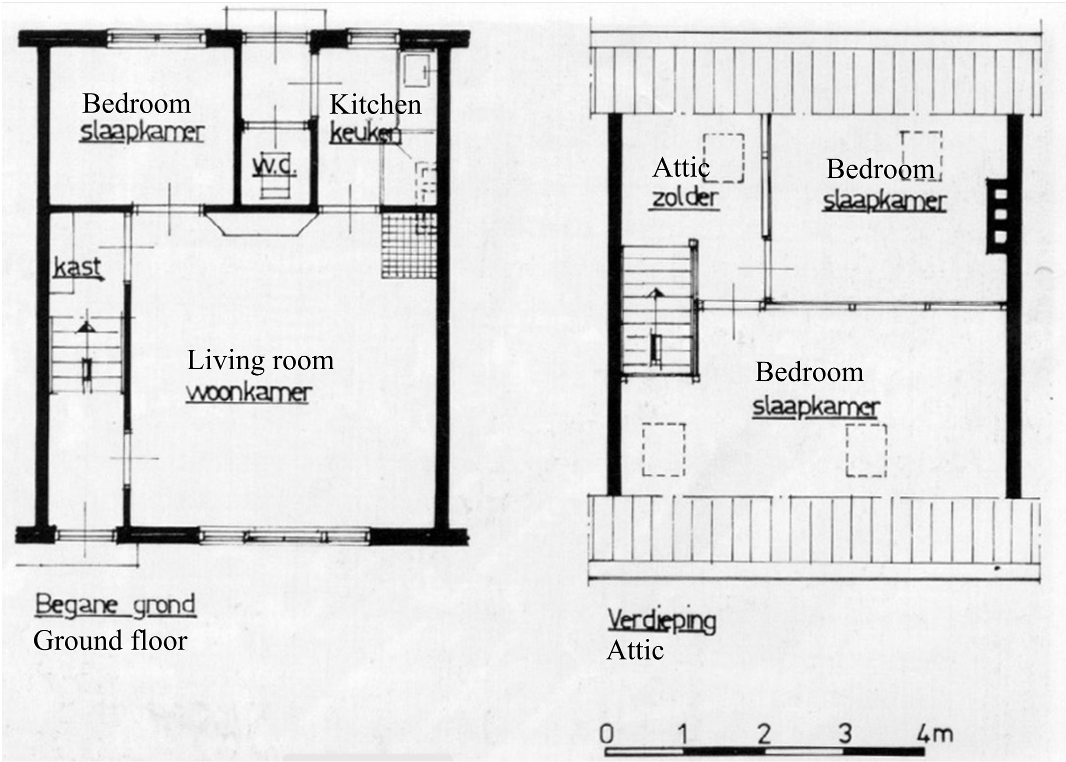

Figure 15: Emergency Housing, Oud-Mathenesse, Rotterdam, 1922-23 plan layout

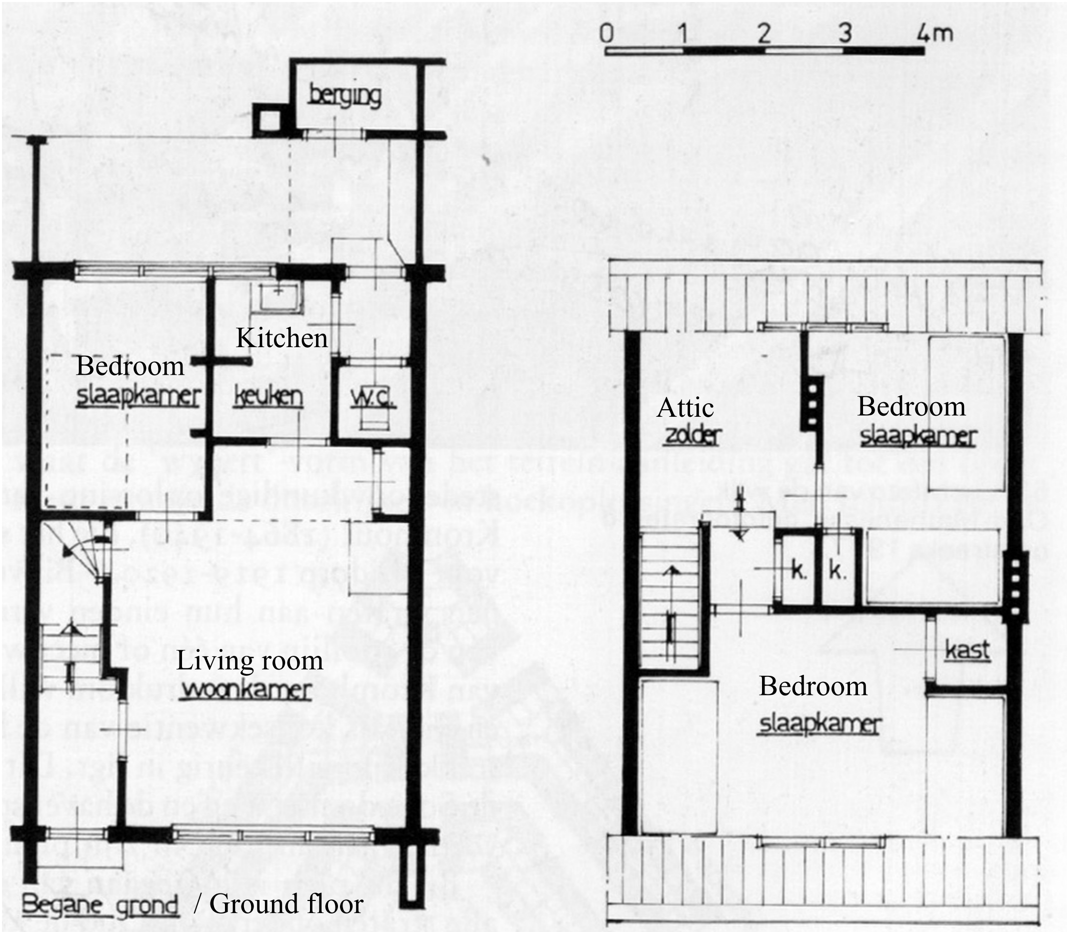

Figure 16: Grampé-Molière and P. Verhage's Vreewijk Garden Village

3.3.5. Hoek van Holland Housing Scheme, 2de Scheepvaartstraat 91-113, Rotterdam, 1924-1927

Oud designed these two interconnected blocks of low-rise terrace houses /apartments (Figure 17) in 1924. The blocks contain a set of ground-floor and first-floor units, as well as house-stores on the rounded corners of the blocks (Figure 18).

According to Oud, the corner solution was the result of weeks of effort. Taverne et al. showed that the first draft produced by Oud was composed of “three rows of housing separated from one another by two gateway buildings, thus allowing for a total of six shops at the ends.” Taverne claimed that a second version of it consisting of “two-storey rows of housing separated by a centrally situated passageway” was in fact the one shown to the Rotterdam Public Housing Committee containing 42 dwellings, including four shop-dwellings and four warehouses. The dwellings were of one to four bedrooms and on either the ground floor or the first floor. The plan was praised from the financial aspect but rejected for its architectural form. Oud was asked to present a different façade solution, meaning a more traditional form for the block (see illustrations). However, the committee of 20 June 1925 rejected the new proposal preferring the first draft (Oud, Taverne et al. 2001, pp. 260-262). This going back and forth in the process of designing seems to ask for consideration in the making of **adequacy criteria** for our model for the re-use of precedents in architectural practice.

Figure 17: Row Houses, Hoek van Holland, 1924

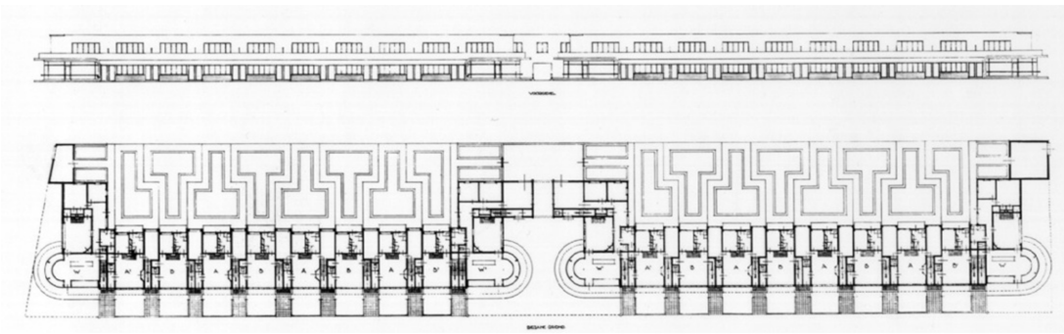

Figure 18: Row Houses, Hoek van Holland, 1924, facade and block layout

Looking to the ground floor layout plan (Figure 19), one can see that the block is subdivided into two modules: the first one contains a living room, a kitchen and a bedroom. The second module contains a hall, a staircase, a toilet and another bedroom. This second bedroom could in principle be connected to either one of its adjacent units.

This plan resulted in three fixed types of standard units. On the ground floor, each unit has alternately three bedrooms or one bedroom, while all first floor units are similar to each other and of the same size, namely having two bedrooms. Analyzing the plan, however, one would find it easy to change, for example, the ground floor units into a type with two bedrooms each. Given the strategic placement of the structural and insulating walls, it would simply be a question of closing one door and opening another in the direction of the adjacent unit.

Access to each unit is placed in groups of two. Looking to the layout plan of the blocks, one can see that each entrance to the right provides access to a unit on the right side on the ground floor; and each entrance to the left side provides the access to a unit to the left above the ground floor unit.

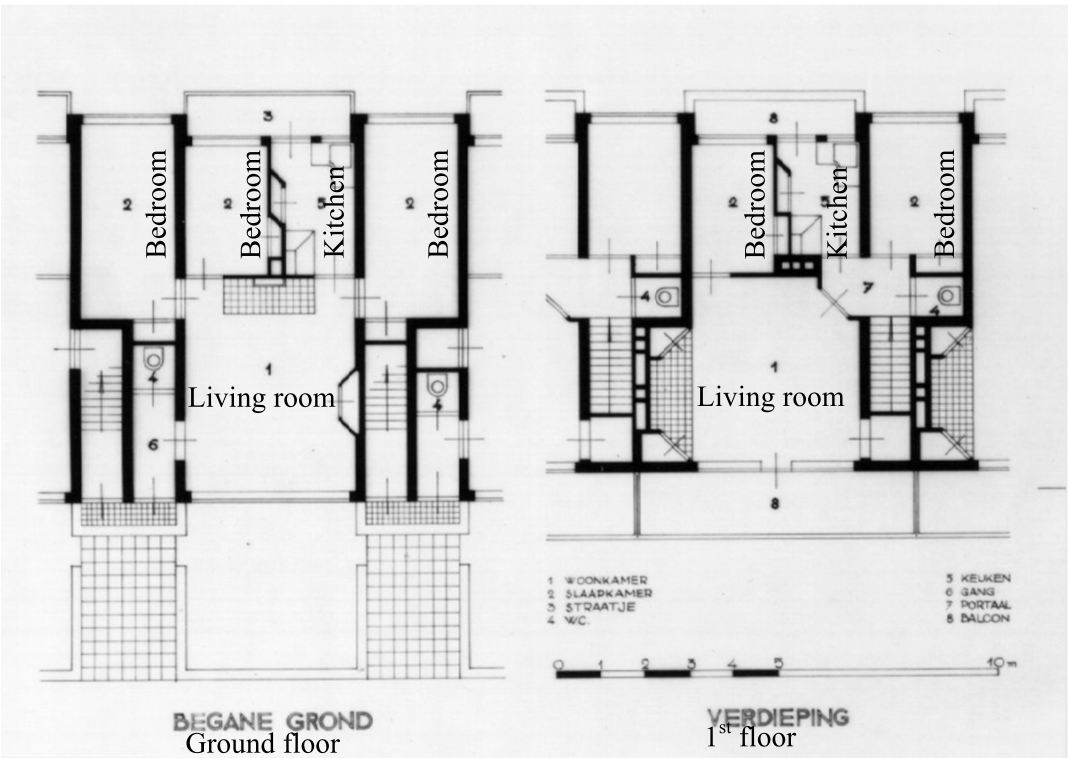

Figure 19: Row Houses, Hoek van Holland, 1924, plan layout

According to Hitchcock, it was allegedly “the influence of Van de Velde that led Oud to introduce curves here, much to the disgust of the Neo-Plasticists” (Hitchcock 1958, p. 378). This change of principles seems to ask for the creation of an adequacy criterion considering that it was part of the creative process of Oud in finding his own architectural identity.

3.3.6. Kiefhoek Workers' Housing, Groene Hilledijk, Rotterdam, 1925-1930

Oud's design for De Kiefhoek (Figure 20) consisted of 291 housing units, two shop-dwellings, one dwelling with a hot water boiler and two warehouses. Oud designed a very compact house, which he called the "Woon-Ford" or "Wohn-Ford" (Hans Oud 1984, p. 90; Oud, Taverne et al. 2001, p. 277), i.e. a house which, despite its minimal space due to economic constraints, could still function perfectly within a minimum comfort.

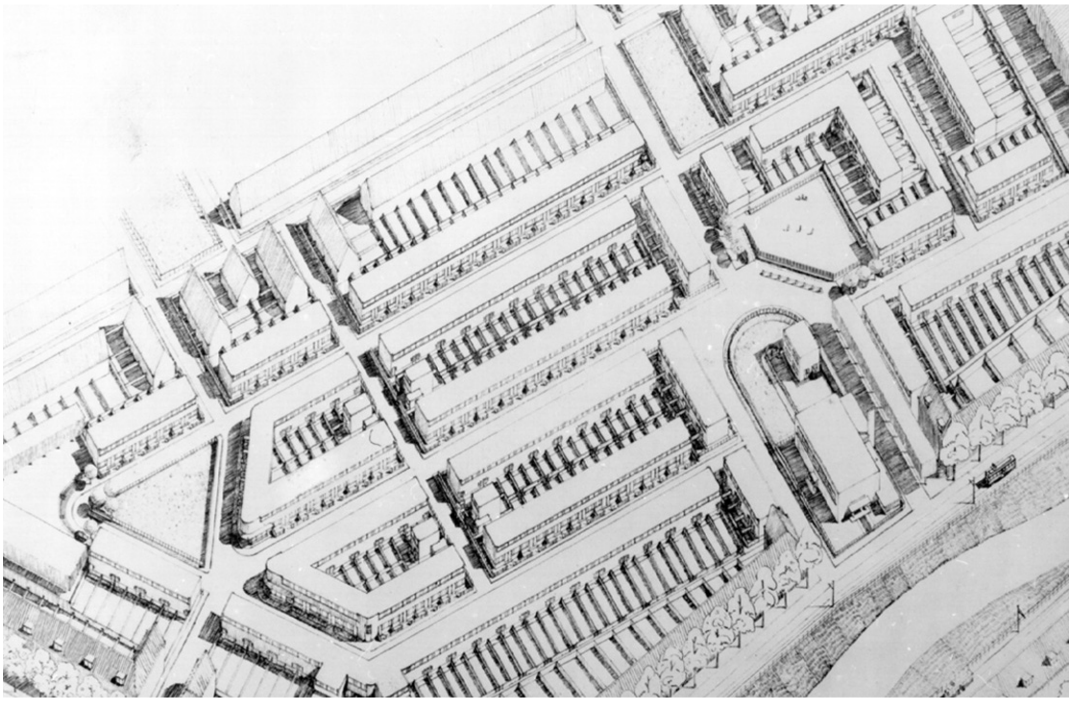

Figure 20: Workers Housing, De Kiefhoek, Rotterdam, 1925

On the ground floor (Figure 21), the living room is entered via a small hall with a meter cupboard and hallstand. The area of the living room is only 17 m² but is designed to facilitate an optimal arrangement of furniture. On the rear side, adjacent to the living room are the kitchen and a small hall. The hall gives access to the staircase and a lavatory.

The first floor is subdivided into four parts: one bedroom for the parents, and two for children (up to three children in each); i.e. a total space for eight beds (Hans Oud 1984, p. 92), and a space adjacent to the stairs for drying the laundry during rainy days as well as for storage. Many facilities in Oud's "Woon-Ford" were either not constructed or altered because of their cost, such as the shower, the coal storage room, the ironing board, and the open cupboard between the kitchen and living room. The units were developed in a module of 3.88m (width) by 7.50m (depth). On the ground floor, the height between the floor and ceiling is 2.70m, while on the first floor it is 2.40m.

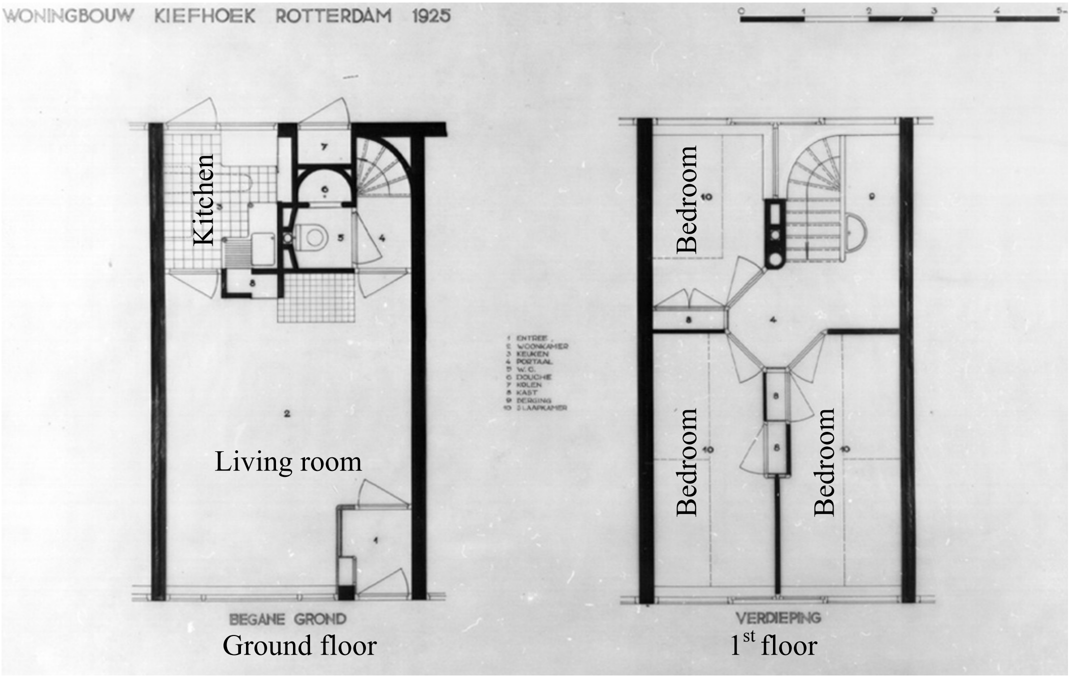

Figure 21: Workers Housing, De Kiefhoek, Rotterdam, 1925, plan layout

According to Taverne et al., the "Wohn-Ford" notion was not so much associated with industrial production methods. However, in his article "The £215 house, a solution to the re-housing problem for rock-bottom incomes in Rotterdam", Oud asserted that "sIts solution was found along the lines indicated by Henry Ford in his production of cars that were to be both good and cheap - namely, the practical construction and production methods, standardization permitting of all components being factory-made, and economical organization of space and material - *Dwelling Fords*, in fact." Later in the article he wrote: "the design allowed for the use of either concrete or brick, according to prices ruling these materials" (Oud 1931)[24], which makes it fair to conclude that the design was produced in a way to facilitate mass production, although the actual and immediate costs of production on the market at the time would ultimately dictate which way production should be brought about.

The access to the units is in groups of two except when the block ends with an odd number. In these cases, Oud designed a round balcony on the first floor that gives a special character to the block, restoring the balance of the design (Figure 22). The gardens of Kiefhoek give less privacy to the inhabitants than those of Hoek van Holland.

[24] Oud, J.J.P. 1931. "The £215 house, a solution to the re-housing problem for rock-bottom incomes in Rotterdam." *The Studio 101, 456*

The façade has a plinth in brickwork and a continuous strip of windows on the first floor, which together with the flat roof, give a horizontal character to the block. The omission of the same plinth and window row on the first floor gives special emphasis to the rounded corners (Figure 23).

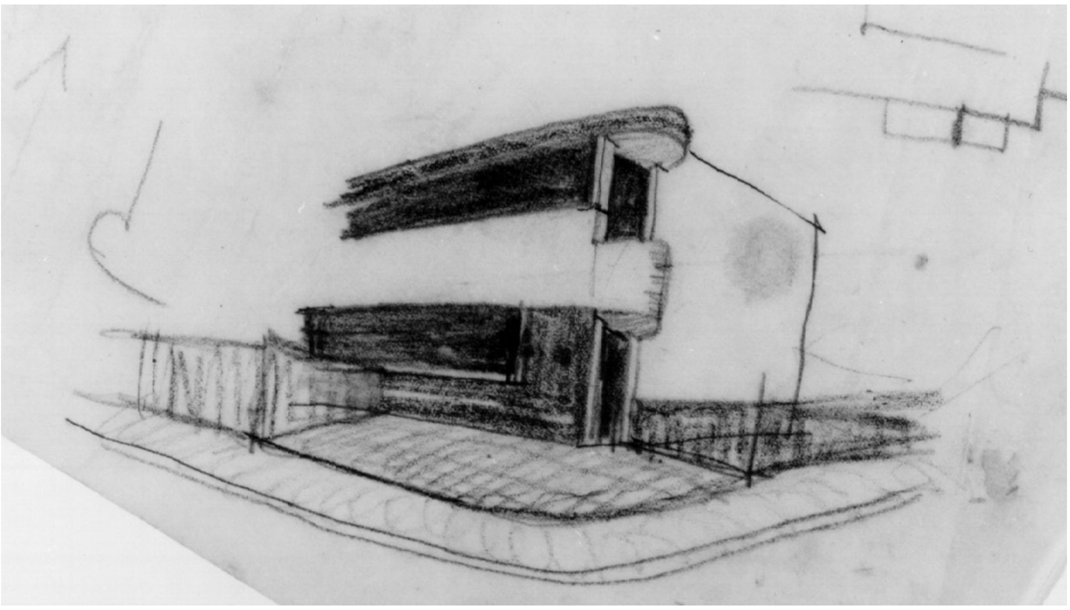

Figure 22: Workers Housing, De Kiefhoek, Rotterdam, 1925, sketch

Figure 23: Workers Housing, De Kiefhoek, Rotterdam, 1925, perspective of the neighbourhood

3.3.7. Five Row Houses in the Weissenhofsiedlung, Stuttgart, 1927

This group of five houses (Figure 24) is Oud's contribution to the municipality of Stuttgart, which built 60 permanent house units as an experiment to improve the housing program of the city. This exhibition gave the opportunity to its participants to create their own experience with new materials, building systems, construction methods, and domestic efficiency (layout and design).

Two types of streets perpendicular to each other comprise the conceptual urban plan: the East-West and North-South streets. The East-West streets give direct access to the houses. With each house having a North and a South access, this street provides access to the service area of the row houses at the south side of the street, and to the social area of the row houses at the north side.

Figure 24: Row Houses, Weissenhofsiedlung, Stuttgart, 1927,

A secondary North-South street crosses the first one after every group of five row houses, and has neither direct access to the houses nor windows facing it.

In the layout plan (Figure 25), the social, utility and sleeping zones are clearly separated. The social entrance is placed in the sunniest direction, south, and it leads through a garden to a small hall and then to the living room. On the ground floor, one finds the utility area to the north and it is more enclosed; it leads to the laundry area of the house and via the kitchen and staircase hall to the living room. On the first floor, one finds the bedrooms, one bathroom, an extra toilet and a small storage room. The master bedroom faces south and has a balcony overlooking the garden, which calls to mind the one used by Rietveld in his Schroderhuis (1924) as well as that used by Gropius in the Bauhaus (1926).

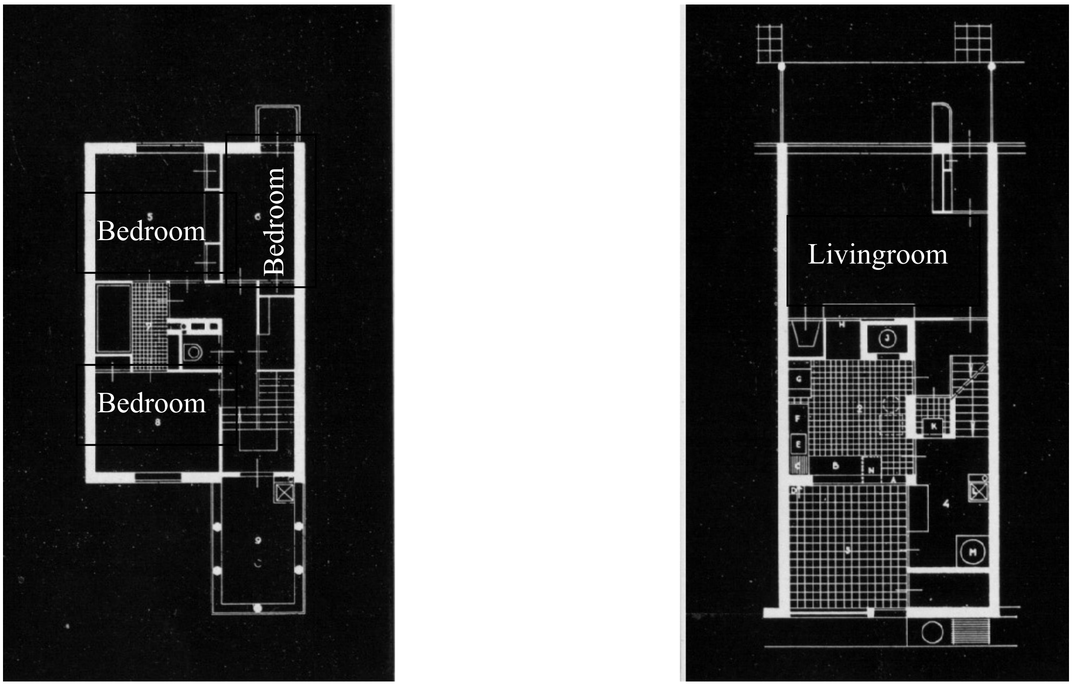

Figure 25: Row Houses, Weissenhofsiedlung, Stuttgart, 1927, plan layout

In this design, Oud played with planes, creating a middle floor that is reserved for storage. Oud's design seems to be the result of a bottom-up approach. It seems that the urban plan and the allocation are designed to solve contradictions that Oud met when designing the house unit layout.

3.4. Changes in Design Precedents through Time

The previous sections described which design precedents were re-used by Oud in each of his projects. This section will provide an interpretation of the phenomenon of change through time involving the reoccurrence of these design precedents. The objective is to find a pattern of change used by Oud and afterwards a set of propositions to serve as adequacy criteria for a model for the re-use of design precedents.

For the purposes of organization, we move from some characteristics at the urban level, to the level of the housing block and finally to the level of the individual unit. We are not suggesting any top-down approach or the isolation of the design of specific parts; this hierarchical order is only used to help in the interpretation of the phenomenon of change in the design process when based on the re-use of design precedents.

3.4.1. The City, the Street and the Housing Block

In the article "Het Monumentale Stadsbeeld" of 1917, Oud extensively describes his approach to architecture. In his view, the building block is substituting the individual housing unit and is the fundamental element in changing and ordering the image of the city. The solutions of the corners of a building block are treated in a way that gives equal value to all surrounding streets; all street façades provide access to the house units. Thus, the streets perpendicular to each other are not hierarchically classified. Spangen and Tusschendijken are developed against this background.

The city and private life form a dichotomy and private life should be protected from city activities. Opposing the city and street life, the courtyard reinforces the dichotomy and provides a space for recreation away from the city. For the same reason, most living rooms of Block VIII at Spangen overlooked the courtyard rather than the small but busy street. Matters like privacy are decided at the urban level.

During the design of Block IX of Spangen, Oud concentrated on developing the courtyard of his 'perimeter block'. The courtyard of Block IX is subdivided between private gardens for the inhabitants of the ground floor and a central area for the use of all inhabitants of the block. This is the prototype of the courtyard of Tusschendijken. However, in the latter, the courtyard is freed of storage rooms, which were placed in the basement. To give emphasis to the concept of the dichotomy between private and public, most living rooms faced the courtyard. The courtyard is the morphologic answer to a desired performance.

In the low-rise and low-traffic designs for Het Witte Dorp and De Kiefhoek, the social character of the square and streets provides a reason to orient the living rooms again to the street side. Here the courtyard idea is converted into the square. One can say that the performance, the desire to allow recreation and life within a protected environment, is still the same. However, the context, low traffic streets and the low-rise buildings, suggests other ways to achieve the goals. The square was Oud's morphologic answer. In Hoek van Holland, presumably because the blocks were not built in a busy part of the city, the living rooms also face the street.

All East-West streets of the conceptual situation plan of Stuttgart have the same value; in other words, each street gives access to, on the one hand, utility entrances (laundry, kitchen), and on the other hand, to social entrances (living room). However, if we observe from the house unit perspective, one can say that the street on the north side is for utilities and the other is for social matters. This is a bottom-up approach. In this plan, privacy is not gained by designing different street patterns. The privacy of the living room (social area) is here solved at the house allocation level by providing a maximum distance between the façade and the sidewalk and not by creating a collective courtyard, i.e. by an urban plan approach. Here the garden is the morphologic answer to recreation and privacy and this time it belongs to the family domain.

With this project, it seems that the perimeter block lost its exclusive position in Oud's design. In fact, when Oud later designed the Blijdorp Housing Estate, he came up with a solution much closer to that of Stuttgart. He even went in opposition to the recommendation of the developers who demanded the design of a perimeter block.

3.4.2. The Housing Block

In this sub-section, we shall present our observations on the block layout; i.e. on the access, on the stacking and grouping of units, on the façades, and on the volume. Oud's housing blocks reflected his search for regularity (from esthetics to industrialization) and for the expression of his privacy-public concept.

Access and House Grouping: precedents and invention

In the "Standard Housing for Workers" experimental project of 1918, Oud grouped six dwellings (3 modules of 4 meters) around a complicated pair of scissor-stairs and main entrances. As mentioned previously, the standard unit of Blocks I and V of Spangen was a recollection and adaptation of a standard layout already used by Van Goor (Oud 1920, pp. 219-222)[25]. However, the access and grouping of these units seem to be a recollection and further development of the housing complex in Leiderdorp (1914) that was designed by Oud in cooperation with Dudok. By adding a zone to the housing complex of Leiderdorp between two main entrances, one may introduce two independent access points to reach the stacked flats. In this manner, the grouping of the dwellings of Blocks I and V are, then, presumably a result of addition, which evolved from the reasoning process of the design of Oud's previous project. With the experimental project published in *De Stijl* (Standardized Housing for Workers of 1918) as well as in Blocks I and V, Oud seemed to have pursued privacy by connecting a maximum of three dwellings to one entrance.

The standard units of Block VIII are clustered in groups of four (two modules) around one main entrance. Each standard cluster is composed of two flats on the ground floor, two on the second floor, and two maisonettes. These maisonettes have the main entry on the third floor by way of reducing the vertical circulation; this solution seems more regular, and moreover, it also saved some space that Oud used for the house units themselves.

[25] Oud, J.J.P.: 1920, *Gemeentelijke volkswoningen, Polder 'Spangen" te Rotterdam,* Bouwkundige weekblad, 41, 37, pp. 219-222, **quoted** in Henk Engel, "De Kiefhoek, een monument voor gemiste kansen?" In *de Kiefhoek, een woonwijk in Rotterdam*, edited by Sjoerd Cusveller. (Laren: V+K Publishing, 1990). p. 20

The entrances to the standard Oud-Mathenesse houses as well as the access to the standard De Kiefhoek houses are grouped and the houses mirrored just as in Leiderdorp. This solution seems to reflect a formal preoccupation concerning the design of the façades. In the design of the housing complex at Hoek van Holland, Oud also grouped the access of pairs of dwellings. In this case, the entrances were not grouped to link, alternately, two units on the ground floor and then two units on the first floor; neither were they grouped to give access to two stacked houses, one above the other, which would be obvious. In the way they are grouped, they give access to one dwelling on the ground floor at one side and to an apartment that is situated above the adjacent neighbor (Figure 26). This peculiar access seems to have emerged to maximize the use of space, to allow alternative layout plans of the house units and, quite probably, to minimize problematic contact between neighbors.

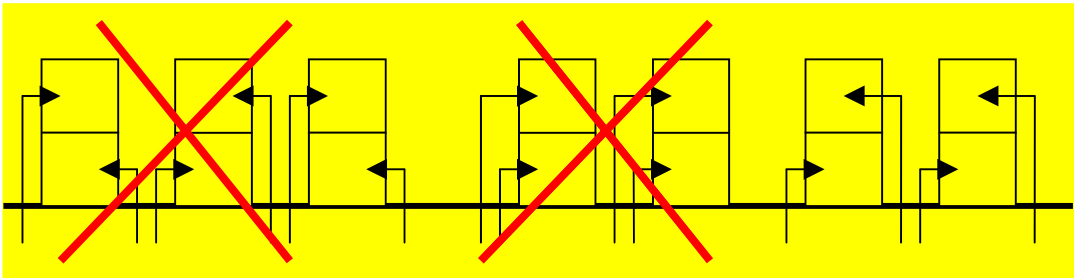

Figure 26: Hoek van Holland: access

Façade and Volume: transcending principles

As we have seen, most of Oud's choices were politically, economically, or culturally constrained[26]. Oud had expressed the intention of substituting the pitched roofs for flat ones as early as his experimental housing projects. After the experiment with the Row Houses on the Strandboulevard (1917), the Standardized Housing for Workers, the Double Workers' Housing in Reinforced Concrete (both of 1918), and after being engaged in the activities of *De Stijl*, Oud designed the Spangen Housing Scheme (1919) and the Tusschendijken Housing Scheme (1920) in an almost Berlagian style. Oud made this four-storey-block the fundamental element of his urban plan; attributing in this manner, as Berlage did in his plan for Amsterdam South, a certain continuity to the area. He also used brick, the element that Berlage appreciated so much.

In block IX of Spangen, Hoek van Holland, De Kiefhoek and in his Stuttgart project, Oud applied the flat roof exclusively. The application of alternately

[26] According to Esser (Esser 1986, p. 133), when Oud entered the municipality of Rotterdam, he "faced the difficult task of building dwellings for the poorest classes as quickly and as inexpensively as possible. He must have been aware of the restrictions inherent to his position of municipal architect; after some doubts, ethical considerations proved to be more important to him than aesthetic ones."

pitched and flat roofs in Tusschendijken is less a hesitation and probably more a result of pressing external constraints, such as the traditional character of public housing and the economic situation. This is certainly true in the case of Het Witte Dorp, when the pitched roof was a requirement of the Public Housing Department (Hans Oud 1984, p. 74)[27].

In his article "Het Witte Dorp: aan de vooravond van een keerpunt", Roy Bijhower claims that the Oud-Mathenesse Municipal Housing Scheme stands on the eve of a turning point in the developments of Oud's career (Bijhower 1987, p. 71)[28]. The roof and the layout plan of the house units are very traditional. However, the façades have a new expression. He uses the colors of *De Stijl*, but also some features from the Spangen and Tusschendijken blocks such as the plinth, the mirrored units resulting in grouped entrances, and the roofline resultant of the pitched roof in its length[29].

Showing great flexibility, Oud used and transformed principles or design rules over the years by searching for the morphologic expression that could fit the requirements and constraints of each situation. Thus, after he had designed Hoek van Holland and Kiefhoek, Oud designed the very traditional looking Beye & Co. Standard Vacation Houses (1933), which have a very traditional façade expression composed of pitched roofs and bricks.

3.4.3. The House Unit

One of Oud's ideas during his experimental standard house units of 1918 was to create a systematic approach that could also improve the efficiency of the building industry. Oud developed his plan within modules of four meters. Each independent set of stacked units contained three modules: the first module accommodating the living room of some units at the main façade and bedrooms and toilets at the "back"; the second consisting of entrance, staircases, storage, extra bedrooms for the dwellings of the first and second storeys, and kitchens of all six units; and the third module, having bedrooms of a mirrored unit at the main façade. This independent unit can then be repeated indefinitely. In the layout of Blocks I and V of Spangen, Oud did not innovate, although he continued searching for a modular systematic building. These layouts are developed within a module, and there are clear differences between structural walls, subdividing the block into units, and non-structural partition walls, subdividing the units into rooms.

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[27] Oud, Hans. 1984. "Ouds opgang als architekt van het Nieuwe Bouwen 1918-1933." *J.J.P. Oud, Architekt 1890-1963 - Feiten en herinnering gerangschikt*. The Hague: Nijgh & Van Ditmar. p. 74

[28] Bijhower, Roy. 1987. "Het Witte Dorp: aan de vooravond van een keerpunt." In *Het Witte Dorp, J.J.P. Oud*, edited by B. Colenbrander. p. 71

[29] Bijhower, Roy. 1987. "Het Witte Dorp: aan de vooravond van een keerpunt." In *Het Witte Dorp, J.J.P. Oud*, edited by B. Colenbrander. pp. 75-76

With a similar systematic approach, Oud designed the housing units of Blocks VIII and IX and the following house projects, in which Oud developed two standard house-units, applied them in Blocks VIII and IX of Spangen, and adapted them to the Tusschendijken Housing Scheme. These two standard types are stacked upon each other around a staircase. The ground and first floors each have a flat while, on the third floor, there are the entrances to two maisonettes. In the Tusschendijken Housing Scheme, when the performance requirements changed and demanded a greater variation of house-unit sizes, a new module was intermittently placed between groups of stacked standard units to provide extra rooms to accommodate bigger families.

Almost nothing is written about the complicated solution of stairs, combining and stacking the units at the corners of Spangen. In contrast to what Oud stated in his article in *De Stijl* on the experiment of the standard units for working-class families in 1918, his approach for example with the corners of Block VIII would still be of no help for improving the efficiency of the building industry due to the lack of regularity. On the corner of this block, the first staircase leads to one unit on the first floor and one on the second floor; the second staircase leads to two units on the second floor. The third staircase leads only to one first-floor unit that has the strange solution of having, in a house for low-income people, a bedroom only accessible via the kitchen. The position of the structural walls did not support a clear internal solution. However, given the constrained structural walls, the layout maximized the use of space; it is possible to come up with better plans with more regularity, but the flats would have fewer bedrooms. On the corners of the buildings, a compact and systematic approach gradually evolves in the way that Block IX already has a more regular layout.

The Oud-Mathenesse standard houses have a traditional plan that is very close to the plan of Grampé Molière and to Oud's housing complex in Leiderdorp. In contrast, Hoek van Holland is unique due to its flexibility. Three standard units are produced which can easily be transformed. This is possible due to the (possibly subconscious) introduction of one horizontal and one vertical margin for variation as was later used by SAR (Foundation for Architects' Research of The Netherlands) with its open building method (SAR 1963).

In Leiderdorp, and also in the Het Witte Dorp and in Hoek van Holland, Oud connects one or more bedrooms directly to the living room, recalling the idea of alcoves surrounding the main room. This was an acceptable solution at that time and, in fact, it saved space. By placing only the master bedroom directly connected to the living area as in the first floor units of Hoek van Holland and in Het Witte Dorp, Oud seems to emphasize the parents' territory (as Le Corbusier did in the Unité d'Habitation). However, in De Kiefhoek and Stuttgart, Oud isolates the “sleeping” area from the “social” area. He returned to the “alcove-bedroom” idea of connecting the living room with the bedrooms later during the design of the Beye & Co. Summerhouses.

In Oud's experiment, Standardized Housing for Workers of 1918, the living rooms face alternately the front or the back of the block, which gives the façades a kind of movement. The direct environment is not shown; i.e. we do not know the sun orientation, or whether there is a courtyard and street sides. The alternating living rooms seem to be a result of the position of the stairs and Oud's emphasis of the street composition; i.e. esthetics.

In Blocks I and V, all living rooms face the street, despite the position which the unit takes in the block, i.e. regardless of the sun orientation. The courtyard was also not a private place, but a public territory, where schools were built. The contrast between city and private life was not clearly established. This changes gradually in the subsequent blocks. In Block VIII, Oud turns the living room to the courtyard side. This seems to happen partially because the courtyard was broader than the street[30], but also because Oud intended to protect private life from the life of the industrial city. On the corners of this block, probably concerned with plastic effects, Oud leaves the living rooms and balconies on the street side. From these observations, one can conclude that the orientation of the sun is not yet Oud's main concern. Block IX of Spangen and Tusschendijken followed along the same lines.

As mentioned earlier, in his low-rise projects such as at the standard house types of Het Witte Dorp and De Kiefhoek, Oud placed the living room at the front side of the house and kept the backyard for the individual households. These projects are situated in a rather enclosed urban plan with low traffic order. The activities of the community take place on the streets and the square, not in the courtyard. Thus, the living room orientation is still a result of an analysis at the urban level. Here, Oud still has no preoccupation with the light factor in relation to the units since there are street façades facing opposite sides.

This changed with the row houses of Stuttgart (1927), which were placed according to an optimal orientation in relation to the sun. The idea of separating private life from that of the industrial city is not pursued at the urban level but at the level of the house unit itself, i.e. the privacy of the living room is obtained by separating the living room from the street with a very deep garden.

The description of these designs has shown how changes in performance requirements and/or context reflected on morphologic solutions.

3.4.4. The Pattern of Change

A pattern of change emerged from the study of the generations of Oud's projects, which we can break down into four steps.

First, Oud moved from a top-down approach – i.e. from the urban to the house unit level – to a bottom-up approach as, for example, in Stuttgart. Focusing on the

[30] Oud, J.J.P. 1923. "Gemeentelijk Woningbouw Spangen te Rotterdam." *Bouwkundig Weekblad 44, p. 2.*

city level, he analyzed the role of the street and of the residential blocks towards the image and growth of the city itself, and brought its consequences to the study of the form and function of its access, courtyard, and corners. Moving his focus to the house unit level, such as in Stuttgart, he tried to solve problems, such as that of privacy, by changing the layout plan of the unit. Oud also focused more and more, from generation to generation, on the functionality of each room, and in particular on that of kitchens.

This observation coincides with an analysis of Oud's texts. In 1917, for example, Oud wrote in the *De Stijl* periodical that the most important task of the modern architect concerns the residential block (Oud 1917, p. 10)[31], while in 1927, he claimed in an article for the *i10* that the priorities of the new architecture lay in the satisfactory fulfillment of the requirements of the inhabitants (Oud 1927, p. 44)[32]. This observation also coincides with that of Roy Bijhouwer who mentions that in the urban and architectural world, there is a general tendency moving away from the image of the city and towards the functionality of the housing unit for everyday life (Bijhower 1987, p. 71)[33].

This brings us to a second peculiarity in Oud's pattern of design. Principles are not immutable: they not only change, but they are viewed from different perspectives. This is the case of matching the courtyard of the initial blocks with the squares and streets of the low-rise, low traffic projects such as Het Witte Dorp and De Kiefhoek.

Third, Oud re-used not only concepts and principles, such as those of *De Stijl* or the aforesaid top-down/bottom-up approach, but he also recalled parts of designs from his own oeuvre and his contemporaries, and adapted them to fit the requirements and constraints bound to specific projects. In fact, his designs often present more than one precedent.

Fourth, Oud seems to "freeze", probably due to particular project constraints, a building part to dedicate his attention to the solutions of other parts. In other words, during the generation of the projects studied, he did not innovate the whole approach of a design at once; he developed new ideas from generation to generation until they eventually formed a new expression. This fourth characteristic of Oud's pattern of change is an intricate observation, considering that Oud did not agree with CIAM's analytic research method (see section 3.2). It is true, however, that Oud developed parts of the projects not as separate problems, but always integrated in a new design as a whole.

Fifth, the description of this series of designs shows how performance requirements and their morphologic expression are constrained by circumstantial

[31] Oud, J.J.P. 1917. "Het Monumentale Stadsbeeld." *De Stijl* nr. 1: p.10
[32] Oud, J.J.P. 1927. "Huisvrouwen en Architecten." *i10* jrg.1, nr. 2: p.44
[33] Bijhower, Roy. 1987. "Het Witte Dorp: aan de vooravond van een keerpunt." In *Oud-Mathenesse, Het Witte Dorp,* edited by B. Colenbrander. p. 71

facts (for example of the environment but also political and economic), how they are interconnected and how changes in one influences the others.

3.5. Adequacy Criteria for a Proposed Model

We investigated Oud's designs in relation to the re-use of design precedents and their adaptation to fit the new solution. The unit of analysis of this case was a group of historically ordered social housing projects, which Oud designed when he was working for the municipality of Rotterdam. Similarities as well as innovations were described and an interpretation of the phenomenon of change was carried out. In our interpretation, he moved from design to design, innovating in particular parts of the building, whenever the situation allowed or pressed him to look for better answers.

From our observations in this case, we develop some adequacy criteria which a design model should satisfy if the model is to be used in architectural practice. In a very straightforward way, we generalized from the actions present in the generation of the above projects to generate some propositions that will serve as provisional adequacy criteria for our model.

1. Given that the architect often uses a part of a design precedent and not the whole of it, the model ought to have mechanisms to explore, select and recall parts of a project. Example: the layout plan of Van Goor was the only part of the design used by Oud in Blocks I and V of Spangen.
2. Given that features of a design are often recruited from diverse design precedents, the model ought to provide mechanisms to search per element. Example: the three-strip plinth of Blocks I and V of Spangen was already used in the "De Vonk" project, while the layout plan came from Van Goor's design.
3. Given that features (characteristics) of a project are only good or bad in relation to a certain environment and specific constraints, the system ought to provide as a search result not only the most fitting but also several precedents.
4. Given that architects go back and forth in the search for solutions to their problems, reflecting while acting (see Schön 1983) such as in Oud's search for a corner solution in Hoek van Holland, the system ought to provide mechanisms to save the desired stages of the project.
5. Given that design precedents are not simply used, but most of the time are adapted to the new situation, the model ought to have mechanisms to support adaptation. Example: the adaptation of the layout plan of Van Goor in Oud's design, and the adaptation of the layout plan of Block IX of Spangen in Tusschendijken Municipal Housing Scheme, where large houses were needed.

6. Given the use of principles in projects, such as those of De Stijl and those used in Spangen, the system ought to be able to recall design precedents based on the use of specific principles.
7. Given that some features appear often combined with others, the model ought to provide a mechanism to apply these elements together. Example: the design of a broad communal courtyard free of buildings such as in Block IX of Spangen and Tusschendijken and most living rooms of the perimeter building facing the courtyard.
8. Given that architects are active agents in the design process, the model ought to have mechanisms that enable them to add, subtract, mutate, substitute and combine elements of design precedents.
9. Subsequently, given architects' traditional way of working, modifying a solution or redrawing it on top of initial designs, the model ought to provide design precedents in manageable formats.

In his Psychology of Architectural Design, Ömer Akin asserts that in architecture, the change of rules and/or the use of analogies are part of the design process (Akin 1986). We found this applicable in Oud's series of designs, and therefore architects ought to be able to customize the model.

This case hinted at an analogy between the process of re-use and the Darwinian evolutionary model – in the sense that evolution is not progress but the survival of the (relative to the actual situation) fittest.

Some adequacy criteria raised the idea of an evolutionary process. We have observed that features were modified, subtracted, and substituted in such a way that the solutions that are the most fitting in that particular situation are chosen and applied. We have briefly seen how Oud moved from a Berlagian style to follow the purist principles of *De Stijl* and to break through it with the design of the Hoek van Holland block, and returned later to some of his early traditional features. This was not a linear process; it seemed more an evolutionary process where some features permeated and alternately reappeared through generations of designs. Some features seem to appear again and again until they become "extinct", either because the architect lost interest in them, or due to internal and/or external constraints. In this sense, the case hinted at an analogy with Genetics in the sense that the expression of design precedents are copied and passed on to a new generation of designs. It seems that the process of the re-use of design precedents by modification and recombination may also lead to innovation, i.e. to the development of new types.

The analogy between the process of re-use of design precedents and the biological theories of evolution and genetics seem to have some fruitful similarities, but also some notable differences. This is what we will investigate further.

The next chapter will present a review of the existent analogies between design and the theory of evolution to see if there is an extant interpretation of the biological evolutionary theories that may help us in developing our model.

CHAPTER 4

LIMITATIONS OF TRADITIONAL AND CURRENT EVOLUTIONARY ANALOGIES

This chapter is a brief review of traditional and current biological evolutionary analogies in design. Starting from a vague analogy between the process of re-use and biological evolutionary models as set out at the end of Chapter 3, we will explore the biological evolutionary model as has already been used. We shall search these analogies for what could be of use in representing the process of re-use of design precedents during the design process.

Chapter three suggested an analogy between the process of re-use of design precedents and the theories of biological evolution and genetics. In this chapter, we will describe and analyze several related analogies, i.e. traditional and current analogies between design and nature, and in particular between design and the biological Darwinian model of evolution and genetics.

Concerned with the forces behind innovation in architectural practice, the objective of this review is to see whether one of these analogies could help us in describing aspects of the phenomenon of change in architecture to the extent that it is based on the re-occurrence of design precedents over the years and according to the adequacy criteria of Chapter 3. A secondary objective is to see whether the use of the analogy was fruitful or not, and for this reason we evaluate the reduction of the theory of evolution provided by the theoreticians. We do not intend to justify our use of the analogy between the re-use of design precedents and biological evolutionary models by describing other analogies and applications (see chapters 1 and 2 for the use of the analogy in this research).

At this stage of the research, our analogy between the re-use of design precedents and biological evolutionary models relied on the following: when recalling from memory we may forget things, and despite our efforts, we do not bring the design fully to the table. In nature, genes are sometimes wrongly copied; these changes from the original are called “mutations”. A mutated organism will pass through selection, and its fitness will determine whether it will survive until reproduction or not. This kind of “natural selection” of designs does not necessarily occur in the built environment as in nature. The environment in design can be a simulative one, where a feature is tested alone as well as with regard to its effect on others, and the whole will be tested in relation to the environment. This simulative environment is a means to get the building right first time.

In nature, the organisms that have the best fitness today may be condemned to extinction if the climate changes or if an environmental catastrophe occurs because the organisms may not be able to adjust to the new pressing external constraints. Organisms are either adaptable, therefore (temporarily) successful, or not. In other words, a very successful species today may prove inadequate for survival and reproduction in the future and thus be condemned to extinction. By analogy, design precedents are not good or bad designs in their essence; they survive if internal and external constraints keep enhancing their validity. By external constraints, we mean also the interaction between building and users, in particular the potential of the building to either fulfill its original function or to adjust to other uses.

As will be shown in this chapter, such analogies are not always applied on the same level of the design process. There are analogies that:

1. Compare the structure of organisms with that of artifacts;
2. Compare an organism-environment to an object-environment relation;
3. Compare the evolutionary model with an account of a historical production of artifacts;
4. Compare the embryological process with designing.

4.1. General Concepts and Theoretical Sources of **Traditional** Biological Analogies

Biological-design analogies have been drawn since Aristotle’s time. Therefore, a priority task is to clarify the terms in biological analogies, first because of their variety and second because they have been used and sometimes camouflaged under diverse names or ‘unconsciously’ adopted within different concepts such as

Functionalism. Various architects and theoreticians of the nineteenth century have applied these traditional analogies.

In his *The Evolution of Design*, Philip Steadman grouped the biological analogies in architecture and applied arts into four categories: a. Classificatory, b. Anatomical, c. Ecological and d. Darwinian (Steadman 1979). These categories are retained in the description and evaluation below, with the exception of Darwinian, which we will call Evolutionary, as Charles Darwin (Darwin 1859) is responsible for one of a number of evolutionary models, such as the evolutionary model of Jean Baptiste Pierre Antoine de Lamarck (Lamarck 1801)[1].

4.1.1. Sources of Pre-Evolutionary Biological Analogies

This sub-section will describe the sources of the classificatory and anatomical analogies. Both are pre-Darwinian, but they inspired some architects and theoreticians such as E.E.Viollet-le-Duc[2] and G. Semper[3] with their ideas about evolution in design.

Source of the Classificatory Analogy: Building Types and Natural Species

This category refers to form and visible differences between subjects. Its main keywords are "taxonomy", "visible similarity", "visible difference", and "variation".

According to Steadman (1979), in eighteenth century natural history, there were two different kinds of approaches taken to classification or systematics, "distinguished as systems – outstanding amongst which was the system of Linnaeus [1707-1778] – and methods, or rather method, since there was essentially only one. In both cases it was imagined that a more or less perfect continuity existed between species, so that they might in principle all be laid out across a two-dimensional surface or table" (Steadman 1979, p. 23).

Steadman asserted: "both the systems and the method turned on the identification of visible elements or characters of the plant or animal, their number, size, shape and spatial configuration" (Steadman 1979, p. 24). Their goal, claimed Steadman, was to group them into species, and these into families, and grade them into the continuous scale of the classificatory table (Steadman 1979, p. 24).

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[1] Lamarck, Jean Baptiste Pierre Antoine de (1744-1829): French naturalist. He is noted for his study and classification of invertebrates and for his introduction of evolutionary theories. From 1793 he was professor of zoology at the Museum of Natural History. His ideas concerning the origin of species were first made public in his Système des animaux sans vertèbres (1801). - Columbia Encyclopedia http://aol1.infoplease.com/encyclopedia.html

[2] E.E. Viollet-le-Duc (1814-1879) is generally acknowledged to be the premier theorist of modern architecture, he was architect and preservationist, scholar of Gothic architecture and theorist and wrote the Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle, published in ten volumes that appeared between 1854 and 1868 (Hearn 1990).

3 G. Semper was architect and "the leading German architectural theorist of mid-nineteenth century" who wrote Die vier Element der Baukunst (Kruft 1994).

According to Steadman, “the systems worked by isolating just a few elements from the whole form of the plant, and using the variations and resemblances in these chosen elements for the basis of the analysis”. Further, “the method worked by taking the first species to be examined, and making a complete description of all features. The process was repeated with successive species, but marking only the differences from species already described, and not repeating any similarities. Thus whatever order the species might be examined in, the same overall distinction and resemblances would in the end emerge” (Steadman 1979, p. 24).

Linnaeus’ system was of great influence and is still in use today. According to William R. Coleman in his *Georges Cuvier, Zoologist,* Linnaeus was essentially a taxonomist, and his objective was “the complete systematization of organic nature” (Coleman 1964, p. 24). He believed that there were two ways to classify nature: a natural system and an artificial system. He asserted that the natural system could only be adopted if we knew all species in the world. Thus, though the natural system remained the naturalist’s true goal, he opted for a less pretentious artificial system.

The Linnaean taxonomy, claimed Coleman, “is an artificial classification in which there is a peculiar blend of elements of the sexual system and the observed features of the flowering plants” (Coleman 1964). The binomial nomenclature created by Linnaeus (genus-species) substituted another based on the genus name and a detailed description of the species.

Georges Louis Leclerc Buffon[4] was opposed to these systems of classification. Buffon refuted, wrote Coleman (1964), “not only the utility of animal classification but the impossibility of such creations. He was convinced that the so-called higher taxonomic categories such as the family or order, and even the genus, had no reality in nature and were only artificial constructions of the taxonomist. He acknowledged the reality in nature of individuals only and asserted that ‘the more we wish to augment the number of divisions of natural productions, the more we approach truth, since there really exist in nature only individuals, and the genera, orders, and classes exist only in our imaginations’” (Coleman 1964, pp. 21-22).

According to Steadman (1979), “Georges Cuvier’s[5] methods of classification and analysis are first held out explicitly as models for the study of buildings and useful artifacts in France by Viollet-le-Duc, and in Switzerland by Semper, both writing from the mid-1850s” (Steadman 1979, p. 40).

4 Buffon, Georges Louis Leclerc, 1707–88, French naturalist and author. From 1739 he was keeper of the Jardin du Roi (later the Jardin des Plantes) in Paris and made it a center of research during the Enlightenment. Columbia Encyclopedia, http://aol1.infoplease.com/ce6/people/A0809360.html
5 Cuvier, Georges Léopold Chrétien Frédéric Dagobert, Baron, 1769–1832, French naturalist, b. Montbéliard, studied at the academy of Stuttgart. From 1795 he taught in the Jardin des Plantes. Columbia Encyclopedia, http://aol1.infoplease.com/ce6/people/A0809360.html

Source of the anatomical analogy: engineering structure and the animal skeleton

The anatomical analogy between engineering structure and the animal skeleton refers in particular to Form and Function. Its main keywords are "functional classification", "proportions", "structure", and "materials". Cuvier was "a pioneer in the science of comparative anatomy, he originated a system of zoological classification that comprised four phyla based on differences in structure of the skeleton and organs" (Columbia Encyclopedia). His classificatory principles form the basis of this anatomical analogy.

Principles of Cuvier's anatomical method:

According to Caroline van Eck in her *Organicism in Nineteenth-Century Architecture*, "The central concept of Cuvier's biology was that of *the conditions of existence:* the conditions that are necessary for the survival and reproduction of an animal (Eck 1994, p. 216)." This concept was a reformulation of Aristotle's concept of final causes: "they both indicate a way of interpreting the form of organisms which concentrates on the contribution of the parts to the survival of the whole – that is, on purposive rather than structural unity" (Eck 1994, p. 217).

According to Steadman, Cuvier described the "universal adaptation of organic form to the special habits, behaviour and surroundings of each creature… by reference to the hypothesis of 'conditions of existence'" (Steadman 1979, pp. 34-5). This means "principles which stated the fundamental characteristics of each and every creature" (Steadman 1979, p. 35). The next two principles come, asserted Steadman, from this condition of existence (Steadman 1979). However, we think that the principle of similitude must be considered as well. These principles were largely used in the beginning of the nineteenth century as a source of organic/anatomical analogy.

Correlation of Parts. This principle was first used by Felix Vicq d'Azir, Cuvier's immediate predecessor. According to Steadman, "by *correlation of parts* Cuvier meant the necessary functional interdependence between the various organs or systems of the body," and "the presence of one organ or structure would necessarily imply the presence of one or several others; and any change in one would imply a correlated change in others" (Steadman 1979, p. 35).

Subordination of Characters. The subordination of characters was first used by A. L. de Jussieu. According to Steadman, it "had an originally classificatory purpose; the reference is to *characters* in the sense of features selected for the purposes of taxonomy" (Steadman 1979, p. 36). This principle imposed a certain hierarchy on the importance of the organs; i.e. that certain organs or bodily systems had greater functional significance than others, and could thus be arranged in order of importance.

However, Cuvier's approach differs from Jussier's by not looking just for visible features. He developed a system, relying on the function of organs or systems responsible for the working of the whole body. "Differences and similarities," wrote Steadman (1979), "which are superficially observed are no longer a sure guide for taxonomy, since the exact nature of hair or fur, external colouring, the precise sizes of limbs, can all alter within limits without endangering the co-ordination and viability of the whole" (Steadman 1979, pp. 36-7).

The principle of similitude from Galileo. According to Steadman, "It was not Cuvier who originated the principle of similitude in fact, although his studies set it in the whole framework of functional anatomy, and he refers to its effects. The principle is as old as Galileo, who first appreciated its workings and found many examples of its operation both in nature and in the world of engineering" (Steadman 1979, p. 49). Steadman claimed that the principle of similitude "was an important consequence of the correlation of parts that functional relations would not only govern the necessary and simultaneous presence of various organs in systematic combination, but would also determine the proportions and dimensions of the overall shape of a creature" (Steadman 1979, p. 49).

In this period, there was already much discussion about what generates what, or "does form follow function, or does function follow form?" According to Peter Collins in his *Changing Ideals in Modern Architecture, 1750-1950*, "The importance of this question to those familiar with modern architectural theories […] will need no justification. Amongst biologists, the distinction was considered sufficiently important to perpetuate a bitter quarrel for half a century, the leader of the 'form follows function' school being Georges Cuvier, the leader of the opposing faction being Geoffroy Saint-Hilaire" (Collins 1965, p. 151).

"In its most naïve expression the anatomical analogy as applied to buildings," asserted Steadman, "takes the form of the animal with the supporting structural framework of columns and beams or piers and vaults" (Steadman 1979, p. 16).

As the classificatory analogy, the anatomical analogy did not particularly involve evolution. These were techniques for animal classification. The description may support the idea of permutation or recombination of parts in such a way that it may at first glance resemble an evolutionary process. But, paradoxically, Cuvier believed that "organic species were fixed, distinct and unchanging for all time" (Steadman 1979, p. 34).

4.1.2. Sources of the Ecological and Evolutionary Analogies

Since the ecological analogy between the environment of the artifacts and organisms seems to be very close to the evolutionary one and is used in combination with others, we shall abbreviate its description and bring it together with the evolutionary analogies.

Source of the ecological analogy: the environment of artifacts and organisms

The ecological analogies refer to form, function and environment. Their main keywords are “functionalism”, “adaptation”, “fitness”, and “environment”. Cuvier is once more the source of the ecological analogy.

According to Steadman, “We have here the clear basis for a rather simple ‘ecological’ analogy of a kind that is almost too familiar in the literature of nineteenth-century functionalism and in the modern movement: in both animals and artifacts, form is related to function, and function is related to environment. The degree to which form suits or is appropriate to function and environment in either case might be expressed in terms of ‘adaptation’ or else (after Darwin and Spencer) in terms of fitness” (Steadman 1979, p. 58).

According to John Tyler Bonner, ‘“adaptation’” is a “word used by biologists in two different senses, both of which imply the accommodation of a living organism to its environment. One form of adaptation, called physiological adaptation, involves the acclimatization of an individual organism to a sudden change in environment. The other kind of adaptation… occurs during the slow course of evolution and hence is called evolutionary adaptation” (Bonner 1995). In Darwinian evolution, the latter kind of adaptation is not subject to the will or control of the organism; it happens as a result of random mutations and natural selection. Below we shall explore the second type.

Sources of the traditional evolutionary analogies

The traditional evolutionary analogies refer to evolutionary adaptation, form, function, environment and time. They differ from the ecological one due to the factor of “time” and due to the discordant use of the notion of “adaptation”. Also, the notion of “transformation” must be distinguished from the notion of “evolution”.

The notion of “transformation” diverges from that of “evolution”. According to Steadman (1979), “transformation … might consist of a systematic permutation or combination of parts or elements.” He says that it is “not to be confused with an evolution in time, since it is conceived of as effecting a movement across the theoretical space of classification of all species, not as constituting a historical process of change in a single species” (Steadman 1979, p. 24).

Some examples of transformational theories are: a) - “Goethe’s transformational system for the generation of all plants from archetypal plant” (Steadman 1979, p. 24); b) - Durand’s system of composition: “Durand’s system of composition [which] involves the setting up of principal and subsidiary axes for the building, around which pre-designed elements – the basic molecules or cells of the structure – are then disposed in symmetrical arrangement" (Steadman 1979, p. 24); c) - Darcy Thompson's Theory of Transformation. This theory supposes that "any material form could be transformed into any other: just as out of a 'shapeless' mass of clay the potter or the sculptor models his artistic product; or just as we attribute to Nature herself the power to effect the gradual and successive transformation of the simple germ into the complex organism", or at least one vertebrate into another vertebrate (Thompson 1992, p. 1094).

The following sources of analogies are based on the work of Lamarck and Darwin. Both saw nature in evolution, although through different mechanisms. Lamarck's theories were not properly tested during his lifetime. Darwin's theory proved to be the right one, or at least the right direction. However, in the opinion of this researcher, it is not important that a theory has proved to be correct in order for it to be the source of an analogy.

1. The evolutionary Lamarckian analogy:

This analogy refers to "adaptation", "inheritance of acquired characteristics", and "time".

According to Steadman, the work of Lamarck became known in the form of a revival, as an opposition to the work of Darwin (Steadman 1979). Lamarck claimed, wrote Collins, that "a change in environment actually modifies the form of animals, and that these changes are transmitted by heredity" (Collins 1965, p. 153). He believed that the adaptations undergone by individuals during their lifetime would be passed on to their offspring. According to Steadman, Lamarck claimed that: "It is not the organs – that is to say, the form and character of the animal's bodily parts –which have given rise to its habits and peculiar properties, but, on the contrary, it is its habits and manner of life and the conditions in which its ancestors lived that has in the course of time fashioned its bodily form, its organs and its qualities" (Steadman 1979, p. 40).

Lamarck's three rules:

- The production of a new organ in an animal body results from the arising and continuance of a new need, and from the new movement that this need brings into being and sustains.
- The degree of development of organs and their force of action are always proportionate to the use made of these organs.
- All that has been acquired, imprinted or changed in the organization of the individual during the course of its life is preserved by generation and transmitted to the new individuals that descend from the individual so modified [inheritance of acquired characters] (Steadman 1979, p. 126).

According to Collins, in contrast to Buffon, and as a result of the study of plants and later on of anatomy, Lamarck "eventually led to conclude that living forms had not evolved retrogressively, but progressively" (Collins 1965, p. 150).

2. The "Darwinian" evolutionary analogy[6]

This analogy refers to "inheritance", "copying instructions", "random mutation", "struggle for survival", "fitness" and "natural selection". A species evolves through time; according to Steadman (1979), it is "a historical process of change in a single species" (Steadman 1979, p. 24). In this Darwinian analogy, asserted Peter Collins, evolution was attributed "to a selection of existing forms by Nature herself" (Collins 1965, p. 153).

However, the evolutionary analogies of the nineteenth century were not much derived from Darwinian theory. In fact, due to the confusion between progress and evolution, they were closer to the evolution theory of Lamarck.

4.1.3. The Use of Analogies According to 19th Century Architects and Theoreticians

In *The Evolution of Design*, Steadman tried "to set out and subject to critical analysis the many analogies which have been made, by a great variety of writers, between biology and the applied arts, in particular architecture" (Steadman 1979).

The purpose of this sub-section is to describe briefly how the analogies were used (or misused). Among the nineteenth century writers on analogies between design and nature are Semper and Viollet-le-Duc.[7] These two architects and theoreticians made use of several of the above-mentioned sources of analogy, which we briefly describe below.

The Analogies of Gottfried Semper 1803 -1879

Semper was an art historian, architect, and the author of – in the opinion of this researcher – at least three kinds of biological analogies as classified by Steadman. These analogies were anatomical, environmental and evolutionary.

During his stay in Paris, Semper would walk in the Jardin des Plantes and visit Cuvier's magnificent collection of fossilized remains of the animal kingdom. According to Adolf Max Vogt, biological analogies derived from Cuvier's collection gave Semper the framework of his theoretical work: "This magnificent collection of Cuvier's", wrote Vogt, "suggested to him [Semper], apparently once and for all, the framework of his theoretical work. It triggered the question: From

6 Chapter 5 will be dedicated to our Darwinian analogy.
7 According to Steadman, "Cuvier's methods – of classification and analysis – are first held out explicitly as models for the study of buildings and useful artefacts, in France by E. E. Viollet-le-Duc, and in Switzerland by G. Semper, both writing from the mid- 1850s (Steadman 1979, p. 40)."

the observation of (animal) nature… shouldn't we be allowed to conclude by analogy that in the creations of our hands, in the works of art, approximately the same kind of process is to be found?" (Vogt 1984, xvi)

From Cuvier's classificatory work, Semper grew to an evolutionary analogy by adding an historical component. About the environmental analogy, one may refer to his definition of style: "Style is the conformity of an art object with the circumstances of its development" (Steadman 1979, p. 64). It is interesting to note that Semper came to an evolutionary analogy before he read Darwin's *The Origins of Species*. Semper, claimed Steadman, "is actually reported to have made the analogy between design and evolution during his visits to the Jardin des Plantes" or even by recalling Seneca (Steadman 1979). According to Steadman, "His idea of a type or motif, as we have seen, is related to constancy of function; and he writes of those 'traditional forms' which over the centuries have proved themselves to be unshakably true expression of types. But at the same time he makes a definite claim that in certain types, particularly those associated with his four key materials, lie the historical origins of the applied arts and architecture; and that in the subsequent progress of these arts the original types have been continuously elaborated and differentiated" (Steadman 1979, pp. 72-3).

According to Norman Crowe in his *Nature and the Idea of a Man-Made World*, Semper "described a fundamental and detailed evolution for architecture that began with the nomadic tent of knotted fabric. He then suggested logical stages of its evolution that could be verified by contemporary archeology and anthropology. His theory focused on the development of the so-called primary elements of architecture – wall, floor, ceiling, and roof – as they might have progressed through history. Like Vitruvius, Semper emphasized in his theory the tectonic qualities of architecture as its true basis" (Crowe 1995, pp. 147-8).

By tectonics, Semper meant the "art that takes nature as a model – not nature's concrete phenomena but the uniformity and the rules by which she exists and creates" (Steadman 1979).

The Analogies of Eugene Emmanuel Viollet -le -Duc 1814-79

Viollet-le-Duc was a French architect who specialized in the restoration of works of medieval architecture. His major theoretical work was the *Dictionnaire Raisonné de l'architecture Francaise.*

According to Steadman, Viollet-le-Duc[8] did not make explicit reference to the classificatory principle of 'subordination of characters' or to Cuvier's use of it. However, his "analogy with the applied arts and architecture allows for the interpretation of this idea as much as it had for the correlation of parts" (Steadman 1979, p. 67). Thus for example in a passage of the *Dictionnaire Raisonné*, Viollet-le-Duc asserted that "Just as when seeing the leaf of a plant, one deduces from it

8 And as a matter of fact, neither did Semper (Steadman 1979, p. 67)

the whole plant; from the bone of an animal, the whole animal; so from seeing a cross-section one deduces the architectural members; and from the members, the whole monument." This method of deduction follows Cuvier's anatomical principle of the 'correlation of parts'[9], and is illustrated admirably in the relation of vault to column in Gothic (Steadman 1979, p. 45).

Collins claimed that "Viollet-le-Duc, like Ruskin before him, drew attention to the way mediaeval sculptors had studied the morphology of vegetation, and how they understood that the contours of plants 'always express a function, or submit themselves to the necessities of the organisms'. He did not, however, draw any major philosophical conclusion from this observation, except to say that the masons 'sought to bring out in the structures of their buildings those qualities that they found in vegetation' (Collins 1965, p. 155)".

Referring to the environmental and evolutionary analogies, Steadman mentioned the example of the ideal cathedral. The ideal cathedral, claimed Steadman, "provides a rational exposition of the structural and functional logic of every member … and their assembly into a coherent, coordinated structural system. Inasmuch as all cathedrals shared the same general function, and employed similar constructional techniques and materials, so their basic structural forms would be similar, and would correspond to the ideal plan. Any variations would result from one of two possible kinds of changes. The first would be changes in these determining factors, i.e. 'environmental' changes" (Steadman 1979, p. 72). And the second kind of change, says Steadman in the following paragraph, is a rather evolutionary one.

As quoted by Steadman (1979), Viollet-le-Duc "talks of medieval architecture as a whole being an organism which develops and progresses as nature does in the creation of beings starting from a very simple principle which it then modifies, which it perfects, which it makes more complicated, but without ever destroying the original essence" (Steadman 1979).

However, Viollet-le-Duc believed in progress, and that is the fundamental principle that brings confusion to an association of architectural history with evolution. Viollet-le-Duc claimed: "Progress always consists in passing from the known to the unknown, through successive transformations of methods. It is not by fits and starts that progress takes place, but by a series of transitions." He was engaged in preparing these transitions to a new architecture (Viollet-le-Duc 1995, p. 231).

According to Steadman, the analogy made between the technological evolution of artifacts and Darwin's concept of organic evolution refers to a three-step process: the first step is to equate heredity with copying as Semper and Viollet-le-

9 Cuvier started his investigation with a survey of the bones themselves and claimed that "…a person who is sufficiently master of the laws of organic structure, may, as it were, reconstruct the whole animal to which that bone had belonged (Steadman 1979, p. 40)."

Duc did. The second adds the need to stabilize designs, i.e. no radical changes; and the third, as a result of copying, refers to the production of slight variations of form.

4.1.4. Evaluation of the Traditional Analogies with Design

As mentioned above, evolutionary design is also used to mean transformation of forms, which does not carry the concept of local fitness so particular to natural evolution. The other association is with the notion of progress. Both progress and evolution mean improvement, and both implicitly bear the idea of time. However, evolution is constrained by the environment, while the notion of progress is overloaded with the idea of universality. Furthermore, evolution involves chance, and even a catastrophe is a chance for some species to survive. Therefore, only when it is ideally assumed that the environment is one and unchangeable or always *better* than before, do evolution and progress coincide.

In this brief description of traditional analogies, it is evident that while extremely interesting, the analogy between design and nature has been loosely used and has referred more to the concept of progress than of biological evolution. Moreover, it did not constitute a clear system. The biological concepts, in particular those from the evolutionary analogy, were often substituted for others which were in fact opposed to their supposed biological sources; and it is a fact that Cuvier, an anti-evolutionist, inspired more architects into making (pseudo-) evolutionary analogies in design than Darwin himself. Finally, the use of these analogies refer more to analogies between two artifacts, and analogies between two artifact-environment relations, than to the re-use of design precedents that refers to the relation between the architect-designs, which would make them more unsuitable as representations of our model,

4.2. General Concepts and Theoretical Sources of **Current** Biological Analogies

This section describes current evolutionary biological analogies in relation to design. Often these analogies involve genetics and/or embryology, such as those based on evolutionary computation.

The section will be sub-divided as follows: first, it will describe François Jacob's considerations between engineering and tinkering. Second, it will describe Richard Dawkins' memes; third, it will describe analogies that are related to John Holland's evolutionary computation; and finally we shall examine the analogies concerning evolutionary design.

4.2.1. Engineering and Tinkering

Bringing up the popular idea that if there are intelligent organisms on other planets, they be like us[10], François Jacob in his "Evolution and Tinkering" tried to point out where this idea failed to reflect the truth. He asserted that organisms are historical structures, evolving according to the "interplay of local opportunities – physical, ecological, and constitutional" (Jacob 1977). This common misunderstanding was derived from the analogy between the actions of an engineer and the action of natural selection. In this article, he pointed out the differences between the two and instead proposed an analogy between the action of a tinkerer and the action of natural selection.

According to Jacob, there were three main differences between the actions of an engineer and that of natural selection. "**First**, because in contrast to what occurs in evolution, the engineer works according to a preconceived plan in that he foresees the product of his efforts. **Second**, because of the way the engineer works: to make a new product, he has at his disposal both material specially prepared to that end and machines designed solely for that task. **Finally**, because the objects produced by the engineer, at least by the good engineer, approach the level of perfection made possible by the technology of the time. In contrast, evolution is far from perfection" (Jacob 1977, p. 1163).

According to Jacob, "Natural selection has no analogy with any aspect of human behavior. However, if one wanted to play with a comparison, one would have to say that natural selection does not work as an engineer works. It works like a tinkerer – a tinkerer who does not know exactly what he is going to produce but uses whatever he finds around him whether it be pieces of string, fragments of wood, or old cardboard opportunities" (Jacob 1977, p. 1163). Jacob also claimed: "Evolution does not produce novelties from scratch. It works on what already exists, either transforming a system to give it new functions or combining several systems to produce a more elaborate one" (Jacob 1977, p. 1164).

At this point, we must say that the action of the "engineer" as described by Jacob seems to be more the action of the engineer who works only by optimization. The action of a creative architect such as Le Corbusier, when designing the Unité d'Habitation of Marseilles, is not so close to that of Jacob's engineer. Firstly, Jacob's engineer foresees the product, while architects have ill-defined problems on their hands; therefore, they may not know what the result will be, in particular at the early stage of design. Secondly, Le Corbusier did not produced novelties from scratch. As he asserted, it was in gestation for 40 years. Finally, though architects want to build right the first time, there is no way to claim that the product approached the level of perfection, since there were innumerous players involved in the process and not all of them were satisfied with the result.

However, architects are not tinkerers either, or rather, they limit their "tinkering" by analytical thinking. According to Jacob, the tinkerer "always manages with odds and ends. What he ultimately produces is generally related to no special project, and it results from a series of contingent events, of all the opportunities he had to enrich his stock with leftovers. As was discussed by Levi-Strauss, none of the materials at the tinkerer's disposal has a precise and definite function. Each can be used in a number of different ways" (Jacob 1977, p. 1164). Though architects may propose materials and tools other than the traditional ones, their tools are generally defined by analytically thinking about the project in hand. By contrast, the tools of the tinkerer will be used in the production of all artifacts. What for? Jacob claimed that it "depends on the opportunities" (Jacob 1977, p. 1164).

All in all, we should be aware of the differences between the processes in nature and in design. This theme will be explored in greater depth in the next chapter. The following sub-section will describe Richard Dawkins' meme, an analogy between cultural and biological evolution that refers to the gene as the unit of selection. Numerous processes will be discussed, which will be described in more detail in the next chapter.

4.2.2. Dawkins's Meme for Cultural Evolution

In searching for an evolutionary framework for the re-use of design precedents, one may come to ask: what, in fact, might be the content of a gene for architecture?

This section focuses the discussion on Dawkins' meme. 'Meme' is a term coined by Richard Dawkins in his book *The Selfish Gene,* and refers to Cultural Evolution. Many researchers (philosophers, designers) were inspired to use it and extended it in many directions. Sometimes, the analogy between culture and biological evolution was pushed too far. In this section, we will describe the meme and explain why we do not make use of this analogy in this research.

This section is divided into four parts. First, we shall describe the meme; second, we shall describe what the role of the designer would be in a meme-framework; third, we shall describe the opposition levelled against this analogy between culture and biological evolution; and fourth, we shall present a brief conclusion.

Characteristics of the Cultural Evolution

According to Dawkins, "Cultural 'evolution' is not really evolution at all if we are being fussy and purist about our use of words, but there may be enough in common between them to justify some comparison of principles" (Dawkins 1986, p. 267). It

10 i.e. mammals walking erectly and varying only in mere details such as the size of the skull, meaning bigger brains, and/or number or capacity of their sense organs.

is not our intention to pursue either a "fussy" or "purist" analogy. Our objective is to find a representation for the re-use and adaptation of design precedents during design that considers the phenomenon of change through the years; with this in mind, we evaluated the possibility of using the meme as the architectural gene.

According to Dawkins, the meme is the unit of cultural transmission. "Examples of memes", wrote Dawkins, "are tunes, ideas, catch-phrases, clothes fashions, ways of making pots or of building arches" (Dawkins 1989, p. 192).

One can say that ideas are selected through argumentation (struggle for survival), which means that the memes are the unit of selection[11]; and that therefore Dawkins equated them with the "selfish gene". Further, Dawkins claimed that the total number of memes belonging to a culture could be called the meme pool, where some memes are stronger than others; obviously, and despite Dawkins' defense of Darwinian gradualism in evolutionary biology, Dawkins recognizes that memes evolve extremely fast.

"Just as genes propagate themselves in the gene pool by leaping from body to body via sperms or eggs," wrote Dawkins, "so memes propagate themselves in the meme pool by leaping from brain to brain via a process which, in the broad sense, can be called imitation" (Dawkins 1989, p. 192). Imitation is thus the cognitive process that translates the ideas from one brain to another. This propagation from brain to brain, which occurs through various means, he termed **replication**. It can be transmitted by means of a speech, or via a book, a silent instruction to make a jar, for example, or the playing of an instrument, and so forth.

This replication occurs at different hierarchic levels. Dawkins claimed that "if a single phrase of Beethoven's ninth symphony is sufficiently distinctive and memorable to be abstracted from the context of the whole symphony, and used as the call-sign of a maddeningly intrusive European broadcasting station, then to that extent it deserves to be called one meme" (Dawkins 1989, p. 195). In another example, Dawkins wrote that the theory of evolution is a meme; however, its mechanisms can also be considered a meme. In the opinion of this researcher, it would have been more practical if, in this case, the theory of evolution would be an analogue of "organism", while the genes would be the concepts within it with its many variables, such as the divergences of Dawkins and Gould. It thus becomes very unclear how in fact *imitation* occurs, i.e. how the ideas operationally replicate from one brain to another.

Dawkins uses the term *parasitism* rather than *reproduction*, meaning the introduction of an idea to someone else's mind. Thus one "parasitizes" the mind of another when he or she places a new idea or meme into it.

11 See the next chapter for a discussion on unit of selection.

Opposition to the Analogy between Cultural and Biological Evolution

In his essay “The Panda’s Thumb of Technology”, Gould claimed: “Biological evolution is a bad analogue for cultural change because the two systems are so different for three major reasons that could hardly be more fundamental” (Gould 1991, pp. 63-65). These reasons are: first, “cultural evolution can be faster by orders of magnitude than biological change at its maximal Darwinian rate” (Gould 1991, p. 65). Second, and in accordance with Maynard Smith, he maintained that “cultural evolution is direct and Lamarckian in form: the achievements of one generation are passed by education and publication directly to descendants, thus producing the great potential speed of cultural change. Biological evolution is indirect and Darwinian, as favorable traits do not descend to the next generation unless, by good fortune, they arise as products of genetic change” (Gould 1991, p. 65). As Maynard Smith wrote, in evolutionary models, acquired characteristics are not inherited; inheritance is Mendelian and the atoms or genes are equally inherited from our two parents, and from no one else.

Third, “the basic topologies of biological and cultural change are completely different. Biological evolution is a system of constant divergence without subsequent joining of branches. Lineages, once distinct, are separated forever. In human history, transmission across lineages is, perhaps, the major source of cultural change. Europeans learned about corn and potatoes from Native Americans and gave them smallpox in return” (Gould 1991, p. 65).

Gould’s reasons to criticize the analogy between cultural change and biological evolution could also be applied to design in general[12]. However, it is the lack of clarification concerning the structure of the meme that causes the greatest barrier in applying the meme in the re-use and recollection of design precedents. As Daniel Dennet posed the question in his ‘Darwin’s Dangerous Idea’, “if you can’t turn it into actual science, with testable hypotheses, reliable formalizations, and quantifiable results, what good is it, really?” (Dennett 1996, p. 353).

The Role of the Designer: the Memetic Option

Let us consider the natural environment to be a simulative environment, where designers recall several precedents to constitute the population of a specific “place.” One could give – as the memeticists do – the designers the role of processors of past experiences and equate the struggle for survival of the organisms/designs with a fitness measurement underlining the constraints and requirements imposed on the specific design process; or give them, as we do, (besides other characteristics that architects have) the role of breeders, with a conscious power of selection towards adaptation.

Memeticists would say that even though designers think otherwise, the role of a designer is “the brain/processing unit in which the cultural solution to the

12 However, we are dealing only with the process of re-use and recollection in design.

problem arranged itself ". The difficulty with this kind of approach is that the designer is less a creator than a brain that processes information from the past. The memeticists eliminate the question of intention by saying: "This intentionality is produced by the rapid sequence of problem and solution. However, the solution was not so much derived by the sheer effort of the designer as intentional subject, but as a meme extracted from the meme pool, quickly mutated and recombined in the brain of the designer, and the results of the process applied to the problem in hand" (Gatherer 1999, p. 98). However, as Michael French maintains, the use of simulation and the concept of "getting it right first time" (French 1999, p. 80) show that there is the intention of the architect who searches for a balance among the diverse categories that make the artifact fit before it is built. We adopt the idea that the architect is one of the main agents in the design process and therefore, we have no reason to keep the architect out of it.

The Architectural Gene and the Memetic Option

Obviously, reductions are part of any analogy; however, Dawkins' reduction would misrepresent the processes of re-use in design. We have two reasons not to adopt this representation. Firstly, the meme concept has been extended and reinterpreted by several researchers; to avoid misconceptualization of the real processes in design, we have decided to keep away from Dawkins' analogy between culture and biological evolution. Secondly, we claim that the meme as used to date can mean anything: a symphony or a part of it, evolution theory or the mechanisms within it. In this sense, it is not serviceable: it is not clear what is being transmitted from generation to generation. Therefore, we will simply call our gene 'the architectural gene' or the d-gene.

4.2.3. Evolutionary Computation

"The beginning of genetic algorithms," claimed Dipankar Dasgupta and Zbigniew Michalewicz in their *Evolutionary Algorithms*, "can be traced back to the early 1950s when several biologists used computers for simulations of biological systems. However, the work done in the late 1960s and early 1970s at the University of Michigan under the direction of John Holland led to genetic algorithms as they are known today" (Dasgupta and Michalewicz 1997, p. 6).

The evolutionary model developed by John Holland in his *Adaptation in Natural and Artificial Systems* departs from an analogy between complex adaptive systems (cas) and the Darwinian Model and Genetics. However, "the reader," says Holland, "should be warned that the generalized operators (…) are idealized to varying degrees. This has been done to emphasize the basic functions of the operators, at the cost of exploring the complex (and fascinating) biological mechanism underlying their execution. Even so an attempt has been made to keep the correspondence close enough to allow ready translation of the results to the original biological context" (Holland 1975, p. 97)."

In *Hidden Order*, John Holland began his experiments by briefly analyzing complex adaptive systems such as the central nervous system, the human immune system and New York City. He claimed: “even though these complex systems differ in details, the question of coherence under change is the central enigma for each”; this common factor being so important that at the Santa Fe Institute they collected these systems under a common heading: complex adaptive systems (cas). According to Holland: “This is more than terminology. It signals our intuition that general principles rule cas-behavior, principles that point to ways of solving the attendant problems” (Holland 1995, p. 4).

Holland described four properties of cas: aggregation, nonlinearity, flows and diversity; and three mechanisms: tags, internal models and building blocks. By way of modeling these characteristics of a complex adaptive system (cas), he made analogical use of the biological evolutionary model. With this description he set out to provide a computer-based model that had enough generality to allow him to carry out “thought experiments” relevant to all cas. A larger objective was “to uncover general principles that will enable us to synthesize complex cas behaviors from simple laws. Complex adaptive systems exhibit coherence under change, via conditional action and anticipation, and they do so without central direction” (Holland 1995, pp. 37-39).

Patrick O’Connor in his article “John Holland Calls for a Radical Reassessment” claimed: “In order to study cas, scientists break them down into components, or building blocks.” He quoted Holland: “Almost all we know or do as individuals at almost every level consists in manipulating building blocks.” And further, “Building blocks play an essential part in physical science, and in recent years we have come a tremendously long way in understanding the building blocks of biology: DNA, the amino acids that make proteins, helices (spiral shapes), and so on. According to Holland, “An individual’s perception of the world can also be explained in terms of building blocks. In the same article Holland asserted that “Building blocks are like trees: If you see something you call ‘tree’, it has certain standard parts, and one of the reasons you can recognize that objects that differ in appearance are trees is because all trees have the same basic components--trunks, branches, and leaves. Almost every object is made up of fairly standard elements, and that plays a key role in how we recognize them” (O’Connor 2002).

As in any heuristic use of analogy, Holland reduces the Darwinian Model to handle problems of optimization pragmatically. Proceeding from chromosomes that are composed of only one string, Holland “emphasizes that “these chromosomes are far removed, in both complexity and function, from biological chromosomes” (Holland 1995, p. 135). Of course there are also some similarities; the two most important are: “a. the chromosome is the agent’s genetic material; and b. the chromosome determined the agent’s capabilities.” Further, there are three operators: point-crossover, mutation and inversion.

Just to illustrate how Holland reduced the concepts from biology, let us look at the case of "crossover".

In nature, crossover is a mechanism that happens before fertilization, during gamete forming. Crossover happens during meiosis by each of the future parents alone at some point in the formation of their sex cells (gametes). In higher organisms, a gamete has half the number of chromosomes of the cell from which it originates. Its chromosomes are not paired and, thanks to the crossover mechanism, not identical to the chromosomes of the original cell (the cell of the parent). Contrary to the description of crossover in evolutionary computation, mating involves no crossover, the gametes fuse and their chromosomes are paired to form the zygotic cell.

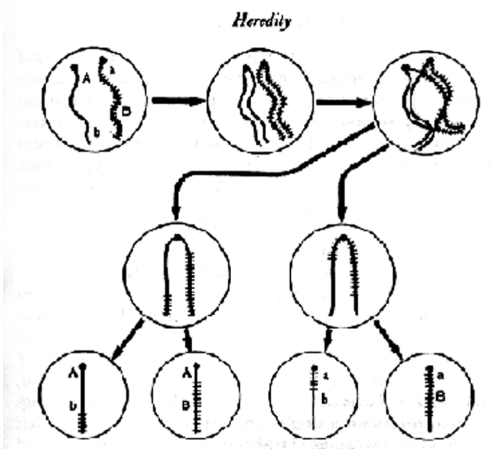

Figure 1: heredity

According to Maynard Smith, the relevant facts in the formation of gametes are:

1. "Each chromosome is replicated, so that it consists of two identical threads.
2. Pairs of homologous chromosomes come to lie side by side, forming 'bivalents'. Each bivalent then consists of four similar threads.
3. The two members of a pair repel one another, but are held together at a few joints, called chiasmata; there are two such chiasmata in the bivalent.
4. There are two successive divisions of the nucleus, without further chromosome replication, giving rise to four nuclei, each containing a single set of chromosomes; these are the gametic nuclei (Maynard Smith 1993, p. 60)."

With the help of the above illustration (Figure 1), Maynard Smith described the process of gamete forming by a future parent as the following: "the chromosome derived from the father (paternal) is shown cross-hatched, to distinguish it from the maternal chromosome. In the four-strand and later stages, sections of chromosome which are copies of the original paternal chromosome are likewise shown cross-hatched. Though, it is not normally possible to distinguish maternal and paternal chromosomes under the microscope. The conclusions incorporated in the figure, concerning the paternal and maternal contributions to the chromosomes of the gametes (i.e. that each consists in part of segments copied from the original paternal and maternal chromosome), are based on genetic experiments and not on direct observation of the chromosomes. It is, however, clear that there is a connection between the formation of chiasmata and the recombination of maternal and paternal elements in a single thread" (Maynard Smith 1993, pp. 60-61). The union of two sex cells starts the development of a zygote into an organism.

Cosma Rohilla Shalizi of the Santa Fe Institute claimed that there are many ways of getting a computer to mimic evolution, but the one with "the cleanest conceptual lines is the 'genetic algorithm' invented by John Holland. Take a population of strings, and measure their 'fitness' against some criterion. Each string has a random number of descendants, i.e. gets copied a random number of times; the expected number of descendants of a string is proportional to its fitness. These descendants can be mutants, or swap part of their length with another descendant string… Repeat as needed. For this basic version of the genetic algorithm, Holland proved what is called the *schema theorem,* showing that, if certain patterns of strings are fitter than others, then, in the long run, the GA can't help but find them, and the average number of strings in the population matching those patterns will increase exponentially" (Shalizi, Eletronic Source)

Holland's algorithm has proved to be successful in questions of optimization, in particular in problems with discontinuous or poorly behaved evaluation functions. In fact, Hans Roubos and Magne Setnes in their "Compact Fuzzy Models and Classifiers through Model Reduction and Evolutionary Optimization" assert: "Other algorithms based on combinatorial optimization, such as integer programming, dynamic programming and branch-and bound methods, are computationally expensive even for a moderate number of variable and often only handle a limited amount of alternatives" (Roubos and Setnes 2001, p.41).

However, according to the purposes in hand, researchers modified Holland's GAs or combined them with other strategies. For example, according to Mario Antonioletti[13] of the EPCC,[14] "selection in the simple GA[15] was based directly on fitness: given a population of individuals, the probability of a particular individual

13 Antonioletti studied Mathematical Physics at Edinburgh, Part Three at Cambridge and finally a PhD at Cardiff.

14 Founded at the University of Edinburgh in 1990, EPCC is a leading European centre of expertise in advanced research.

15 A simple genetic algorithm is approximately the same as John Holland's genetic algorithm of mid-1970's - Mario Antonioletti, 1996

passing its genes into the next generation was directly proportional to its fitness. Various ranking and selection schemes are now used instead of raw fitness in order to ensure that genetic drift does not occur, i.e. that good genes are less likely to disappear because of a bad accident.[16]"

Examples of the applications of GAs in combination with other strategies in the dissertations of TU Delft are found in the Faculty of Aerospace Engineering in A.H.W. Bos' Multidisciplinary Design Optimization of a Second-Generation Supersonic Transport Aircraft using a Hybrid Genetic/Gradient-Guided Algorithm (Bos 1996).

Lately, there are authors arguing that GAs can bring innovation. According to David E. Goldberg in this *The Design of Innovation, Lessons from and for Competent Genetic Algorithms*, what people are doing when they are being innovative in a cross-fertilizing sense is "grasping at a notion – a set of good solution features – in one context, and a notion in another context and juxtaposing them, thereby speculating that the combination might be better than either notion taken individually". Goldberg asserted that selection and recombination might result in innovation. Therefore, given that GAs are developed with these operators, a competent GA may generate innovations.

4.2.4. Evolutionary Design

Currently, albeit with some exceptions such as Eugene Tsui's architecture, most evolutionary models in design make use of evolutionary computation to generate them, whereby Genetic Algorithms (GAs) are the most used. Thus, in this sub-section, a brief description of this approach in design is given. The question is whether this cas model (Echo) can represent design and in particular the re-use of design precedents. We hope to answer this question later in this chapter with the analysis of two applications. This sub-section will (briefly) describe concepts of design evolutionary models that were meant for further computational applications, which, according to Peter Bentley, can be subdivided into the following categories:

1. Evolutionary Optimization
2. Evolutionary Art
3. Evolutionary Artificial Life Forms
4. Creative Evolutionary Design

Many evolutionary applications have been developed concerning optimization or the improvement of designs, art and artificial life. Though we can learn much with those applications, this research does not particularly concern them. Of these three, evolutionary art is the closest to our objective due the creation of form and creativity, among which one can find Stephen Todd (Todd and Latham 1992) and

16 http://www.epcc.ed.ac.uk/epcc-tec/documents/GAs-course/main.html

William Latham's Mutator (Todd and Latham 1992)[17] and Karl Sims' Galapagos (Sims 1997)[18]. Steven Rooke, Darrel Anderson (GroBot), and Charles Ostman have also developed applications. However, form in architecture has not only to be pleasant but has to allow certain functions; and due to the scope of this research, we need to look to applications closer to our own.

In 1998, during the Case-Based Reasoning and Design workshop at the Eindhoven Technical University, Mary Lou Maher put the question of how much of modification processes should be in a design support system and how much should be left to the human cognitive process. Programmers have often avoided adaptation systems, partially because it is a delicate matter in what concerns designers and their role in the process. Maher mentioned CADSYN and GENCAD as academic examples of design case adaptation systems. GENCAD combines design precedents (by "crossover"); this crossover system seems to be a random machine mechanism, which may follow some rules or constraints (to avoid two kitchens in one house unit, for example). It seems unlikely such a system would inspire designers into producing innovative designs because, as in nature, most mutations are senseless, many are inadequate, and some will be eliminated by natural selection. The cognitive mechanisms of adaptation carried out by designers are better represented as mutation-for-fitness and only then natural selection. It can be more appropriately compared to domestic breeding selection. In domestic breeding, variation is produced by means of a guided selection to eliminate, to add or intensify certain characteristics of an animal or plant. For example, horses have been paired to generate others that may race faster. Also, designer's constraints must be a part of the system, as it seems to be in CADSYN. However, it was not possible to know which kind of constraints were considered, if they were relevant and how to input them in the system since constraint recognition is part of solving problems with efficiency.

John Gero[19]'s "Adaptive Systems in Designing: New Analogies from Genetics and Developmental Biology" deals with many constraints found in the above mentioned models, and is one of the clearest papers examining adaptive systems in design. According to Gero, "The basic genetic analogy in designing utilizes a

17 Mutator was developed by Stephen Todd and William Latham (IBM United Kingdom Scientific Centre in Peterlee, –Durham County). Mutator is, (Todd and Latham 1992) in particular, designed "to help artists to explore form and space by means of subjective decisions." These systems are all based on artificial life. Todd, Stephen and William Latham, 1992. Evolutionary Art and Computers, Academic Press, p. 100

18 Galapagos was developed by Karl Sims (GenArts, Inc.; Cambridge, MA). Galapagos (1997) is "an interactive media installation that allows visitors to 'evolve' 3D animated forms (Sims 1997)." Galapagos simulates evolution where the users direct its course by being the agent for selection; i.e. "by choosing which virtual organisms are 'fit for survival' at each evolutionary interaction (Sims 1997) ". It is designed for collaboration between human and machine. However, in an earlier project, Sims implemented a system that uses the ideas of Biomorph and Mutator where a structure-matching algorithm - used in "marriage" - was built into the system, which reduced the participation of the artist in the whole process.

19 Key Centre of Design Computing, University of Sydney, Australia

simple model of the Darwinian theory of improvement of the organism's performance through the 'survival of the fittest.' This occurs through the improvement of the genotype[20] which goes to make up the organism. This is the basis of most evolutionary systems" (Gero 1998).

The operational aspects of this genetic analogy in designing, however, differ from models that do not separate phenotype from genotype. "Fundamental to this analogy", claimed Gero, "are a number of important operational aspects of the model: 1.The design description (structure) maps on the phenotype; 2. Separation of the representation at the genotype level from that of the design description level; 3. The processes of designing map onto the evolutionary processes of crossover and mutation at the genotype level; 4. Performances (behaviours) of designs map onto fitnesses; and 5. Operations are carried out with populations of individuals" (Gero 1998).

Gero claimed: "Designing as a search is a foundational designing method but one that is restricted in its application to routine or parametric designing. In such designing all the possible variables which could occur in the final design are known beforehand as are all the behaviours which will be used to evaluate designs. Since the goal is to improve the behaviours of the resulting designs, the processes of designing during search map well onto those of optimization. This sits well with our notion of genetic algorithms and genetic programming. They can be readily viewed as robust optimization methodologies"[21](Gero 1998). Trying to escape from mere optimization or to add more to the possibilities of using the evolutionary model, he tried to extend the genetic analogy to involve "genetic engineering" and "reverse engineering" in designing as well as a closer look into "developmental biology".

For Gero, genetic engineering means "locating genetic structures which are the likely cause of specified behaviour in the organism," which "provides a direct analog with finding significant concepts during the process of designing and giving them a specific primacy." Genetic engineering is the "reverse of synthesis in the sense that one aspect of an already synthesized design is converted into the means by which it could be generated" (Gero 1998). He asserted that gene therapy, gene surgery and radiation therapy already have a computational analog, and that they could allow an evolutionary system to adapt itself in ways that differ from tradition.

20 Although his text suggests it, we believe that Gero knows very well that a genotype does not improve for itself. It copies itself and sometimes with errors, which are called mutations. Selection is responsible for what could be called 'local improvement', by eliminating all organisms, and therefore the parts of genotypes, which do not fit the specific environment. This selection, however, is only strongly felt when it refers to internal constraints (structural or organ malfunction) or when the environment is under pressure, which puts the individuals in a struggle for survival.

21 Not all kinds of re-use of precedents will result in just optimisation; these characteristics are inherent to the designs evaluated by Gero.

Gero asserted, however, that in the computational model of genetic engineering used in design, “the evolved genes are complexes of the original genes,” and therefore “the boundary of the state space of possible designs is unchanged, so that the designs produced are no different to those which could have been produced using the original genes only” (Gero 1998). In order to produce novelties in design, Gero introduced the concept of “reverse engineering”, i.e. emergent design properties (phenotypes) are sought and new genes which generate those properties are produced, although the processes are different and the result is quite different. These new genes are then introduced into the gene pool.

Finally, Gero claimed that an analogy between designing and developmental biology would “open up numerous research paths with possible interest in designing”, and named concepts such as ‘“switch genes’, ‘regulatory genes’ and ‘gene networks’. Setting out from analogies drawn from genetics and developmental biology, Gero wanted to analyze the possibility “to change the state-space of possible designs” (Gero 1998).

Gero indicated some fruitful directions that coincide with some of the ideas that we consider in developing our model. More important, though, is how those directions/mechanisms can represent design, what the gene is, and how the domain knowledge can be used to express architectural artifacts. The differences and similarities will be presented through the course of the next chapter.

The next part of this chapter analyzes two applications that approach design from different angles and levels. These applications clearly demonstrate the challenges and fallacies of the analogy between designing and biological evolutionary and genetic models as currently used, in particular with regard to our adequacy criteria developed in Chapter 3.

4.3. Critique of Current (Pseudo) Evolutionary Applications in Design

To understand the potentials and shortcomings of applications from a survey of the last 10 years of evolutionary models in architecture, it is necessary to go through the whole process of making a tool, starting with the objectives and going through the terminology borrowed from the analogy between design and biological evolutionary models. Then, one must ask at which hierarchical level was the specific analogy applied (at the process or object level); Were analytical or analogical reasoning considered, or both? What was the position of the architect? And, how, where and when was the biological evolutionary model reduced? K. Moraes Zarzar already discussed these applications in earlier articles (Zarzar 2000a; Zarzar 2000b; Zarzar 2000c)

The advances in the computational field of genetic algorithms, as conducted by John Holland (Holland 1975), induced the development of several design evolutionary models. In this section, two evolutionary applications will be described, and their effectiveness and ethics will be briefly discussed. Each application will be analyzed according to the following aspects:

1. Analogy: the misuse of the evolutionary model.
2. The objective of the model.
3. The Domain Knowledge built in the model.
4. Achievements: the advantages and fallacies of the evolutionary analogy in relation to its objectives.

Next, we will describe and analyze three applications that refer either to architecture or to industrial design. Presumably, Bentley could classify these three applications as "creative evolutionary design".

4.3.1. The Electronic Emulator of Building Scenarios (Zarzar 2000)

Celestino Soddu and Enrica Colabella's (Milan Polytechnic University, Italy) Argenìa Design (Soddu and Colabella 1997) is a Model for Electronic Emulation of Building Scenarios and for managing these scenarios in the manufacturing process. "This tool," claimed Soddu, "is, in fact, a design of species, and we can use it as an artificial DNA to generate a multiplicity of architectural or environmental possible events" (Soddu 1994).

Soddu and Colabella have been applying the idea to architecture as well as to industrial design. Their idea is that "the morphogenetic approach can realize operative meta-projects that are new design products. These are something like idea-products, plus these are able to generate an endless sequence of object-products. The idea-projects create a new market: an industry can buy a morphogenetic idea-project of lamps, for example, and use the endless sequence of generated 3D-models to produce always different lamps (the idea-project can be used as an auto-reprogramming tool for robots). The customer can choose his unique object by activating, on the Internet, the generative tool and sending his request to the industry... or...a Mayor can order the idea-project of evolution (this means an increasing complexity) of his town and use it to control the incoming possibilities and the identity in progress of the environment."

Soddu and Colabella's model is based on an analogy at the process level, in particular on the development process of idea-products, and not in the evolution of ideas, i.e. from one idea-product to another.

The role of fitness in Soddu and Colabella's model is of great importance to understand the reduction that they applied in the biological evolutionary model. Soddu and Colabella's model produces scenarios of an idea-product, i.e. it is specific for one kind of design (one species) and cannot be applied to architectural projects in general. After the establishment of the parameters in the tool, it provides variation of the same theme, i.e. one may have countless successful examples or scenarios.

In Soddu's generation of chairs (see Figure 2), development only happens if the object conforms to the set of rules built in the representation (idea and design logic); in this aspect, the generated chairs have the same fitness. This system possesses inheritability; the chairs are offspring of the same idea and design logic. It produces variation; the chairs are each of them unique. And it posses a selection mechanism: the client (the buyer), according to his/her esthetic values, selects one of the offered chairs to be produced (a mechanism to be compared with "sexual selection"). However, the process is not cyclical. The select population will produce no new generation. Evolution is not a one-generation process. It is not merely variation within one generation; it depends of the accumulation of these variations within innumerous generations. After generations, one could see the emergence of a new type, perhaps with a slightly different idea and design logic.

The design knowledge in Soddu and Colabella's tool is built in parameters, which represents their idea-product. In their model, designers participate at the level of the idea-product, but they lose all the control of the object-product generated by their software. Because clients buy idea-products that can produce an unrepeatable number of object-products, the creation process will be concentrated in very few hands, and even for those very few designers the number of assignments is likely to diminish.

Figure 2: Celestino Soddu's chairs

Authorship is, for designers concerned with the issue, likely to be a problem, because it seems very difficult to prove that a "unique chair" generated by this tool belongs to the oeuvre of a certain designer. Darwin and Wallace came independently to the idea of Natural Selection. Marsupial and placental mammals converge in "design" because they fill the same environmental niche. Since the tool will produce an "infinite and unrepeatable number of designs", there is a probability that convergence in design may occur, or at least doubts will occur about the origin of many products.

4.3.2. The Form Generator Model

In *An Evolutionary Architecture,* John Frazer (School of Design, The Hong Kong Polytechnic University) described a model for form generation. The objective of his model was "to achieve in the built environment the symbiotic behaviour and the metabolic balance that are characteristic of the natural environment" (Frazer 1975, p. 9).

Thus, *An Evolutionary Architecture* investigated "fundamental form-generating processes in architecture, paralleling a wider scientific search for a theory of morphogenesis in the natural world" (Frazer 1975, p. 9). He proposed the model of nature as a generating force for architecture, considering Form, Space and Structure as the outward expression of architecture. By applying some generative rules, he then accelerated and tested his process of evolution.

Unlike Tsui (Tsui 1999), Frazer's analogy concentrates on the process level. Central in his study is the process of how to grow a seed toward a final structure, i.e. development or epigenesis. To help understand the way in which Frazer reduced the biological evolutionary model, his terminology is briefly described here.

Gamete forming, mating and development may be considered as one process. However, the mechanisms involved in each of these phases follow a determined order. Frazer, like most of the evolutionary computation scientists, changed the order of the factors.

Frazer has at least five main concepts diverging from the biological evolutionary model. First, he concentrates on the evolutionary process during a seed's development. Second, he uses an Epigenetic Algorithm to breed a population by crossover or mutation (Frazer 1975, p. 89). Third, his idea of 'seed' diverges from the biological one: in biology, a seed corresponds to a zygote, a fertilized cell in higher organisms, which will generate an organism. Frazer's seed is yet to be fertilized. Fourth, the fertilization of the seed is done using Holland's genetics operators: crossover and mutation. In nature, crossover is a mechanism that happens before fertilization, during gamete forming**.** The process of breeding involves no crossover, the gametes fuse and their chromosomes are paired to form the zygotic cell.

The development of this zygotic cell into an organism, by growth, morphogenetic movement and differentiation is called epigenesis. The fifth divergent feature of Frazer's model involves the role of the environment in the development of the seed towards an organism. Frazer's seed evolves according to the environment. The environment may also change during the process and even then, it can greatly influence the seed growth. Consequently, Frazer's idea of fitness also diverges from the biological one. In Frazer's concept, natural selection has no role in it since changes in the environment immediately redirect the development of the organism. He considers fitness to be such that if he modifies the artificial environment, the seed growth, by cellular automaton, will be forced to adapt to the new situation.

Frazer built into his tool some conceptual knowledge for the production of form. But since architecture is not only form but also function, one may conclude that the design knowledge in the system is not sufficient to produce architecture (see Figure 3). Buildings accommodate functions that are developed and archived in the memory of the architects. Their successful layouts are remembered, reused and adapted into new situations. In Frazer's tool, the design knowledge to help architects to "remember and reuse" some of their successful solutions are not built in his application, neither are there the physical built environment or the social aspects inherent to the project. Users and clients may play with the system but they are in fact playing with form.

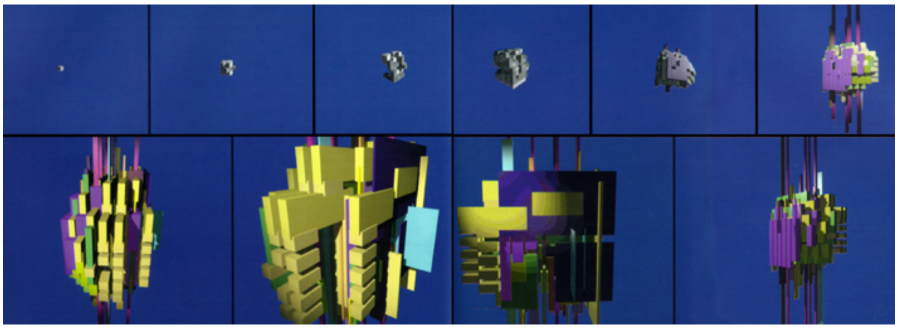

Figure 3: John Frazer's evolution

Concerning procedural knowledge, Frazer does not consider architects and their practice as the target group for his tool. Architects who wish to use the tool must adapt to an imposed methodology. In his paper "A Conceptual Seeding Technique for Architectural Design" together with J.M. Connor, "A Conceptual Seeding Technique for Architectural Design", he says that it "rejects the notion that a CAD approach should reflect the traditional non-CAD architectural methodology on the grounds that, first, the present architectural design process is fundamentally unsatisfactory in any known form and not worth imitating and, second, imitating the human process is unlikely in any case to represent the most imaginative use of a machine" (Frazer and Connor 1979, pp. 425-34). In other words, in *An Evolutionary Architecture*, he says that his tools "are clearly not intended to reinforce existing practice" (Frazer 1975).

Moreover, in his *How Designers Think*, Bryan Lawson analyzed and criticized Frazer's application. He claimed that the generator is "surprising but predictable, therefore not truly creative," and that "the experience and skills required of a designer to work with such tools may well be quite different to those needed for a traditional design process" (Lawson 1990, pp. 290-1).

4.4. Conclusions

Besides the general theories derived from analogies between nature and design, this chapter has provided an analysis of two applications of major researchers in the field of evolutionary design to show their efforts, their successes and their shortcomings. Besides those examples and setting out with the same analogy, some tools have being developed to optimize, modify and combine design precedents. Some of the tools try to handle problems that come from architectural practice, where, as is well known, architects make use of their previous experience in searching for solutions. All in all, the analogy between the domains of design and evolution is, in what concerns our purpose, often unproductive and misapplied. The problem is not so much that, in applying the analogy, the meaning of many biological concepts used is distorted, as the fact that the analogy misrepresents the design process itself.

Most applications, and not only those illustrated in this chapter, present more than one of the following bottlenecks:

1. Confusion between the scientific notion of evolution and the cultural, value-added, notion of progress;
2. Reduction of the notion of evolution to that of biological transformation eliminating the notion of fitness;
3. An arbitrary and/or overstated application of Shape Grammars in combination with Genetic Algorithms (GAs);
4. A reduced amount of design knowledge built into the systems;
5. A lack of understanding of the cognitive processes used by designers. Some tools ignore the architect's cognitive aspects and impose their work methods upon the architects, while other tools even try to replace the architect with a machine.
6. A failure to provide a measure of fitness in the environment.
7. A lack of consideration in the adaptation of buildings to the external environment as well as to the internal structure of the individual as they constrain a possible solution.

Thus, the current applications of evolutionary models are extremely limited for developing a model for the re-use of design precedents: a model that we assume may help architects in practice. But, can the Darwinian evolutionary model help architects to perform their tasks more efficiently and more effectively? Could we avoid the aforementioned bottlenecks? One way to verify it is by re-evaluating the analogy between design and biological evolutionary models and to see where it can be extended or reduced in other ways. However, one must not forget to include design knowledge in the system. Frazer''s 'seed' carries a minimum of data if compared with the information carried by features like "piloti", "roof gardens", and "arches and hangers" as design precedents. Not that DNA carries structures as it was meant by the biological 'pre-formationist' approach; DNA carries information, instructions. In spite of that, we can look to phenotypes – just like good breeders would do – and attempt to describe their recipes.

Among creative designers, the re-use of design precedents seems to be not a straightforward activity; their design precedents are adapted and recombined along the years. Can we understand the phenomenon of change? What is changing; what is adapting and recombining in the process of re-use? Is there a way to describe the precedents considering this phenomenon? If we follow our heuristics, the analogy between the process of re-use of design precedents and biological Darwinian and genetic models of evolution, the question remains of how far to extend the analogy, because it is necessary not to lose focus on the problems that one is addressing in design. But it is also necessary not to reduce the evolutionary model before one can get a glimpse of its potential which may in future help architects in practice or to serve as a didactic device in design education to analyze the re-use of design precedents in architectural practice.

The next chapter will go deeper in studying the theories of evolution and genetics, this time from the main source: evolutionary biology and genetics themselves. We will examine this reference with one purpose in mind: to model the phenomenon of change in architecture to the extent that it is based on the re-occurrence of design precedents in the generation of designs.

CHAPTER 5

TOWARD AN EVOLUTIONARY DESIGN MODEL

In our search for a good representation for the re-use of design precedents, we go to the sources of Darwinian Evolution, Genetics and Embryology. This chapter shall present the similarities and differences between the two models, and we shall attempt to find some concepts to serve as a hypothesis for our Evolutionary Design Model.

In the review of old and new applications of the evolutionary model (Chapter 4), we have seen misunderstandings and/or sharp reductions of the theory, and above all, we have seen that these reductions would not help us to develop a model for the use and adaptation of design precedents for architects in practice. Nevertheless, we argue that the analogy between the re-use of design precedents and the biological Darwinian and genetic models may somehow assist in developing a representation of the re-use of elements of design precedents, in the sense that new organisms "re-use" the genes of their ancestors.

Motivation

We turn to the sources of evolutionary biology for three reasons: first, as mentioned previously in Chapter 1, it became fashionable to refer to the Darwinian theory of evolution and genetics in constructing theories about design processes and this instigated our interest in studying the reference; second, because of the increasing number of inaccurate or vague references to Darwinian evolution and genetics in the context of the "evolution" of design as described in Chapter 4; and finally, because of our yearning to be precise in the construction of our analogy.

Goals

The goals of this chapter are to analyze biological concepts, to map the similarities between the mechanisms of "re-use" in design and nature, and subsequently, to enhance the development of our design model. As might be expected, it is neither possible nor of interest to us to describe here everything about Evolutionary Biology.

Procedure and Expect Results

Like most researchers in the field of evolutionary design, we are not pursuing a true comparison of the two processes; we are looking pragmatically for some similarities that may help us to represent and develop a design tool for the re-use of design precedents in architectural practice. Therefore, setting out from specific architectural questions, we will describe and discuss concepts of Darwinian Evolution, as well as Genetics and Embryology in relation to the re-use of design precedents.

Each issue will be handled in three parts: a) the architectural question; b) the description of the biological concepts and/or mechanisms; and c) the final considerations on analogues as well as a discussion of their possible contributions for the development of our design model.

At the end of the chapter we shall present a set of assumptions that will guide us in developing a proposed model to represent the re-use of design precedents carried out by any architect over the years.

Premises

The analysis of the process of re-use and adaptation in design involves purpose and reliance on past information. On the one hand we have the intentional activities of architects related to purpose. This intentionality is not found in Darwinian evolution theory. Based on two main mechanisms, random variations and natural selection, the biological evolutionary model has no analogue for the notion of purpose in design. Darwin's idea was to search for an explanation on how, given the variations available, evolution could happen. However, in the heuristics of Darwin's evolution theory, we can find some analogue for purpose. On the other hand, we have the intentional activities of architects concerning reliance on past "information." With the exception of the first section of this chapter, this review is meant to give us insight into the re-use of past information.

Chapter Structure

This chapter will be subdivided as follows. The first section of this chapter describes issues related to the development of the Darwinian theory of evolution and the notion of Purpose in design. The second section presents concepts of Darwinian Evolution in relation to the re-use of designs, while the third presents concepts related to Mendelian Inheritance in relation to the process of re-use of design precedents in architecture. The fourth section presents concepts of Genetics and Embryology in relation to conceptual design and development. The fifth section introduces some nuances of new-Darwinism in relation to the mechanisms of evolution (gradualism versus punctualism) that we relate to design production and frequency of change, as well as the units of selection that we relate to units for recollection in design. The sixth section discusses the two levels of evolution: phylogeny and ontogeny as an analogue for the architect's oeuvre (his designs, principles and observations) and the actual development of a design (e.g. the design of a house). Section seven discusses the difference in mechanisms for survival between D'Arcy Wentworth Thompson's theory as described in his *On Growth and Form* and the Darwinian model. It briefly discusses the importance of integration of parts in a structure and structural stability in Thompson's theory; and its importance in design, in particular, as criteria for the development of a fitness function that could control the adaptation of design precedents in new projects. Finally, the eighth section will present the chapter conclusions.

5.1. Designers as "Breeders": an Analogue for "Purpose in Design" in the Development of the Darwinian Theory of Evolution

This section describes the main theories and principles that guided Charles Darwin (1809-1882) in developing his theory of evolution. We are particularly interested in this historical account because, in modification under domestication (inbreeding), Darwin referred to an analogue for purpose in design.

Designers often recognize particular qualities in artifacts that will help them in the making[1] of their designs. Their designs need not be the copy of this design

[1] In his article "Designing: rules, types and worlds", Donald A. Schön treated designing not primarily as a form of 'problem solving', 'information processing', or 'search', "but as a kind of making". He claimed: "on this view, design knowledge and reasoning are expressed in designers' transactions with materials, artifacts made, conditions under which they are made, and manner of making" (Schön 1988, p.182). He distinguishes several levels of 'making' moving "from a general view of designing to a more specifically architectural one." He asserted that in designing things are first made under conditions of 'complexity' - i.e. "a designer must fashion each move to satisfy a

precedent or even a copy of part of it; but it will somehow express at least some of their underlying principles. Designers often recall precedents from memory and/or archives and, after evaluation, adapt them (or not) to their current work. This section refers to the architect's role in the selection of design precedents and its possible representation in a model for re-use and adaptation based on an analogy with evolutionary models.

As mentioned previously, our main reason for undertaking this section on Darwin's research strategy is Darwin's reflection on the mechanisms of modification in nature through variation and modification under domestication, where breeders effectuate crosses with the intention of achieving better grains, fruits or animals. Darwin's explanation on variation and selection under domestication provides us with a rationale for purposeful activities in architectural processes when related to the re-use of design precedents. A secondary reason for undertaking this section is Darwin's multidisciplinary approach and use of analogy, providing us with a way to reflect on our own research strategy.

5.1.1. The Development of Darwin's Evolution Theory

Succinctly, Darwinian evolution is based on two major principles: variation, which is random, and selection, which gives the direction in evolution. Nature does not intentionally produce any useful characteristic for the future; however, selection will only eliminate nature's variations that decrease the performance of organisms in the environment, their reproduction and their struggle for survival among fitter organisms. The chances are that variations, which are neutral to selection today, can be accumulated. These neutral variations might increase the rate of survival in future or disappear in the long run by environmental pressure.

Charles Darwin would probably have worked on his theory of evolution for several more years,[2] if it were not for Wallace, who independently came to the idea of Natural Selection. In *The Origin of Species* published in 1859, Darwin presented what he called an abstract of his theory based on the material he observed and collected during his five-year voyage around the world in H.M.S. Beagle (1831-

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variety of requirements and can never make a move that has only the consequences intended for it"; second, "architects make things under conditions of uncertainty" - i.e. design is a ill-defined problem where "problem solving triggers problem setting"; and finally, "architectural designing is a dialogue with the phenomena of a particular site." Donald A. Schön. 1988. "Designing: rules, types and worlds". *Design Studies*. Vol. 9. no. 3. pp. 181-190.

[2] In the introduction to his "The Origins of Species" (Darwin 1993), he mentioned: "I have been urged to publish this Abstract. I have more especially been induced to do this, as Mr. Wallace, who is now studying the natural history of the Malay Archipelago, has arrived at almost exactly the same general conclusions that I have on the origin of species (Darwin 1993, p. 18)." Later he wrote: "This Abstract which I now publish, must necessarily be imperfect. I cannot here give references and authorities for my several statements; and I must trust to the reader reposing some confidence in my accuracy" (Darwin 1993, p. 19).

1836). However, it was not enough for Darwin to present some evidence in nature that pointed towards evolution. In the introduction to *The Origin of Species*, he wrote that for his or any theory of evolution to be considered satisfactory, one should show "how the innumerable species inhabiting this world have been modified, so as to acquire that perfection of structure and coadaptation which justly excites our admiration." Darwin thus argued that it is "of the highest importance to gain a clear insight into the means of modification and coadaptation (Darwin 1993 Reprint, pp. 19-20)." Searching for the processes that would justify this perfection in structure and coadaptation, Darwin found enlightenment in theories of other fields.

In *The Theory of Evolution*, John Maynard Smith gives a concise summary of facts and ideas that influenced Darwin's thought from the acceptation of the idea of evolution to the "understanding" of the means of modification and coadaptation (Maynard Smith 1993, p. 42). Maynard Smith claimed that in addition to the "knowledge of the problems of classification, including first-hand experience gained in his study of barnacles", Darwin often used facts and theories which were often from other or related fields, namely:

1. Geography: features of the geographic distribution of plants and animals;
2. Geology: in particular, the theory of Sir Charles Lyell and his *Principles of Geology* of 1830 (Lyell 1838-32);
3. Domestication: knowledge on the artificial selection of domestic animals[3];
4. Economics: the theory of Thomas Robert Malthus[4] and his influential *Essay on Population* of 1766 (Malthus 1798).

In their *Darwinism Evolving, Systems Dynamics and the Genealogy of Natural Selection,* David J. Depew and Bruce H. Weber also recalled Adam Smith's economic theory and Newtonian influences on the thought of Darwin (Depew, Weber et al. 1995); however, we shall limit ourselves to Maynard Smith's explanations, which serve our purposes and the scope of this research.

5.1.2. Geographical Distribution

P. J. Bowler argued in his *Evolution, The History of an Idea* that Darwin was "convinced of evolution by his study of how physical barriers such as oceans affected the geographical distribution of species." According to him, Darwin's

[3] "The results of artificial selection of domestic animals and plants revealed the enormous, but largely hidden, variability within a single species which could be made manifest by selecting and breeding from particular individuals" (Maynard Smith 1993, p. 42).

rationale was: “if adaptation were the Creator’s sole concern, one would have expected Him to employ the same species in all areas subject to the same conditions” (Bowler 1984, p. 152), which was not true, since there were animals in Africa and South America, such as the rhea and the ostrich, which shared similar habitats, although presenting clear differences.

Bowler claimed that it was the mockingbirds[5] of Galapagos that provided the clue to evolution, because Darwin could then identify several species with obvious resemblances to those of the American continent. Once he was convinced that similar forms on the Galapagos comprised no varieties of a single species but a group of distinct (but related) species, Darwin was placed in a quandary (Bowler 1984, pp. 153-4)[6]. Darwin’s reasoning, claimed Bowler, brought him to believe that a South American form had migrated to the islands and had evolved in different directions, due to a lack of normal competitors as well as the geographical isolation of the parent stock. At that particular moment, Darwin seemed to be convinced of the importance of the geographical isolation. However, he would later (in *The Origin*) refute this idea in favor of his belief “that Natural Selection was powerful enough to break up an originally continuous population by adapting its extremes to different life-styles” (Bowler 1984, p. 200).

5.1.3. Lyell’s Principles of Geology

Accepting the idea of evolution, Darwin would proceed in search of the mechanisms of change. The principle of gradualism was borrowed from Charles Lyell’s *Principles of Geology* (1830-32), a book which Darwin took with him on the Beagle and in which Lyell explained the principle of uniformity and claimed that “the natural processes that change the earth in the present have operated in the past at the same gradual rate” (Encarta 1994), and that this change was caused by “processes such as erosion, sedimentation, and volcanic activity which can be observed at the present time” (Maynard Smith 1993, p. 42). Lyell’s Uniformitarianism was opposed to the then influential Catastrophism, a theory that asserted that only major catastrophes could change the basic formation of the earth.[7] Catastrophists frequently justified events in the earth’s past in accordance

[4] Thomas Robert Malthus (1766-1834) was a British economist, born in Surrey, England in 1766. His book *An Essay on the Principle of Population* of 1798 influenced by analogy the work of Darwin.

[5] And not the finch as it is believed.

[6] The answer could be that some populations which “probably first diverged when spatially isolated from one another, have subsequently expanded their ranges, so that today they live side by side in the same regions without losing their separate identities” (Maynard Smith 1993, p. 245).[0]

[7] According to this theory, the most recent catastrophe, Noah's flood, wiped away all life except those forms taken into the ark. The rest were visible only in the form of fossils. In the view of the catastrophists, species were individually created and immutable, that is, unchangeable for all time. Randy Bird and Garland E. Allen, “Darwin, Charles Robert,” in Microsoft (R) Encarta. Copyright (c) 1994 Microsoft Corporation. Copyright (c) 1994 Funk & Wagnall's Corporation.

with biblical records, claiming, for example, that the earth was only about 6000 years old; a fact that, if it were true, would make Darwin's slow gradual evolution impossible. "The work of Lyell and his forerunners," wrote Maynard Smith, "both provided Darwin with an account of the geological backcloth against which organic evolution has occurred, and set him an example in the methods whereby such evolution was to be explained" (Maynard Smith 1993, p. 42). Even though Lyell was mistaken in claiming that the same principles could be extended to the complex effects shaping the earth's surface (Bowler 1984, p. 128), according to Bowler, the principle of uniformity of natural laws was admitted in science as a means of eliminating the supernatural.

5.1.4. Varieties and Selection under Domestication

According to his autobiography, Darwin came to the idea of Natural Selection due to his study of selection under domestication (Darwin 1993b Reprint). Looking for an explanation for the perfection of structure and coadaptation of the organisms seen in nature, in *The Origin of Species* Darwin claimed that "One of the most remarkable features in our domesticated races is that we see in them adaptation, not indeed to the animal's or plant's own good, but to man's use or fancy" (Darwin 1993 Reprint, p. 49). It seemed to him thus probable "that a careful study of domesticated animals and of cultivated plants would offer the best chance of making out this obscure problem", i.e. the mechanisms of modification and co-adaptation. He claimed to have not been disappointed: "in this and in all other perplexing cases I have invariably found that our knowledge, imperfect though it be, of variation under domestication, afforded the best and safest clue. I may venture to express my conviction of the high value of such studies, although they have been very commonly neglected by naturalists" (Darwin 1993 Reprint, pp. 20-21, emphasis added).

Darwin wrote that in domestication, "nature gives successive variations; man adds them up in certain directions useful to him" (Darwin 1993 Reprint, p. 50); after generations of what was then called Artificial Selection, the breeder will achieve some of the characteristics that he/she was looking for; i.e. variations which, from the human point of view, are profitable. Artificial selection is intentionally carried out with the aim of producing animals and plants with specific performances.

Having reflected on artificial selection and their effects under domestication, Darwin recognized that **accumulative selection** was the power of the breeders **towards adaptation**. Darwin stressed further that the "great power of this principle of selection is not hypothetical. It is certain that several of our eminent breeders have, even within a single lifetime, modified to a large extent their breeds of cattle and sheep" (Darwin 1993 Reprint, p. 50). Considering the steps by which domestic races have been produced, he claimed that "some effect may be attributed to the direct and definite action of the external conditions of life, and some to habit; but he would be a bold man who would account by such agencies for the differences between a dray- and race-horse, a greyhound and bloodhound, a carrier and tumbler pigeon" (Darwin 1993 Reprint, p. 49).

By analyzing Artificial Selection, its effects and its possible causes under domestication, Darwin would come up with the question: what is the mechanism of selection in nature that produces the perfection of structure and coadaptation? This mechanism he would later appropriately coin Natural Selection.

5.1.5. Malthus' Economic Doctrine

In his autobiography*,* Darwin wrote that in 1838, thus after his journey on the Beagle and fifteen months after he had begun his systematic inquiry, he read, for "amusement", Malthus' *Essay on Population*, which would help him to explain the mechanism(s) of selection in nature.

According to Maynard Smith in *The Theory of Evolution,* "Malthus was concerned to justify the existence of poverty among a considerable section of the population; he argued that the human population is capable of increasing indefinitely in a geometric progression, and must therefore be held in check by the limited quantity of food available, and so by starvation" (Maynard Smith 1993, p. 43). In his autobiography, Darwin wrote that when he read the *Essay on Population,* he was "well prepared to appreciate the struggle for existence which everywhere goes on, from long continued observation of the habits of animals and plants." Under such circumstances, he realized that favorable variations would tend to be preserved, and unfavorable ones would be destroyed; in the long run, the result of this would be the formation of new species. "Here, then," wrote Darwin, "I had at last got a theory by which to work" (Darwin 1993b Reprint, 120).

The notion of "struggle for survival" was borrowed by Darwin from Malthus' doctrine and applied as part of the selection mechanism in nature. Later, in The Origin of Species (1859), Darwin would write: "A struggle for existence inevitably follows from the high rate at which all organic beings tend to increase. Every being which during its natural lifetime produces several eggs or seeds, must suffer destruction during some period of its life, and during some season or occasional year, otherwise, on the principle of geometrical increase, its numbers would quickly become so inordinately great that no country could support the product. Hence, as more individuals are produced than can possibly survive, there must in every case be a struggle for existence, either one individual with another of the same species, or with the individuals of distinct species, or with the physical conditions of life. It is the doctrine of Malthus applied with manifold force to the whole animal and vegetable kingdoms; for in this case there can be no artificial increase of food, and no prudential restraint from marriage" (Darwin 1993 Reprint, pp. 90-91).

5.1.6. Purposeful Activities in Design and under Domestication: the Designers as "Breeders"

In considering the design environment a simulative environment, where designers recall several precedents to constitute the population of a specific "place", one could recognize that, among other roles, architects have the role of a "breeder", with a conscious power of selection towards adaptation.

In *The Blind Watchmaker*, Richard Dawkins wrote: "Natural selection is the blind watchmaker, blind because it does not see ahead, does not plan consequences, has no purpose in view" (Dawkins 1986, p. 21)[8]. One could even say that sometimes when architects are reading or working in something other than design, associations may "suddenly" come to their mind and help them to cope with problems in actual design; if the association comes unexpectedly it comes without conscious intention. However, it remains difficult to imagine that those situations happen as a rule; in other words, that architects do not recall "things" having any purpose or intention in mind, such as: "I need performance 'x'. Do I know anything with such performance?"

We therefore argue that Darwin's observation of selection of varieties under domestication is closer to design than the "unconscious" selection in nature. By accepting artificial selection, the fundamental difference between nature and design – i.e. the presence of designers – is abridged. The role of the architect is the role of the breeder who performs the selection and, therefore, directs the modification of designs.

In some ways, then, this design evolutionary model for re-use and adaptation may be called an evolutionary breeding model based on artificial selection. Designers improve designs according to their intention, which may concern esthetics, technique, use of a particular material, and so forth. These intentions do not need to be the most economic with the most essential structure. As Darwin wrote, the breeder "modifies" the organisms not for the organism's sake, but for the breeders' pleasure or profit. In fact, some acquired characteristics in domestication are even pernicious for the organism itself. In architecture, the design of the house units on the corners of J.J.P. Oud's Spangen Housing State could show more regularity; however, he was probably then more concerned with

[8] Dawkins: "Yet the living results of natural selection overwhelmingly impress us with the appearance of design as if by a master watchmaker, impress us with the illusion of design and planning. The purpose of this book is to resolve this paradox to satisfaction of the reader, and the purpose of this is to resolve this paradox to the satisfaction of the reader, and the purpose of this chapter is further to impress the reader with the power of the illusion of design." P.21

making use of as much space as possible.[9] Besides the designers' intentions, a building must be an artifact built for the benefit of the clients and end-users.

In summary, by looking to variation and selection under domestication, Darwin came to the question of how the same processes happen in nature. In other words, given the observed variations, "who" or "what" is responsible for the selection. Malthus' concept, the "struggle for survival", was the beginning of an answer: "a theory by which to work", while facts of geography and geology were used as evidence. Our position so far is that architects often recollect design precedents according to their fitness with the intention of finding solutions for real problems encountered during design. Designers are in charge; they select designs that might help them in solving their (characteristically ill-defined) problems, which do not need to be the most economic, or the simplest but the ones that make the maximum use of resources and satisfy the constraints of the moment.

The analysis of the design process involves: a) intentional activities of architects relating to purpose; and b) intentional activities of architects concerning reliance on past "information." Our analogue for "a" refers to designers as "breeders", which was found in the heuristics of Darwin's own theory. The remainder of this chapter will deal with "b", the architect's reliance on past information.

5.2. Re-Use of Design Precedents: Darwinian Evolution?

Generalizing from the results of our case study on J.J.P. Oud's social housing, we have put forward assumptions about re-use and adaptation in design and associated them with Darwinian evolution (see Chapter 3). Having already dealt with the idea of "purpose" in design, this section refers to the possibility of representing re-use and adaptation in design with the help of the Darwinian evolutionary model.

We shall describe the evolutionary model as Darwin developed it, without the subsequent discoveries in genetics. The processes of evolution such as inheritance, variation, the struggle for survival and selection will be presented in other sections where their utility with respect to architectural design will be discussed and evaluated.

[9] The Alamillo bridge of Santiago Calatrava could also be "simpler" than it is, probably with a traditional cantilever solution as a superstructure; however, Calatrava's solution is more audacious and emphasizes its character as a technological achievement and a landmark.

5.2.1. Darwinian Evolution

In the essay "Shades of Lamarck", Steve Jay Gould asserted that the Darwinian evolutionary theory "requires two separate processes, rather than a single force," or in other words, that Darwinism "is a two-step process, with different forces responsible for variation and direction." For Darwinians, the first step, variation, is "random", which, according to Gould, "is an unfortunate term because we do not mean random in the mathematical sense of equally likely in all directions. We simply mean that variation occurs with no preferred orientation in adaptive directions." Selection is the second step; it "works upon unoriented variation and changes a population by conferring greater reproductive success upon advantageous variants" (Gould 1980, p. 67).

Between these separate processes, there are some facts and mechanisms that are fundamental for an understanding of the processes of adaptation in the Darwinian model. In his essay "Como pensar sobre o que ninguém jamais pensou", William H. Calvin (Calvin 1997) summarized these facts and mechanisms of the Darwinian model as follows:

1. A pattern is given;
2. Its characteristics are heritable;
3. Variations of the pattern occasionally happen;
4. The modified patterns or variables compete for a limited space (Struggle for Existence);
5. A multifaceted environment influences the relative success of the new pattern (natural selection resulting in the survival of the fittest);
6. The next generation will be based on the variables that survived to reach maturity. It is a cyclical process.

Starting with an initial pattern or feature, we shall follow this summary in our exploration of the Darwinian evolutionary model.

5.2.2. Inheritance

At the time when Darwin wrote *The Origin*, the laws governing inheritance were for the most part unknown; yet by observation he could show some evidence of its occurrence. As he wrote: "No one can say why the same peculiarity in different individuals of the same species, or in different species, is sometimes inherited and sometimes not so; why a child often reverts in certain characters to its grandfather or grandmother or more remote ancestor; why a peculiarity is often transmitted from one sex to both sexes, or to one sex alone, more commonly but not exclusively to the like sex. It is a fact of some importance to us, that peculiarities appearing in the males of our domestic breeds are often transmitted, either exclusively or in a much greater degree, to the males alone" (Darwin 1993 Reprint, pp. 31-32).

In Chapter 1 of *The Origin of Species* entitled "Variation under Domestication", Darwin asserted that breeders have no doubt about the "tendency to inheritance" or that "like produces like", and claimed that "doubts have been thrown on this principle only by theoretical writers." Darwin argued that "When any deviation of structure often appears, and we see it in the father and child, we cannot tell whether it may not be due to the same cause having acted on both; but when amongst individuals, apparently exposed to the same conditions, any very rare deviation, due to some extraordinary combination of circumstances, appears in the parent – say, once amongst several million individuals – and it reappears in the child, the mere doctrine of chances almost compels us to attribute its appearance to inheritance" (Darwin 1993 Reprint, p. 31). Convinced of the validity of this principle, he concluded: "If strange and rare deviations of structure are really inherited, less strange and commoner deviations may be freely admitted to be inheritable. Perhaps the correct way of viewing the whole subject would be, to look at the inheritance of every character whatever as the rule, and non-inheritance as the anomaly" (Darwin 1993 Reprint, p. 31). Inheritance is of fundamental significance for evolution; as Darwin wrote: "any variation which is not inherited is unimportant for us" (Darwin 1993, p. 31), i.e. unimportant for the study of evolution.

According to Depew and Weber, "to underwrite, ensure, and explain blending inheritance, as well as the transmission of useful variations from generation to generation, Darwin invented his theory of Pangenesis" (Depew and Weber 1995). In *Ontogeny and Phylogeny,* Gould maintained that for Darwin, "Somatic cells contain particles that can be influenced by the environment and the activity of organs containing them. These particles can move to the sex cells and influence the course of heredity" (Gould 1977, p. 484). This would prove not to be true; the theory that would closely approach reality, Mendel's theory, was yet to be developed.

5.2.3. Variation

Proceeding from the analogy with the formation of breeds under domestication, and their conscious and unconscious selection, Darwin wrote: "Varieties are species in the process of formation", or are, as he called them, "incipient species" (Darwin 1993 Reprint, p. 143). Turning to the transmutation of species in nature, he asked himself how "does the lesser difference between varieties become augmented into the greater difference between species?" (Darwin 1993 Reprint, p. 143) This process of augmenting differences from varieties to species is inferred due to the fact that most of the species throughout nature present "well-marked differences; whereas varieties, the supposed prototypes and parents of future well-marked species, present slight and ill-defined differences. Mere chance, as we may call it, might cause one offspring of this variety again to differ from its parent in the very same character and in a greater degree; but this alone would never account for so habitual and large a degree of difference as that between the species of the same genus" (Darwin 1993 Reprint, p. 143). Again, like inheritance, the notion of variation is fundamental; if there were no variation, evolution would be impossible.

5.2.4. Struggle for Survival

Through reading Malthus' *Essay on Population,* Darwin arrived at the idea of the struggle for survival, an idea that provided the answer to the aforesaid question: "how does the lesser differences between varieties become augmented into the greater difference between species?" According to Darwin, "The struggle for the production of new and modified descendants will mainly lie between the larger groups which are all trying to increase in number. One large group will slowly conquer another large group, reduce its number and thus lessen its chance of further variation and improvement" (Darwin 1993 Reprint, p. 159).

5.2.5. Selection

"Breeders," wrote Darwin, "habitually speak of an animal's organisation as something plastic, which they can model almost as they please" (Darwin 1993 Reprint, p. 50). However, Darwin argued that even within the conscious selection carried out by breeders, a kind of unconscious selection was happening as a consequence of everyone trying to possess and breed from the best individual animals. According to Darwin, "a man who intends keeping pointers naturally tries to get as good dogs as he can, and afterwards breeds from his own best dogs, but he has no wish or expectation of permanently altering the breed. Nevertheless we may infer that this process, continued during centuries, would improve and modify any breed." He claimed that the "Slow and insensible changes of this kind can never be recognized unless actual measurements or careful drawings of the breeds in question have been made long ago, which may serve for comparison" (Darwin 1993 Reprint, p. 55).[10]

[10] Darwin asserted: "There is reason to believe that King Charles's spaniel has been unconsciously modified to a large extent since the time of that monarch. Some highly competent authorities are convinced that the setter is directly derived from the spaniel, and has probably been slowly altered from it. It is known that the English pointer has been greatly changed within the last century, and in

According to Darwin, “As many more individuals of each species are born than can possibly survive; and as, consequently, there is a frequently recurring struggle for existence, it follows that any being, if it varies however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be naturally selected. From the strong principle of inheritance, any selected variety will tend to propagate its new and modified form” (Darwin 1993 Reprint, p. 21). Thus, claimed Maynard Smith, “Just as a husbandman selects from his stock as parents of the next generation those individuals which seem to him best to meet his requirements, so in nature those individuals best fitted[11] to survive in the given environment are selected as parents” (Maynard Smith 1993, p. 44). Natural selection is unconscious and relative, i.e. if the environment conditions were to suddenly change, there would be a good chance that other varieties would survive. Varieties that present any advantage in surviving and reproducing in a time-bound environment will be “represented” by the process of inheritance in the next generation.

Darwin argued that Natural Selection was probably the most important type of selection in nature, though not the only one; Darwin himself wrote extensively on sexual selection. François Jacob asserted in *The Logic of Life* that “Natural selection imposes finality, not only on the whole organism, but on each of its components” (Jacob 1993, p. 300). This idea of finality, if taken to the extreme, will result in what Gould and Richard Lewontin called adaptionism in the essay “The Spandrels of San Marco and the Panglossian Paradigm: A Critique of the Adaptationist Programme.” According to them, there are some features such as the analogous example of the spandrels of San Marcos, which are there just because they are “necessary architectural by-products of mounting a dome on rounded arches (Gould and Lewontin 1995).” In nature, some features are there as a by-product, as a result of the selection of other body parts or because they were selected for other functions, such as the wings of birds and the human brain.

5.2.6. The Cyclical Process

The evolutionary process is cyclical in the sense that it repeats itself by the occurrence of variation, the struggle for survival and the inheritance of the advantageous characters.

this case the change has, it is believed, been chiefly effected by crosses with the foxhound; but what concerns us is, that the change has been effected unconsciously and gradually, and yet so effectually, that though the old Spanish pointer certainly came from Spain, Mr. Borrow has not seen, as I am informed by him, any native dog in Spain like our pointer” (Darwin 1993 Reprint[0], pp. 54-55).

[11] The fittest means the organisms who are “better than others at catching food or escaping from predators, at finding mates or at raising their offspring (Maynard Smith 1993, p. 44)” in a given environment.

To summarize what has been said above, by observing organisms under domestication, Darwin recognized that generations are produced in slightly modified forms; and that their characteristics seem to be inherited by their descendants. In nature, a struggle for survival would follow wherever the organisms and their resources become unbalanced; and according to their endurance towards internal, external and behavioral constraints, the individuals would then be selected. The advantageous characteristics of the fittest individuals will go forth to the next generation by means of reproduction.

5.2.7. The Analogy between the Re-Use of Design Precedents and Biological Evolution

Can the re-use of design precedents be described typically as an evolutionary process in a fruitful way? Recalling Calvin, a process can be called evolutionary if it fulfils the steps mentioned earlier in this chapter, i.e. starting with a pattern or feature, the characteristics of its elements should be heritable; variations of the pattern ought to occur among its offspring; the individuals will eventually compete for limited space; the environment will influence the relative success of the individuals so that the next generation will be based on the "successful" individuals, i.e. the fittest (Calvin 1997). If we assume that in design, precedents are patterns; that inheritance is the transference of characteristics from one design to another to solve actual problems; that many designs are only variations of a theme; that sketches produced during one design process are compared so that the fittest, the design which shows the highest performance, will survive, then we can say that in this perspective, the process of re-use of design precedents can be called evolutionary.

It goes without saying that, firstly, survival depends on internal (concerning the stability and functionality of the structure as well as of the organs) and external (environmental) constraints; secondly, that the fittest is not always the physically strongest, or the most attractive, or the greatest predator, but the one that matches the actual requirements for existence.

As in the case of variation under domestication, the architect may have a purpose for the development of each project; however, he/she cannot foresee how his/her own design concepts and designs approaches will be modified in the long run. This seems to be true for J.J.P. Oud. He was seeking a new expression in architecture; however, examining the drawings and projects of his early years, and how he followed and afterwards broke the principles of *De Stijl*, one can find plenty of evidence that he did not know where he would arrive.

The Darwinian theory of evolution was in fact one hypothesis about the way species evolved and did not expose the underlying mechanism of inheritance. The next sections will describe the developments in genetics, which explain many of the Darwinian sub-processes.

5.3. Inheritance in Design: Mendelism?

To describe the mechanisms of re-use, one has to explore the process behind design generation. This requires a description of all information concerning the building: not only the information that can be observed on the final design or artifact, but all information accumulated during the design process including the mental processes. This would be impossible; therefore, we use an analogy with the biological mechanisms of inheritance as a tool to find a representation for re-use in design. This representation must be demonstrated and tested with the help of two case studies.

This section investigates inheritance as viewed by the Austrian monk Gregor Mendel,[12] deducing a process from outside a "black box". It will describe the experiments of Mendel and afterwards, the notion of phenotype and genotype will be introduced. Later in the chapter, we will search for more specific help in the transmission and expression of reused parts of design precedents through genetics.

5.3.1. Mendelism

According to Jacob, "The theory of evolution demanded a process able to reproduce parental traits in the offspring, as well as to vary them slightly" (Jacob 1993). With experiments with pea-plants, Mendel discovered, to a certain extent, the laws underlying this process. The results of these experiments were published in the journal of a local natural history society in 1866, although they remained rather unnoticed until 1900, when they were simultaneously rediscovered by Hugo de Vries and Carl Correns. Jacob commented that contrary to Darwin's pangenesis, Mendel looked at heredity in terms of phenomena that could be analyzed with precision. As Jacob claims, "regular segregations, dominance of characters, persistence of hybrid state, none of these is in accord with pangenesis" (Jacob 1993, p. 207).

In his experiments, Mendel did not try to dissect organisms or study cells to discover what and where the units for inheritance were. He regarded plants and organisms as if they were a 'black box' and deduced how certain traits could possibly be transferred to the offspring even if the parents apparently did not possess them.

[12] The work of the Austrian monk Mendel was published in 1866; however, it was only after 1900 that this research became widely known.

5.3.2. Mendel's Experiments

Concentrating his efforts on discontinuous variations (Bowler 1984, p. 257), i.e. variations that seemed to have vanished from one generation to another only to reappear in a second or later generation, Mendel used a quantitative or mathematical method and analyzed the offspring statistically. As Jacob affirmed, with Mendel's strategy, "A whole internal logic was imposed on heredity by methodology, statistical treatment and symbolic representation" (Jacob 1993, p. 207).

According to Brian Hoffman, Mendel selected the pea-plant as his object of research due to its particular characteristics such as: the plant size, which is namely small and therefore permitted the collection of a high number of them in a relatively small space; the short life-cycle, which permitted the observance of several generations; its sexual reproduction, which provided a higher level of variation in the experiment; the possibility of mating control[13]; and the prolific **production** of peapods, because an extensive number of descendants would also mean a larger number of variations (Hoffman, Electronic Source).

Mendel started his experiments assuming that characteristics passed from parents to offspring by means of units that he called factors (and later were renamed genes). Each individual would have two factors per trait, one from each parent. He selected seven characteristics, such as the color and shape of the seed and the height of the plant.

Mendel studied the traits separately; he crossed true-breeding[14] pea-plants of opposing expression such as those that produced round with wrinkled seeds. The pods of the first generation all had round seeds. By applying self-fertilization on the plants of the first generation, Mendel produced plants of both types, with the round seed more abundant than the wrinkled one in the proportion of 3:1. Afterwards he observed several traits together per generation and concluded that traits were individually transferred from generation to generation without interference of another trait. The results of his experiments were formulated as rules.

The three laws of Mendel:

1. Law of Segregation: there is no blending of characteristics; the factors inherited for a determined trait remain separated in the offspring.

[13] "Mating can be controlled by removing the male parts from the flower and covering the flower so pollen can only be placed on the pistil by the experimenter" - Hoffman, Brian, Department of Biology, Park University, Parkville, Missouri, U.S.A.

[14] Those plants that supposedly produce no variation of their characteristics.

2. Law of Independent Assortment: each pair of factors determinant for one characteristic is independent of the factors determinant for the other characteristics. [15]

3. Law of Dominance: one of the two factors for each characteristic is dominant and the other recessive. Mendel observed that the first generation of true breeding parents of opposing expression always express the same variation. The color, shape or height that were expressed in this generation was called dominant.[16]

"To represent a recognizable feature in an individual," wrote Jacob, "two symbols are needed. One symbol, therefore, cannot correspond either to an observable character or to its delegate, the gemmule[17]. Hence the necessity of distinguishing between what is seen, the character, and something else underlying the character; or, in other words, between what twentieth-century genetics would call phenotype and genotype" (Jacob 1993, p. 207); this is the subject of the next sub-section.

5.3.3. Phenotype and Genotype

According to Maynard Smith, "One of the fundamental distinctions in genetics is between genotype and phenotype". He says that this is a distinction between what can be deduced about the genetic constitution of an individual from its ancestry or progeny, and what can be observed of the individual itself (Maynard Smith 1993, p. 114).[18]

As Jacob argued, "Genotype determines phenotype, but is only partly expressed in it. Observable characters simply bear witness to the hidden presence of particles or units which Mendel called 'factors'." What is transmitted by heredity, concluded Jacob, "is neither a complete representation of the individual nor a series of ambassadors from all parts of the parental bodies, subsequently

[15] Later, with the advances in genetics and the discovery of gene linkages, the second law proved not to be totally true; i.e. there is a tendency of some characteristics to appear together with others. Those linkages can be broken by crossing over, which will be explained later in this chapter, whereby the stronger linkages are between genes located near to each other on the same chromosome.

[16] The third law would have some complementary information as well, such as that some traits have an incomplete dominance; i.e. some organisms show a third characteristic when opposing factors are inherited, for example, a third color of a flower. There is also the case of co-dominance of factors when each factor inherited has an effect on the resulting trait: such as the co-dominance in blood types.

[17] Darwin used earlier the term gemmule meaning "a hypothetical particle or heredity carried by all cells and capable of moving to sex cells, thus permitting a direct influence of environment upon heredity" (Gould 1977).

[18] Maynard Smith, John p. 114

rearranged in the offspring like stones in a mosaic. It is a collection of discrete units each controlling one character. Each unit can exist in different states that determine the different forms of the corresponding character" (Jacob 1993, p. 207).

For the definition of genotype, some concepts are fundamental. On the one hand, we must look at the concepts of heterozygote and homozygote. A homozygote is a true breeding organism or, in other words, an organism that carries two genes for the same variation. Heterozygotes are hybrids; they carry two different genes for a trait "x"; for example, one for round and the other for wrinkled peas. Of course, one organism can be homozygote for one trait and heterozygote for another. On the other hand, we have the definitions of dominant and recessive genes. A dominant gene expresses itself whether the organism is homozygote or heterozygote for that characteristic; while the recessive factor/gene is only expressed if the organism carries two copies of the gene; i.e. if it is a homozygote.

Though always generated by its genotype, a phenotype is also the result of development, lifestyle and other environmental factors.

5.3.4. Genotype and Phenotypes in Design Generation

One may say that in order to understand design generation with the support of design precedents, the researcher should not only look to the design product and avoid the design process. In other words, to represent the mechanism of re-use in design, we need to explore the process behind design generation in relation to re-use. The distinction between genotype and phenotype provides us with a tool that supports our exploration; in this classification one can easily assume that a phenotype is the representation of a building, i.e. the group of characteristics visible in the product. We assume that the phenotype is the representation of the building product, while the concept of genotype[19] in our design model refers to decisions applied at process level, in particular, decisions concerning the re-use of design precedents. In other words, by analyzing a design process, one can see all the "crosses" which were effectuated, whether they were accepted or not. The characteristic that appears in the product is the dominant factor, while those not selected at that time are considered "recessive factors"[20]. Here we make a distinction from the use of genotype in nature, where recessive factors are always recessive. However, as in nature, these recessive factors do not disappear; instead, they may be re-used in future designs. The genotype of a design may only be

[19] This characteristic of our model contrasts with that described in our review of the current applications (Chapter 4); we have seen that in those applications the genotype of an artefact matched its phenotype; i.e. there was one factor per trait and therefore the discoveries made during the design process could not be re-used in future.

[20] By design recessive factors, we mean all alternatives, which after evaluation of their fitness for that specific environment, were not employed in the final artefact.

observed if one can explore the design process and identify the used design precedents. Saving the design states as well as the design precedents, one may re-use them in future.

In summary, by bringing the notions we explored in this section to the earlier idea explored of "artificial selection", we could say that if architects recall by "artificial selection", they recall design precedents just like breeders select animals or plants that have the characteristics closer to their ultimate goal (speed, strength, seedless fruits, abundance of milk, and so forth): by their phenotypes. Analogically, architects recall objects.

However, by breeding, breeders made use of a "mechanism" that they did not quite understand, and nor did Mendel. Classical breeders had to wait and see what results their crossings would have. Geneticists and embryologists would little by little clarify the mechanisms of transmission and expression of characteristics. Today with modern molecular genetics one can intentionally add specific genes or destroy them. It is in molecular biology that we will try to find out what and how designers re-use design precedents.

5.4. The Transmission and Expression of Design Precedents: Genetics and Embryology?

What kind of processes or mechanisms can be (analogically) used to represent transmission and expression of design precedents?

How do some characteristics "pass" from one design to another?

How are characteristics expressed?

This section describes processes and concepts of Genetics and Embryology. The first sub-section describes some historical facts about these disciplines. The sub-sections following that describe the notions of genes, mutation, and the process from gamete forming to zygote. The next sub-section will then describe the work of the genes of development, and the final sub-section will try to answer the questions formulated above.

5.4.1. Genetics and Embryology

In *The Logic of Life, a History of Heredity,* Jacob asserted: "Classical genetics belongs to the field of biology which studies the organism as a whole or populations of organisms. It does not try to dissect the animal or the plant in order to recognize its components and study their function." He wrote that the type of analysis used by genetics has been called the "black box" method; a method which equates the organism with a closed box "containing a large number of cogwheels geared together in a very complex mechanism." In this box, explained Jacob, "Chains of reactions occur, intersecting and overlapping in all directions. One end of each chain lies at the surface of the box: it is the character." Furthermore, he claimed that "classical genetics does not try to open the box and take the cog-wheels apart." Through the visible character, wrote Jacob, "it attempts to find the invisible ends of the chains of reactions, to detect the structure that lies hidden in the box, controls its shape and properties. Genetics completely ignores the intermediate cog-wheels between the gene and the character" (Jacob 1993, p. 225). Embryologists, by contrast, were interested in studying what was inside the box.

According to Scott F. Gilbert[21] in the paper "Enzymatic Adaptation and the Entrance of Molecular Biology into Embryology", the difference between geneticists and embryologists was accentuated around the 1920s and 1930s. Morgan's laboratory, wrote Gilbert, "gradually refined the gene concept, and **by** 1926, T. H. Morgan formally separated genetics – the transmission of nuclear genes – from embryology, the expression of those genes" (Gilbert 1996). According to Gilbert, it was the embryologist Morgan who, through experiments, showed that the chromosomes[22] were the seat of important determinants not only of sex, but of other traits as well.

During the second half of the 20th century geneticists and embryologists were reunified when molecular genetics provided a common discipline for both.

The next sub-sections will describe concepts such as those of gene, mutation, as well as mechanisms towards the expression of genes; i.e. the genes of development, their functions, and some genetic engineering experiments. These concepts will be used to answer our problem of the representation of re-use and adaptation in design.

5.4.2. Genes

According to Jacob, "After the middle of the nineteenth century, the cell became a focus of biological research. It was no longer merely the unit of structure of all living organisms, the final point of anatomical analysis. It had become the place where all the activities of the organism were conjoined, the 'seat of life', in the words of Virchow. In the cell, metabolic reactions take place and the characteristic molecule of living beings are fashioned. Through cell differentiation, organs are formed and the body of the adult is constructed" (Jacob 1993, pp. 209-210).

[21] site: http:/zygote.Swarthmore.edu/gene5a.html

[22] According to Jacob, "Everything marked them [the chromosomes] out for this role: their constant numbers and shapes; the precision of their cleavage and distribution in cell-division; the reduction of their number to half in the germ cells; and finally, their fusion in the egg at fertilization, as a result of which the offspring received equal numbers of chromosomes from father and mother. Only the nuclear substance could carry the 'hereditary tendency'. And this tendency included not only the characters of the parents but also those of more distant forebears" (Jacob 1993, p. 218).

In the twentieth century, cytologists,[23] wrote Jacob, "increased their means of discrimination and identification. In this way, they even obtained an insight into the chemical composition of cell constituents: the nucleus, for example, is easily stained by certain basic substances. Gradually the landscape revealed by the microscope was thrown into relief" (Jacob 1993, p. 211). In 1953, James Watson and Francis Crick discovered the DNA structure.

Mendel's factors were renamed 'genes' by the Danish geneticist, Johannsen; and it was discovered that structurally, with the exception of some organisms – viruses – whose genetic material is RNA, most genes are segments of DNA (Kitcher 1995, p. 383). Functionally, genes are instructions: some to produce, some to maintain the organism, and others still to control the activities of the others by switching them on and off. Genes are the codes for instructions translated in the production of proteins.

5.4.3. Mutations and Linkages

In his essay "1953 and All That", Philip Kitcher asserted that "A mutation is the modification of a gene through insertion, deletion, or substitution of nucleotides" (Kitcher 1995, p. 392). They occur, stated Hugo de Vries in his *Espèces et variétés*, "at random and represent 'regression' just as often as 'progression'." Contrary to Gould (see subsection 5.2.1.), De Vries claimed that "They develop 'in all directions.' Certain changes are useful, others are harmful, but many are unimportant and are neither favorable nor unfavorable." Accordingly, they provide "a very considerable amount of material to be sorted by the sieve of natural selection (De Vries 1909, 179-180)."

By studying the generations of mutant Drosophilas, it was discovered that there were some links between genes (Jacob 1993, p. 223). Also, "By determining the frequency with which characters were united or separated in successive generations," wrote Jacob, "it became possible to arrange them in linear order along the chromosomes like a string of beads. The relative distances between the genes could be estimated and a genetic map of the species drawn up" (Jacob 1993, pp. 223-224). As we will describe later in this chapter, the study of mutants will help researchers to understand the function of some genes of development, the so-called regulatory (hox) genes.

5.4.4. Regulatory Genes and Genetic Engineering

Regulatory genes control the development of a fertilized egg (zygote) by turning other genes on and off, thus guiding its growth, differentiation and morphogenesis. In his *Genome, the Autobiography of a Species in 23 Chapters,* Matt Ridley wrote

[23] Cytology is the science that attempts to chart cellular space - Jacob 1993

that in the late 1970s, two scientists named Jani Nusslein-Volhard and Eric Wieschaus set out to find and describe as many mutant flies in a lineage as possible. “They dosed the flies with chemicals that cause mutations,” wrote Ridley, “bred them by the thousand and slowly sorted out all the ones with limbs or wings or other body parts that grew in the wrong places. Gradually they began to see a consistent pattern. There were ‘gap’ genes that had big effects, defining whole areas of the body, ‘pair-rule’ genes that subdivided these areas and defined finer details, and ‘segment-polarity’ genes that subdivided those details by affecting just the front or rear of a small section.” According to Ridley, the developmental genes seemed to act hierarchically, “parceling up the embryo into smaller and smaller sections to create ever more detail” (Ridley 1999, p. 176).

Ridley asserted that until then, “it had been assumed that the parts of the body defined themselves according to their neighbouring parts, not according to some grand genetic plan.” A second discovery was made “when the fruit-fly genes that had been mutated were pinned down and their sequences read.” According to Ridley, “The scientists found a cluster of eight homeotic genes lying together on the same chromosome, genes which became known as Hox genes.” He asserted that “each of the eight genes affected a different part of the fly and they were lined up *in the same order as the part of the fly they affected.* The first gene affected the mouth, the second the face, the third the top of the head, the fourth the neck, the fifth the thorax, the sixth the front half of the abdomen, the seventh the rear half of the abdomen, and the eighth various other parts of the abdomen.” In other words, “They were,” stressed Ridley, “all laid out in order along the chromosome – without exception” (Ridley 1999, pp. 176-177).

Even more astonishing was the conservation of these regulatory genes during evolution. Similar genes were found in mice and in man, and in fact, as Maynard Smith explained in his *Shaping Life, Genes Embryos and Evolution*, in all “main bilaterally symmetrical animal phyla, including mollusks (e.g. snails, octopus) and annelid worms.” This discovery drove Ridley to the conclusion that at the level of embryology, we are “glorified flies” (Ridley 1999, p. 178). They are so similar that according to Maynard Smith, if the gene responsible for making the eye of a fly is substituted for the so-called small-eye gene of a mouse, the developing fruit fly, i.e. the Drosophila, will develop an eye; however, not a mouse eye (a camera-like eye of the vertebrates), but a compound fly-eye with its characteristic facets (Maynard Smith 1998, pp. 7-17). That means that an instruction is given to produce a perception organ in a particular region of the embryo. However, the structure, materials and appearance are different from each other; they are probably “coded” by other genes, which we will call the “structural genes”.

5.4.5. Can Genetics and Embryology Represent the Transmission and Expression of Design Precedents?

As already mentioned above, genes in biology works as recipes; they are each a *segment* of DNA, a molecule which, via chemical reactions and its translation into RNA, produces proteins. These proteins are responsible for the making and maintenance of organisms. This research does not pursue an analogy with the physical structure of a gene, but with how it performs. Genes are instructors and instructions (recipes). They are organized to perform tasks alone and within linkages, as well as according to their hierarchical division between regulatory genes and structural genes.

A gene for architecture needs to have its own domain-specific structure. We provide this structure with the use of the P.O.M. system, which we shall explain in the next chapter. However, it is our claim that regulatory (hox) genes, as well as the other genes for generation and maintenance of an organism, can give the overall framework of the model and form the basis for a successful representation of the process of re-use of design precedents, also when they are based on analogies.

We could call a gene any instruction to make an element of a building; however, if we are trying to develop a model for the intelligent architect, then there is no need to make innumerous obvious genes. This is not the same as saying that the computer should not generate or recognize columns or that the designer would not recollect a column; however, what we want is to represent the use and adaptation of multifaceted and insightful features that helped the architect in making a new design.

Regulatory Genes and Representation

Regulatory genes are genes that occur in many species and they are responsible for development by switching *on* and *off* the correlated genes of the species that they are acting upon (Watson 1994).

This chapter has already showed that when a mouse regulatory gene called small eye[24] is transferred to the embryo of a fruit fly and substitutes the “fly-eye” regulatory gene, the fly will develop an eye. The regulatory gene of mice “orders” the genes of a very distinguished species to make a perception organ in a certain time and location. However, it cannot “order” the generation of the camera-like eye of the mouse. This obviously happens because the mouse regulatory gene is then “giving orders” to a different set of genes (that of the fruit-fly) than its original set (“structural genes” of mice). Therefore, we confer to regulatory genes

[24] Already explained in chapter 5

a higher-level description of the structure, its general operation (perception) and the position of the parts in a whole, as well as its links with other structures.

The "Structural Genes"

Each species has a particular set of "structural genes", which carry the specific characteristics of the species; not only in types of differentiation or quantities, but also in time of development (or Heterochrony, which will be explained later in this chapter). As mentioned earlier, these genes are switched on and off by regulatory genes such as the hox genes to develop and maintain the organism; also, they are responsible for the growth, differentiation and morphogenesis of structures and organs in individuals.

Following the same example, the fruit-fly gene which executes the order of the mouse regulatory gene cannot produce the mouse eye; at least, not at the stage of evolution at which the fly finds itself now; if it could produce it by an empowered mutation, then internal and external constraints would render it impossible for survival. The "structural gene" of a perception organ of a fly cannot produce a mammal eye but only the multi-faceted eye of the fly self. This gene is probably constrained by other fly genes which avoid the otherwise monstrous outcome: a fly with an eye heavier and bigger than a normal fly, which would make all the other structures and organs of the fly collapse. Besides, according to D'Arcy Wentworth Thompson in his *On Growth and Form,* if the mammal eye was developed on a small scale, it would be useless: the "pupil would be so small that diffraction would render a clear image impossible" (Thompson 1942, p. 53).

Evolution finds its balance between two opposing directions. On the one hand, mutations bring variations for selection favoring changes in the lineages through natural selection, although most mutations are harmful and do not favor the survival of the organism. On the other hand, the constraints imposed on ontogeny by controllers like hox genes (switching the "structural genes" on and off) as well as the linkages among various structural genes create stable organisms (species). Organisms which, according to former selections, were "considered" fit. It is nature's balance between variation and stability that makes evolution possible by producing organisms which have a reasonable chance of survival in their environment.

Modification

Two things are interesting in modification by re-use . On the one hand, regulatory d-genes[25] give orders to other genes that will execute the command. Proceeding

[25] In this research, architectural genes will be called "d-genes", therefore, we shall refer to " regulatory d-genes" and "structural d-genes"

from a design precedent, the architect looks to its structure and may want to re-use part of it in his present situation. For example, when designing the first blocks of the Spangen Housing State, J.J.P. Oud used and adapted a plan layout of Van Goor. Oud was not concerned with Van Goor's building structure, façade composition or the use of materials. He only used the plan layout because it could fit the lifestyle of the users of Spangen as well. He transferred a configuration or a regulatory d-gene.

5.5. The Selection of Design Precedents and the Mode of Production of Innovative Designs: Some Issues from Neo-Darwinism

Chapter 3 provided us with 10 adequacy criteria for the model. These are based on generalizations drawn from the case study of the social housing of J.J.P. Oud. This section deals with four of these generalizations, which are: (1) architects often use part of a design precedent rather than the whole design; (2) elements of a design are often recruited from diverse design precedents; (3) characteristics or elements are successful or not depending only on the external (environment) and internal constraints imposed on it; and (7) architects often apply principles in their projects. If we say that things are being recalled, can we really answer what is recalled and transmitted? Is it the whole design or a precedent-component? What is the unit of selection?

If we can answer this, can we add the factor "time" to it and try to find out whether are there some patterns of change in design? In other words, does it happen gradually? Or are there moments of great change and others where only variations of a theme happen? Does it happen linearly? Hierarchically? Or are there many paths running parallel to each other? We believe that these questions can shed some light on the question of what is really being recalled and how it is integrated to the whole.

In this section, we shall bring two issues to the discussion. First, we shall briefly present a discussion on the principle of "Gradualism" introduced by Darwin and defended by Dawkins, while Gould and Niles Eldredge extended the principle of Gradualism to involve the principle of "Punctuated Equilibrium."

Second, we shall discuss the unit of selection in which evolution takes place. This time Gould takes the orthodox position, i.e. the unit of selection is, as Darwin determined, the individual organism, while Dawkins defends the idea that the gene is the real unit of selection.

At the end of this section, we shall present our position by comparing the ideas and selecting those that clarify and/or support some of the processes in design, in particular those of recollection.

5.5.1. Gradualism versus Punctuated Equilibrium

By publishing his gradualism in *The Origins*, Darwin had to face the great opposition of the Catastrophists for whom only major events such as major floods could change the face of the Earth. The problem then with gradual changes was that they could not be seen by anyone because of the great time spans (million of years), and also because they could not be confirmed by geological data, i.e. by fossils. According to Darwin, the great gaps found in the study of fossils between what was supposed to be a daughter species and its ascendants was a problem of the extremely imperfect geological record.

Darwin's position is nowadays defended by Dawkins who claims that "*the living things"* evolved "by gradual, step-by-step transformations from simple beginnings, from primordial entities sufficiently simple to have come into existence by chance. Each successive change in the gradual evolutionary process was simple enough, relative to its predecessor, to have arisen by chance." (Dawkins 1986, p. 43).

If the defense of gradualism comes from the corner of zoology, the expansive theory of Punctuated Equilibria (PE) comes from the opposite corner: from paleontology. Proposed as a criticism to the Darwinian theory of evolution, in the essay "The Episodic Nature of Evolutionary Change" Gould advocates that "The modern theory of evolution does not require gradual change. In fact, the operation of Darwinian processes should yield exactly what we see in the fossil record. It is gradualism that we must reject, not Darwinism." Before describing this theory, it is worth noting that the last sentence of this quotation is not the proclamation of the death of gradualism as Dennet assumed in his *Darwin's Dangerous Ideas* (Dennett 1996, pp. 291-292), but if so, it would only be the death of the exclusive orthodox gradualism. In Gould's own words: "I emphatically do not assert the general 'truth' of this philosophy of punctuational change. Any attempt to support the exclusive validity of such a grandiose notion would border on the nonsensical. Gradualism sometimes works well" (Gould 1980).

Gradual change is also called "phyletic change", i.e. an entire population is transformed from one state to another. In "Punctuated Equilibria: an alternative to phyletic gradualism", Niles Eldredge and Gould identified the following tenets of phyletic gradualism: new species arise by the transformation of an ancestral population into its modified descendants; this transformation is even and slow, involves large numbers, usually the entire ancestral population, and occurs over all or a large part of the ancestral species' geographic range (Gould and Eldredge

1972). According to Gould, “if all evolutionary change occurred in this mode, life would not persist for long. Phyletic evolution yields no increase in diversity, only a transformation of one thing into another” (Gould 1980, p. 151). Speciation, on the other hand, “replenishes the earth. New species branch off from a persisting parental stock” (Gould 1980, pp. 151-2).

In the essay “Punctuated Equilibrium”, F. Heylighen wrote: “Eldredge and Gould observed that evolution moves sometimes very fast, and sometimes very slowly or not at all”; “typical variations tend to be small. Therefore, Darwin saw evolution as a slow, continuous process, without sudden jumps. However, if you study the fossils of organisms found in subsequent geological layers, you will see long intervals in which nothing changed (‘equilibrium’), ‘punctuated’ by short, revolutionary transitions, in which species became extinct and replaced by wholly new forms. Instead of a slow, continuous progression, the evolution of life on Earth seems more like the life of a soldier: long periods of boredom interrupted by rare moments of terror” (Heylighen, 1999)[26]. The zoologist Wesley Elsberry makes an excellent and systematic summary of the essential features of Gould and Eldredge’s Punctuated Equilibria to clarify the misunderstanding around this theory in his essay “Punctuated Equilibria” (Elsberry 1996). The essential features that make up Punctuated Equilibria are as follows:

1. Paleontology should be informed by neontology (the study of the evolutionary process from living biological species).
2. Most speciation is derived from a splitting of a daughter species from an ancestral species.
3. Most speciation occurs via allopatric[27] speciation; i.e. a population of an ancestral species in a geographically peripheral part of the ancestral range is modified over time until even when the ancestral and daughter populations come into contact, there is reproductive isolation.
4. Large, widespread species usually change slowly, if at all, during their time of residence.
5. Daughter species usually develop in a geographically limited region.
6. Daughter species usually develop in a stratigraphically limited extent, which is small in relation to the total residence time of the species.
7. Sampling the fossil record will reveal a pattern of most species in stasis, with the abrupt appearance of newly derived species being a consequence

[26] Principia Cybernetica Web on: http://pespmc1.vub.ac.be/:/PUNCTUEQ.html
[27] allopatric means “in another place” - Gould

> of ecological succession and dispersion. Adaptive change in lineages occurs mostly during periods of speciation. Trends in adaptation occur mostly through the mechanism of species selection (Elsberry, 1996).[28]

Punctuated Equilibria "is not mutually exclusive of phyletic gradualism. Gould and Eldredge take pains to explicitly point out that PE is an expansive theory, not an exclusive one (1977)" (Elsberry, 1996).

On the one hand, Gould and Eldredge postulated that speciation events comprise most of the observable evolutionary adaptive change. Punctuated Equilibria explains the abrupt appearance of new species in the fossil record which do not frequently show the intermediate steps from one species to another; it also explains the relative stasis of most species, as claimed by Gould: "Large, stable central populations exert a strong homogenizing influence. New and favorable mutations are diluted by the sheer bulk of the population through which they must spread (Gould 1980)." On the other hand**,** from the fossil record, a pattern arises which "includes the characteristically abrupt appearance of new species, the relative stability of morphology in widespread species, the distribution of transitional fossils when those are found, the apparent differences in morphology between ancestral and daughter species, and the pattern of extinction of species" (Elsberry 1996).

Dennet criticized Punctuated Equilibria due to the need for large and successful mutations in a very short time to cause a daughter species to split from their parents. "It is possible," argued Dennet, "for the molecular replicating machinery to take large steps in the Library of Mendel – there are cases in which whole chunks of text get transposed, inverted, or deleted in a single copying 'mistake.' It is also possible for typographical differences to accumulate slowly (and, in general, randomly) over a long time in the large portion of DNA that never gets expressed, and if these accumulated changes suddenly got expressed, thanks to some transposing error, a huge phenotypic effect would be expected. But it is only when we turn to the third sense of macromutation – large differences in fitness – that we get clear about what seemed to be radical in Gould's proposal." The terms 'saltation' and 'macromutation', claimed Dennet, "have tended to be used to describe a successful move, a creative move, in which offspring in a single generation shift from one region of Design Space to another and prosper as a result. The idea had been promoted by Richard Goldschmidt (1933, 1940), and made unforgettable by his catchphrase 'hopeful monsters'" (Dennet 1996, pp. 287-288).

However, the very short time that Gould and Eldredge refer to does not mean that of 10 years or only one generation. In Gould's words, "In describing the

[28] http://www.verslo.is/skolanet/Kennsluefni/lif/Itarefni/Throun/Rykkjott%20jafnvaegi(e).htm

speciation of peripheral isolates as very rapid, I speak as a geologist. The process may take hundreds or thousands of years; you might see nothing if you stared at speciating bees on a tree for your entire lifetime." It is a short time, however, if we think of the millions of years required by gradual change.

5.5.2. The Unit of Selection: the group, the individual and the selfish gene

Either by "Gradualism" or "Punctuated Equilibrium," *something* is selected giving direction to evolution (direction though no intention). In the essay "A Matter of Individuality", David Hull stated: "The major dispute among contemporary evolutionary theorists is the level (or levels) at which selection operates. Does selection occur only and literally at the level of genes? Does selection take place exclusively at the level of organisms, the selection of genes being only a consequence of the selection of organisms? Can selection also take place at levels of organization more inclusive than the individual organism, e.g. at the level of kinship groups, populations, and possibly even entire species? Biologists can be found opting for every single permutation of the answers to the preceding questions" (Hull 1995, p. 196). This subsection briefly describes the concepts and the discussion around what indeed is selected in nature, i.e. the unit of selection. We shall focus on three main views: V.C. Wynne-Edwards – defending the group as the unit of selection; Gould – defending the organism as the unit of selection; and Dawkins – defending genes as the real unit of selection.

The Individual as the Unit of Selection

Gould identifies three units in the process of evolution: the unit of variation, the unit of selection, and the unit of evolution. He claimed that life "operates at many levels, and each has its role in the evolutionary process. Consider three major levels: genes, organisms, and species. Genes are blueprints for organisms; organisms are the building blocks of species. Evolution requires variation, for natural selection cannot operate without a large set of choices. Mutation is the ultimate source of variation, and genes are the unit of variation. Individual organisms are the units of selection. But individuals do not evolve – they can only grow, reproduce, and die. Evolutionary change occurs in groups of interacting organisms; species are the unit of evolution" (Gould 1980, 73).

The Gene as the Unit of Selection

For Dawkins and those who support this theory, genes and not individuals are the units of selection. In *The Selfish Gene,* Richard Dawkins argues that "A body is the genes' way of preserving the genes unaltered"; or more forcefully, "we are survival machines – robot vehicles blindly programmed to preserve the selfish molecules known as genes… They swarm in huge colonies, safe inside gigantic lumbering robots… they are in you and me; they created us, body and mind; and their preservation is the ultimate rationale for our existence" (Dawkins 1989)[29]. According to Gould, "They begin recasting Butler's famous aphorism that a hen is merely the egg's way of making another egg. An animal, they argue, is only DNA's way of making more DNA (Gould 1990, p. 75)."

However, according to Gould, it is of the utmost importance that "No matter how much power Dawkins wishes to assign to genes, there is one thing that he cannot give them – direct visibility to natural selection. Selection simply cannot see genes and pick among them directly. It must use bodies as an intermediary. A gene is a bit of DNA hidden within a cell. Selection views bodies. It favors some bodies because they are stronger, better insulated, earlier in their sexual maturation, fierce in combat, or more beautiful to behold." He claimed: "Dawkins's vision requires that genes have an influence upon bodies. Selection cannot see them unless they translate to bits of morphology, physiology, or behavior that make a difference to the success of organism." Furthermore, said Gould, we do not have a one-to-one mapping between gene and body (Gould 1980, pp. 76-7); often a gene is a part of a linkage working in combination with other genes to produce a part of an organism.

The Group as the Unit of Selection.

Gould and Dawkins seem to agree at least in their position against group selection as the unit of selection, both, among other reasons, because they refute the idea of altruism (Dawkins 1989, pp. 7-10; Gould 1980).

According to Gould, the Darwinians attacked Wynne-Edwards' group selection from two sides. On the one hand, they accepted his observations but interpreted them as individual selection: "the losers don't walk away with grace, content that their sacrifices increase the common good. They have simply been beaten; with luck, they will win on their next try" (Gould 1980, p. 74). On the other hand, they reinterpreted apparent altruistic acts "as selfish devices to propagate genes through surviving kin – the theory of kin selection." In kin selection, parents make sacrifices for their offspring because the latter will carry their genes ahead to the next generations (Gould 1980, p. 75). We may ask ourselves, though, whether

[29] "Dawkins," wrote Gould, "explicitly abandons the Darwinian concept of individuals as units of selection: 'I shall argue that the fundamental unit of selection, and therefore of self-interest, is not the species, nor the group, nor even, strictly, the individual. It is the gene, the unit of heredity.' Thus, we should not talk about kin selection and apparent altruism. Bodies are not the appropriate units. Genes merely try to recognize copies of themselves wherever they occur. They act only to preserve copies and make more of them. They couldn't care less which body happens to be their temporary home" (Gould 1980, p. 76).

animals can understand that they are going to die and that their offspring's DNA is the only "part" of them which may survive in the form of a duplicate.

Wynne-Edwards presented his defense of 'group selection' in his *Animal Dispersion in Relation to Social Behavior*. According to Gould, Wynne-Edwards "began with a dilemma: why, if individuals only struggle to maximize their reproductive success, do so many species seem to maintain their populations at a fairly constant level, well matched to the resources available? The traditional Darwinian answer invoked external constraints of food, climate, and predation: only so many can be fed, so the rest starve (or freeze or get eaten), and numbers stabilize. Wynne-Edwards, on the other hand, argued that animals regulate their own populations by gauging the restrictions of their environment and regulating their own reproduction accordingly. He recognized right away that such a theory contravened Darwin's insistence on 'individual selection' for it required that many individuals limit or forgo their own reproduction for the good of their group" (Gould 1980, p. 73).

Wynne-Edwards admitted that some groups do not evolve a way to regulate reproduction, and in these cases, individual selection is the unit for selection. Though, for those that can regulate reproduction, Wynne-Edwards argued that depending on the resources of the environment, a number of tickets would be printed for reproduction. "Animals then," explained Gould, "would compete for tickets through elaborate systems of conventionalized rivalry. In territorial species, each parcel of land contains a ticket and animals (usually males) posture for the parcels" (Gould 1980, pp. 73-74). However, if Wynne-Edwards is right, argued Gould, members of the groups should know how many "tickets" were available: "how do animals know the number of tickets? Clearly, they cannot, unless they can census their own population" (Gould 1980, p. 74).

In the essay "Excerpts from Adaptation and Natural Selection", George C. Williams wrote: "...an individual who maximizes his friendships and minimizes his antagonisms will have an evolutionary advantage, and selection should favor those characters that promote the optimization of personal relationships" (Williams 1995, p. 125). Even if a group can be favored as a whole if their members behave altruistically, we can say that it is still the organism that is being selected because of its fitness towards the environment.

Natural Selection is perhaps the major mechanism but not the sole one; sexual selection may be its second mechanism and behavior can probably be a third one. As Darwin would argue, all these mechanisms of selection are acting upon one unit of selection: the individual.

5.5.3. Neo Darwinism and the Architectural Design Model

Turning back to design, what, then, is recalled and how can we describe the pattern of change in time?[30]

The Pattern of Change in Design: Gradualism and Punctuated Equilibrium

In the history of architecture, we can see a concept analogous to Punctuated Equilibria: long periods of stability such as Classicism, Gothic, Eclecticism and Modernism; and short periods of 'revolution'. One may say that the early years of Modernism, around the 1920s, when architects such as Oud, Rietveld, Gropius and Le Corbusier were developing their principles, was a moment of rapid evolution towards Modern architecture.

If we think on a smaller scale, the oeuvre of an architect has some periods of rapid change. Some innovative designs, generally referred to as turning points in an architect's career, take years of what Le Corbusier would call "gestation", and we could term it 'architectural evolution at a punctuated equilibrium'. The architect's world seems, then, to be like an island to which several (and sometimes 'strange') design precedents migrated by artificial selection and are transformed through generations into a new and fitter "organism".

However, in nature, the species are much more defined than in design. Among the migrants to this fictive island, we can find sculptures, and all kind of artifacts. By "conferring" on the architect-breeder "knowledge on genetic engineering", we abridge this gap between design and nature.

Unit of Selection in Design: the Group, the Individual and the Gene

On the one hand, architects select artifacts (individuals) by their name; on the other hand, they select artifacts by their special features (the phenotypic expression of genes); architects may even select a group of artifacts, whereby attractiveness could be: a particular position of (part of) a house in relation to the courtyard such as in J.J.P. Oud's Block VIII of Spangen Housing State would help them in enriching the 'value' of the house-unit[31]; or the way in which J.J.P. Oud's Spangen block position in relation to the surrounding streets emphasizes the dichotomy between the city and private life (see Chapter 3 for details).

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[30] Time scale is one of the differences in the analogy. Architecture is a human cultural expression on the scale of a thousand years, while evolution in nature happens over millions of years. As Prof. Galjaard has put it in a discussion, perhaps architecture is an extreme form of primitive nest building.

[31] Designers can enrich the value of something only regarding a particular purpose, in this case if they want to emphasize the dichotomy between city and domestic life.

We will initially take a pluralist view and make use of three units of selection because of one of our earlier assumptions, that in design there is artificial rather than natural selection. There can be the selection of a whole design as a precedent, or of a particular architectural feature or design-component from one design to another.

5.6. A Historical Account of Change and Design Generation: Ontogeny and Phylogeny, the Two Levels of Evolution

There are changes which can be described within the development of one design; however, innovative or extreme changes within the work of an architect are often only noticed when one views a chronological set of designs in retrospect, such as the changes that occurred from J.J.P. Oud's Spangen blocks through the Witte Dorp to the row houses of Stuttgart. Major changes often happen as a process that refers to the architect's experience in design.

5.6.1. Ontogeny and Phylogeny

This section discusses the two levels in which changes become evident: Phylogeny and Ontogeny. The first, wrote Gould in *Ontogeny and Phylogeny,* is "the evolutionary history of a lineage, conventionally (though not ideally) depicted as a sequence of successive adult stages (Gould 1977, p. 484)", while the second is "the life history of an individual, both embryonic and post-natal (Gould 1977, p. 482)." Each adult individual, argued Maynard Smith, is "the end-product of a process of development; the development of an individual from fertilized egg to adult is called its 'ontogeny.' Evolutionary changes are usually described in terms of the differences between successive adults, i.e. as phylogenetic changes, the differences between those adults were the consequence of differences between the paths of development which gave rise to them, i.e. of ontogenetic changes; **phylogenetic changes are the result of changes in ontogeny**. It follows that a study of ontogeny, even though confined to living animals, can throw a good deal of light on the processes which in the past were responsible for phylogenetic change" (Maynard Smith 1993, p. 310).

5.6.2. Haeckel's Recapitulation versus Von Baer ' Opposition

Karl Ernst Von Baer and Haeckel developed rival theories explaining the process of ontogeny in relation to phylogeny. On the one hand, Haeckel's theory of recapitulation asserted that "ontogeny recapitulates phylogeny", which affirmed that "individuals in the course of their own ontogenetic development pass through stages representing the adults of their ancestors." Recapitulation is "the repetition of ancestral adult stages in embryonic or juvenile stages of descendants" (Gould 1977, p. 485). On the other hand, Von Baer presented "his famous laws of development, the epitome of his contribution (and probably the most important words in the history of embryology)." The laws of Von Baer are the following:

1. "The general features of a large group of animals appear earlier in the embryo than the special features.
2. Less general characters are developed from the most general, and so forth until finally the most specialized appear.
3. Each embryo of a given species, instead of passing through the stages of other animals, departs more and more from them.
4. Fundamentally therefore, the embryo of a higher animal is never like [the adult of] a lower animal, but only like its embryo." (Gould 1977, p. 56)

Von Baer refuted Haeckel's recapitulation with two arguments. First, argued Von Baer, "Embryology is differentiation, not a climb up the ladder of perfection"; i.e. the embryo of a vertebrate is from its very early beginning already a vertebrate (Gould 1977, p. 56). The second argument that Von Baer leveled against recapitulation was that "the occurrence of recapitulation is 'necessarily bound' to the view of a unilinear scale of animals. Recapitulation permits "only one direction of metamorphosis that reaches its higher stages of development either in an individual (individual metamorphosis) or through the different forms of [adult] animals (metamorphosis of the animal kingdom). Abnormalities [of birth] had to be designated as retrogressive metamorphosis because unilinear metamorphosis is like a railway that moves only forwards or backwards, never to the side" (Gould 1977, p. 56)[32]. In summary, recapitulation seems to be only adding in complexity, it is a linear development from lower organisms into higher ones. Any anomalies in this climbing up towards perfection should be understood as retrogression, i.e. that the development of that specific organism stopped before completion.

This brought huge misunderstandings in explanations of origins of anomalies such as Down's syndrome. In his essay "Dr. Down's Syndrome", Gould stated that Dr. Down believed that the individuals that presented an anomaly showed an arrest of development.[33] Based on recapitulation, Down's rationale, wrote Gould, was that "the more serious the deficiency, the more profound the arrest of development

[32] Originally quoted from B.E. Raikov's book *Karl Ernst Von Baer 1792-1876*, of 1968

[33] Gould described Down's fallacious scale of races. Concerning Down's syndrome, he wrote that "A very large number of congenital idiots are typical Mongols. So marked is this, that when placed side by side, it is difficult to believe that the specimens compared are not children of the same parents (Gould 1980)."

and the lower the race represented" (Gould 1980, pp. 136-7)[34]. This whole argumentation collapsed, even before the discovery of trisomy-21[35], when it was discovered that the syndrome also occurs among Asians and Africans.

As Maynard Smith pointed out, Von Baer was right and Haeckel was wrong with his theory of recapitulation. According to Maynard Smith, recapitulation "was abandoned for two reasons. First, there is no good reason why animals should recapitulate their evolutionary history. Second, and more importantly, it was realized that, early in development before the phylotypic stage, related animals may be more different from one another than they are later" (Maynard Smith 1998, p. 15).

5.6.3. Heterochrony: between Phylogeny and Ontogeny

Heterochrony is a disruption in the proper relation between phylogeny and ontogeny. It does not directly concern mutation of form; heterochrony means changes in timing of appearance of features that may very well already exist, i.e. an earlier or later appearance of an organ in the ontogenic development. "The embryonic heart of vertebrates, for example," wrote Gould, "now appears far earlier in ontogeny than its time of phylogenetic development would warrant" (Gould 1977, pp. 481-482). An example of a later or prolonged event is the development of the brain in humans. Contrary to most mammals, primates, wrote Gould, "prolong brain growth into early stages of post-natal ontogeny. Macaca mulatta achieves 65 percent of final cranial capacity by birth, chimpanzees 40.5, and humans only 23 percent. Chimps and gorillas reach 70 percent of final capacity early in the first year, while we do not attain this value until early in our third year" (Gould 1977, p. 371). The brain reaches its full size by retaining fetal growth rates after birth, i.e. by retardation of a process which, such as that by most mammalians, should be almost ready by the end of embryo development. **A** favorable result means a redirection of selection.

Heterochrony is a process which can use several possible strategies, such as Progenesis and Neoteny. Progenesis is "paedomorphosis[36] produced by precocious sexual maturation of an organism still in a morphologically juvenile stage" (Gould 1977, p. 485), while Neoteny is "paedomorphosis produced by retardation[37] of somatic development" (Gould 1977, p. 483). The Adaptive Significance of

[34] The Panda's Thumb

[35] Now it is well known that the syndrome is caused during meiosis, the formation of the sexual cells, when the paired chromosomes called 21 do not split forming an egg or a sperm with 24 instead of 23 chromosomes. By fertilization, the zygote will have three number 21 chromosomes.

[36] Retention of formerly juvenile characters by adult descendants

[37] Retardation is "a slowing down of development in ontogeny (relative to any criterion of standardization), so that a feature appears later in the ontogeny of a descendant than it did in an ancestor (Gould 1977, p.485)."

Retarded Development is that “for instance a reduced time as an embryo may bring possibilities that were before unthinkable. Human children are born hopeless, depending on their parents for everything if compared with the offspring of other animals; however, they develop their brains [also] outside the womb, giving them the possibility to develop larger brains [more capabilities] than the [other] mammalians” (Gould 1977, pp. 400-401)[38].

5.6.4. Ontogeny, Phylogeny and the Architectural Design Model

In design, recapitulation could be understood as a further development of one design into another, adding in complexity though not directly supporting creativity. Von Baer’s laws match with the development of the design process from general to specific, though without giving much insight into how to do it.

From all the concepts described above, it seems that, in creative architectural design, heterochrony can be the most empowered one.

Changes in the timing of appearance of certain features of the buildings, the design analogue for “the retention of juvenile characters by an adult descendent”, resemble parts of the processes of design. In other words, it instigates us to ask whether heterochrony was not one of the processes unconsciously carried out by the Modernists; when they refused to decorate their structures, showing us, for example, a “naked cubism” and, as in the process of speciation, not necessarily extinguishing their parent stock (think of the production of the Amsterdam School, a contemporary of the Modern Movement). This concept of Heterochrony may be extended until the period of usage of the buildings.

Phylogeny and ontogeny seem ideal concepts to picture the changes over the years and the adaptations in development of the designs respectively.

5.7. Structural Forces in Design: on Growth and Form

Until now, we have not touched upon two important issues in design: structural forces and stability. Architects may design all kinds of structures on paper or with a CAD program; however, only designs representing a stable form in accordance with their configuration, specified materials, technology and scale can potentially be built. All the others will collapse due to forces such as compression, tension and, in particular, bending moments.

[38] “From the child's standpoint: the newborn human child is about as dependent a creature as we find among placental mammalian infants. This dependency is then extraordinarily prolonged, and the child requires intense parental care for many years. The flexibility of childhood persists during more than a decade of necessarily close contact with adults. The adaptive premium thus placed on learning (as opposed to innate response) is unmatched among organisms.” (Gould 1977, pp. 400-401)

So far in this chapter, we have proposed a "genetic" framework (see sub-section 5.4.5.). "Regulatory d-genes" carry the configurational characteristics of an element or a group of elements in design. These are often conveyed from one artifact to another. In the particular case of design, the regulatory d-genes may be transferred from artifacts (species?) other than architecture, such as sculptures, ships, and so forth. The "structural d-genes" follow the instructions of the "regulatory d-genes". These structural d-genes work as settings that describe a construction method. A particular set of structural d-genes will be put to work with technology "x" and materials "z" as required by the design (e.g. a high-rise apartment building will presumably be built in reinforced concrete while a savage hut can alternatively be built with wood).

The need for a reliable structural calculation of the forces is undeniable. Besides an analysis of the structural forces, the fitness test of the designs should particularly involve the integration of the parts, without which the transference of configurations from one artifact to another would become useless.

This section thus brings us to a brief analysis of Thompson's book *On Growth and Form.*[39] As we shall see, his theory opposes Darwin's Theory of Evolution in several points. Next, we will briefly describe Thompson's views in comparison to those of the Darwinians and discuss Thompson's insights on the importance of structural forces and integration in his theory of transformation. Finally, we shall discuss the importance of this theory for our model of re-use and adaptation of design precedents.

5.7.1. Structural Forces versus Natural Selection

Thompson discussed the importance of internal (structural) and external (environmental) forces in biological evolution. His goals were "to see how, in some cases at least, the forms of living things, and of the parts of living things, can be explained by physical considerations, and to realize that in general no organic forms exist save such as are in conformity with physical and mathematical laws" (Thompson 1992, p. 15). Thompson argued that there was too much credit given to Natural Selection. In his opinion, theories based on the principle of Natural Selection explained everything as adaptation[40] and as the instinct or conscious intention of living organisms; Thompson otherwise would not agree that Natural Selection could account for the great diversities of form in nature. He wanted to demonstrate that "organisms are shaped directly by physical forces acting upon them" (Gould 1980, p. 37).

[39] The Dove unabridged version of 1992 is an unaltered republication of the Cambridge revised edition of 1942.

[40] Though not thinking that this was in the essence of Darwinism, Gould and Lewontin would agree somewhat with him against the idea of what they called adaptationism (see sub-section 5.2.5. on Selection).

In the chapter "On the Shapes of Eggs", Thompson asserted that "the pointed, conical egg of the guillemot is generally supposed to be an adaptation, advantageous to the species in the circumstances under which the egg is laid", i.e. unlike a more spherical egg, they will not roll off the narrow ledge of rock on which this bird is said to lay its solitary egg. However, he showed that other birds such as the plover or the sandpiper that breed in very different situations, also lay eggs that are conical. Thompson refused to believe, as the supporters of natural selection did, that there would be another explanation such as "that here the conical form would permit the large eggs to be packed closely under the mother bird" (Thompson 1992, p. 936). Instead, he argued that in the bird's egg, he had "an admirable case for direct investigation of the mechanical or physical significance of its form." From this analysis, he concluded that the form of the egg is due to the direct pressure of the oviduct. He argued that before the egg becomes rigid, it "is subject to pressure within the oviduct, which is an elastic, muscular tube, along the walls of which pass peristaltic waves of contraction." Thompson concluded that "The pointed eggs are those that are large relative to the tube or oviduct through which they have to pass, or in other words, are those which are subject to the greatest pressure while being forced along" (Thompson 1992, pp. 937-9).

When discussing the bee's cell in the chapter "The Forms of Tissues", Thompson described an experiment stated in the Penny Cyclopedia of 1835, in which G.H. Waterhouse showed that "when the bees were given a plate of wax, the separate excavations they made therein remained hemispherical or were built up into cylindrical tubes; but cells in juxtaposition with one another had their forms more or less prismatic." Thompson agreed with Bartholin's suggestion that "this result is due to mere physical pressure, each bee enlarging as much as it can the cell which it is a-building, and nudging its wall outwards till it fills every intervening gap, and presses hard against the similar effort of its neigbour in the cell next door." Thompson recognized that "Darwin had a somewhat similar idea, though he allowed more play to the bee's instinct or conscious intention" (Thompson 1992, p. 541).

From the above-mentioned examples, Thompson speculated on form achieved by growth (e.g. the pointed egg) as well as on form produced by organisms such as bees and their cells. In both ways he claimed that structural forces were responsible for the result and not mere chance (the egg's form preventing its own fall from the rocks) or instinct (the case of the bees).[41]

As Gould asserted, "we now know that physical forces are too weak, in most cases, to build form directly – and we look to natural selection instead" (Gould 1980, p. 38). Here, we can say that structural forces, although highly influential, cannot justify the adaptation of organisms, which is firstly caused by random mutations and secondly by selection; i.e. if the modified egg of the example above did not happen to be an advantage in the environment, either by having bigger chicks or because the egg will not roll down the rocks, then the large pointed egg, which resulted from the forces in the oviduct at the expense of the bird itself, would not prevail in the coming generations. All in all, we would say that, although structural forces cannot be the only factor during the transformation of forms, Thompson's physical forces are one of the ingredients in natural selection.

5.7.2. The Principle of Discontinuity: Saltationism versus Gradualism

Thompson asserted that Darwinian evolution "has not taught us how birds descended from reptiles, mammals from earlier quadrupeds, quadrupeds from fishes, nor vertebrates from the invertebrate stock" (Thompson 1992, p. 1093); he argued against those small changes in long periods of time which are thought to have produced all the forms extant in nature. He wrote: "An algebraic curve has its fundamental formula, which defines the family to which it belongs; and its parameters, whose quantitative variation admits of infinite variety within the limits which the formula prescribes." Therefore, "we never think of 'transforming' a helicoid into an ellipsoid, or a circle into a frequency-curve." In an analogical way, "we cannot transform an invertebrate into a vertebrate … by any simple and legitimate deformation" (Thompson 1992, p. 1094).

He claimed that a principle of discontinuity is "inherent in all our classifications, whether mathematical, physical or biological; and the infinitude of possible forms, always limited, may be further reduced and discontinuity further revealed by imposing conditions" (Thompson 1992, p. 1094). And further, "nature proceeds from one type to another among organic as well as inorganic forms; and these types vary according to their own parameters, and are defined by physico-mathematical conditions of possibility." In fact, he believed in the idea of **types** like Cuvier, the anti-evolutionist who believed in the fixity of species. Thompson thought that it would be of no use to seek the stepping-stones across the gaps between one "type" (species) and the other; men would indeed "seek in vain for ever."

Thompson did not argue against the theory of evolution by descent, only about its procedure. He claimed that his "geometrical analogies weigh heavily against Darwin's conception of endless small continuous variations; they help to show that discontinuous variations are a natural thing, that mutations – or sudden changes, greater or less – are bound to have taken place, and new types to have arisen, now and then" (Thompson 1992, p. 1094).

[41] In a Darwinian way of thinking, this instinct was once also mere chance, and because it happened to help the organism in its struggle for existence, it remained and prevailed in new generations.

As Gould put it, if for instance a certain adaptation would require 500 entirely separate modifications to attain a special kind of mimicry, then how did the process begin? In Gould words, “what possible benefit is step one [in 500 necessary changes] alone?” Gould asserted that Thompson’s answer to this question was that “organisms are shaped directly by physical forces acting upon them.” Thompson found it very unlikely that small changes on bones or muscles alone within a species would bring any benefit to the organism. A sequence of rapid “linked” (or simultaneous) changes would otherwise give the mutant organisms a possible advantageous difference in the struggle for existence; or in Gould’s words, that “Organisms jump suddenly from one optimum to another when the regime of physical forces alters” (Gould 1980, p. 38). This is the reason why some have classified Thompson as a Saltationist.

Trying to answer the question of how the species arose, Gould recalled Thomson’s insights into growth and agreed that “Complex forms are often built by a much simpler (often very simple) system of generating factors. Parts are connected in intricate ways through growth, and alteration of one may resound through the entire organism and change it in a variety of unsuspected ways” (Gould 1980, p. 38). As an example of this, Gould then described the case of basic forms of coiled shells, which change considerably when, in a computer program, three gradients of growth are modified.

5.7.3. The Effect of Scale

In Chapter II, entitled “On Magnitude” Thompson showed that structural forces act unequally in different scales and a stable structure can collapse if its size increases in all directions retaining its proportions and the materials used in the smaller scale. According to Thompson, some forces in action in a system often “vary as one power and some as another, of the masses, distances or other magnitudes involved; the ‘dimensions’ remain the same in our equation of equilibrium, but the relative values alter with the scale.” He asserted that “this is known as the ‘Principle of Similitude’[42], or of dynamical similarity, and its consequences are of great importance. In a handful of matter cohesion, capillarity, chemical affinity, electric charge are all potent; across the solar system gravitation rules supreme; in the mysterious region of the nebulae, it may haply be that gravitation grows negligible again” (Thompson 1992, p. 25). [43]

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[42] Galileo was the first to lay down the general principle of similitude. According to Thompson, Galileo argued that “if we tried building ships, palaces or temples of enormous size, yards, beams and bolts would cease to hold together; nor can Nature grow a tree nor construct an animal beyond a certain size, while retaining the proportions and employing the materials which suffice in the case of a smaller structure.”

[43] “For the smaller organisms, and in the individual cells of the larger, we have reached an order of magnitude in which the intermolecular forces strive under favourable conditions with, and at length

According to Thompson, “The effect of scale depends not on a thing in itself, but in relation to its whole environment or milieu; it is in conformity with the thing’s ‘place in Nature’, its field of action and reaction in the Universe” (Thompson 1992, p. 24). Besides, some physical forces “act either directly at the surface of a body, or otherwise in proportion to its surface or area; while others, and above all gravity, act on all particles, internal and external alike, and exert a force which is proportional to the mass, and so usually to the volume of the body” (Thompson 1992, p. 25). As a result of these forces, elephants, dogs and indeed all animals have acquired their particular forms.

Thus, there are certain structural constraints towards growth. In chapter II, “On Magnitude”, Thompson gave a good example of the high efficiency of the lobster’s structure and its constraints towards growth. Thompson argued: “The mechanical construction of an insect or crustacean is highly efficient up to a certain size, but even crab and lobster never exceed certain moderate dimensions, perfect within these narrow bounds as their construction seems to be. Their body lies within a hollow shell, the stresses within which increase much faster than the mere scale of size; every hollow structure, every dome or cylinder, grows weaker as it grows larger, and a tin canister is easy to make but a great boiler is a complicated affair. The boiler has to be strengthened by ‘stiffening rings’ or ridges, and so has the lobster’s shell; but there is a limit even to this method of counteracting the weakening effect of size. An ordinary girder-bridge may be made efficient up to a span of 200 feet or so; but it is physically incapable of spanning the Firth of Forth. The great Japanese spider-crab, *Macrocheira*, has a span of some 12 feet across; but Nature meets the difficulty and solves the problem by keeping the body small, and building up the long and slender legs out of short lengths of narrow tubes. A hollow shell is admirable for small animals, but Nature does not and cannot make it for the large” (Thompson 1992, p. 52).

According to Thompson, “To come back to homelier things, the strength of an iron girder obviously varies with the cross-section of its members, and each cross-section varies as the square of a linear dimension; but the weight of the whole structure varies as the cube of its linear dimensions. It follows at once that, if we build two bridges geometrically similar, the larger is the weaker of the two.” Thompson extracted this information from several engineers’ references such as “Comparison of similar structures as to elasticity, strength and stability”, a paper by Prof. James Thomson, of 1912.

altogether outweigh, the force of gravity, and also those other forces leading to movements of convection which are the prevailing factors in larger material aggregate.” (Thompson 1992, p. 58).

5.7.4. Fitness Measurement in Design: Integration of Parts and Structural Stability

The more complex a structure becomes, the harder the integration of its parts will be during transformation. Thompson would say that several mutations are often needed to retain the effectiveness of the structure and thereby give the organism a chance in the "struggle for existence"; i.e. by altering a single part of an organism, the whole will probably collapse. Thompson therefore concludes that an organism changes from an optimum to another whenever the structural forces alter. However, a Darwinian would say that the resultant form from such a process would never come into existence, evolution has no intention and natural selection is blind. The selection mechanism works only on the "survival of today", even if some changes would lead the species to extinction in the future. Natural selection, though, cannot overlook the great internal (structural) and external (environment) structural constraints.

Regarding scale, structural forces and stability, one can say that a structure cannot just increase in proportions; by increasing the size of a structure, one ought to analyze the forces acting on the structure according to the law of dynamical similarity, i.e. considering that some forces in action in a system can vary in power such as masses or distances while other forces vary according to other dimensions. Varying scale and keeping the same material, such as the bones of an organism or the iron-girder of a bridge, can give rise to the total collapse of the structure; however, by changing materials and/or technique, one may change the scale of an artifact while keeping its proportions; e.g. without needing to produce an elephant from a dog.

In the case of design, the idea of randomness, blindness and intention have already been discussed (see earlier sections). But in view of the discussion on these themes earlier in this chapter, we argue that a fitness measurement has to be considered in the model for the re-use and adaptation of design precedents. This fitness should refer to the two above-mentioned factors: integration and stability; i.e. a fitness evaluation should be possible indicating the effectiveness of the structure in relation to the integration of its parts each time changes occur in the project, as well as indicating the effect of the structural forces on the overall structure, in particular when changes are effectuated on scale.

5.8. Chapter Conclusions

As already mentioned in Chapter 2, the analogy between the process of re-use of design precedents and evolutionary models pursued in this research is intended to help in developing a system to find a representation of the process of re-use of design precedents. It refers to the designer's mind (processes of use and adaptation) and the projects.

5.8.1. Summary

The Darwinian model showed us certain aspects of the process of evolution in Nature; namely, that organisms reproduce and pass their characteristics onto their descendants; among their descendants variations occur; due to a shortage of environment resources, a struggle for survival will occasionally happen; the pressure exerted by the environment on the organisms leads to the survival of the fittest organisms for the specific situation; the fittest organisms reproduce and pass their adapted characteristics onto the descendant generation.

Variation and Selection

Proceeding from the Darwinian model, we have seen that the randomness during the generation of variations in nature versus the purposefulness of architectural designs is the most striking difference between evolution and design.

We have reviewed the heuristics that guided Darwin in developing his evolutionary model and have discovered that an "evolution under domestication" could help us to solve some of the antagonisms between evolution in nature and architectural design: breeders are in charge during "evolution" under domestication; they have a purpose, i.e. an objective to be achieved in hybridizing organisms and plants. In an analogous way, architects are also in charge when recalling design precedents and when adapting them to specific situations.

In nature, but also under domestication, selection occurs in the physical environment, while in architecture designers try to 'get it right first time' in a simulative environment. It goes without saying that architects and clients would not have the time or financial resources to rely solely on a post-occupancy evaluation (which does not mean that POE is not a valuable tool). In other words, architects have the purpose of producing a fit design. During the design process, a simulative environment comes into existence as a moment of rapid change in a punctuated equilibrium within an isolated geographical territory; i.e. an island where migrants (design precedents) are selected to become part of its initial population. However, in the long run, there is no ultimate goal. In other words, designers can hardly ever foresee the paths that they will follow.

On the genetic level, it was Embryology and the genes of development that introduced us to mechanisms that could become the analogue for the transference of characteristics from one design to another. However, the exchange between d-genes of different kinds of artifacts in design can only find its analogue in genetic engineering, which is the only way an organism will receive a gene of another species. Therefore, in nature, the idea of species is more defined than in design[44].

In nature, the timescale of evolution refers to millions of years, while in architecture we refer in particular to a designer's professional lifetime (or a part of it), and to a thousand years of cultural development.

The transference of "regulatory d-genes" from design to design showed us a pattern of change through time. However, this transference faced certain kinds of problems in relation to the fitness of the structure that would acquire the d-gene. The main problems concern the integration of the parts and the change of scale and materials, which together affect the structural stability of the design. These two issues were both studied in biology by Thompson (who referred also to Galileo, Aristotle, and others). Even with some of his premises in relation to natural selection discredited (see section 5.8.), Thompson has provided us with examples of fitness that are very closely related to design due to the consideration of the interaction of forces on structures, as well as of the interdependence of elements in the overall structure. The study of linkages between genes[45] confirms in part this interdependence.

Moreover, the explanation of the two levels of evolution, ontogeny and phylogeny, gave us guidance in building the total system: ontogeny, being the development of projects, and phylogeny being the historical account of a lineage of projects.

Our intention in revisiting evolutionary biology was to find a good representation for the problem of the re-use and adaptation of design precedents, since the present representation in evolutionary computation and derived applications (see Chapter 4) are not satisfactory in helping to solve this specific problem in architectural practice. Now, we present 10 assumptions related to the similarities and differences of biology and design with the intention of summarizing the ideas put forward in this chapter.

5.8.2. Ten Evolutionary Assumptions:

This journey through the evolutionary model brought about the following assumptions:

1. A final design representation expresses its "phenotype", while the "genotype" is expressed in the design process (i.e. by all the "recessive" features which were not expressed because of their poor fitness).

[44] One of the main characteristics of a species is that its organisms cannot produce fertile offspring with organisms of another.

[45] Gene linkages which are responsible for the appearance of some characteristics together in an organism and therefore in the alteration of the set of characteristics involved if one mutates.

2. As “breeders”, designers recall by “Artificial Selection:[46]”
    a. They recall from memory and/or from archives;[47]
    b. They recollect parts or even a whole design precedent according to the matching features of its “phenotype”.
3. Such as in Nature, the design is generated by a set of instructions that guide its development from zygote to organism, from sketch to the detailed project.
4. In the architectural domain, the regulatory d-genes guide growth, differentiation and morphogenesis; the structural d-genes fulfill the “orders” of regulatory d-genes according to their own “technique” and “materials”. In design, the description of characteristics in a project can be two-fold: on the one hand, the configurational features of the elements involved (regulatory d-genes); on the other hand, the structural, material, technological description (structural d-genes).
5. “D-genes” may be transferred from one design to another, even if they belong to another “species”.
6. “Gene Linkage” is the tendency of some features to appear often in combination with other features such as the support arches of Santiago Calatrava’s bridges and their cables or blades.
7. There are three units of selection:
    a. The genes: not as Dawkins proposed, but we will consider the selection of the expression of genes. In other words, the selection of features (phenotypes) by the designer carries with itself the genetic instructions;
    b. The organism: selection of a project;
    c. The group: selection of prototype.
8. Punctuated Equilibrium is the mode of evolution. It is assumed that:

[46] We use the term “Artificial Selection” in this research in the same manner as Charles Darwin: the purposeful selection of organisms for procreation by breeders with the intention of modifying generations of animals and plants to satisfy men's goals.
[47] Natural selection is composed of a series of events such as mating (including already a sexual selection), reproduction, environmental pressure and struggle for survival. Architects do not try out all the possibilities available to them and then select the best version, they work according to their requirements, the imposed constraints, as well as a ‘hunch’.

   a. The design process happens in a simulative environment, a fictive island, where design precedents are recalled to be part of the "gene pool";

   b. Design precedents "breed" to form a new design.

9. There are two levels of evolution:

   a. "Phylogeny": the evolutionary history of a lineage, which can also be used in historical research and as an educational tool;

   b. "Ontogeny": the life history of an individual design, both "embryonic" and "post-natal"; i.e. the development of a project by architect(s).

10. The fitness of a project that re-uses and adapts design precedents relies on the integration of its parts, on its form-function configuration and on the analysis of the structural forces at work on the overall structure.

The biological analogy seems to be a fruitful analogy in discussing how the elements of design precedents can be adapted and possibly recombined during the design process. The reevaluated and sometimes modified biological concepts will be applied in the following chapters to develop our model for re-use and adaptation. However, some of these concepts, such as that of "artificial selection", will not be applied further in this dissertation. They were discussed here because they show interesting aspects that may support a future development of the model.

Next, Chapter 6 will describe the P.O.M. system, and Chapter 7 will illustrate how the concepts selected in evolutionary biology together with the P.O.M. system can possibly help in developing an evolutionary model for design.

CHAPTER 6

CONCEPTUAL STRUCTURE OF THE QUALITATIVE EVOLUTIONARY DESIGN MODEL

This chapter introduces the P.O.M. Reasoning System as a tool to describe the instructions of the architectural genes.

As Le Corbusier claimed, first one sees, then observes, and finally perhaps discovers something. Intelligent architects will always be needed, among other reasons, because of their powerful way of recognizing and analyzing features in artifacts that may improve the fitness in their designs; In our opinion, there is no reason to provide a model to do their thinking for them, but to support their activities.

In the previous chapter, we searched evolutionary biology for concepts and theories that would help in developing a design model for the re-use of design precedents: we formulated ten assumptions. Our point of departure in this chapter is the transference of genes, as an analogue for what is transferred from one design to another.

This chapter will describe how "architectural genes", which we will call d-genes, could be described and transferred within our evolutionary design model. In other words, there are two main issues to be solved in the making of our model. We need to describe firstly what a gene could be in the architectural world[1] and how it could be constrained and linked with others, and then secondly, how it could be transferred.

[1] To avoid misunderstanding, genes in design will be called d-genes.

Due to the fact that a design precedent is often obtained from a metaphor or analogy[2], the question is: how can we provide a model that shows this transference from one field (one species) to another?

The first issue, the description of the architectural genes, is solved with the support of the Performance, Operation and Morphology reasoning (P.O.M.) system developed by Alexander Tzonis in his article "Huts, Ships and Bottleracks: Design by Analogy for Architects and/or Machines". The model contains two kinds of d-genes: "regulatory d-genes" and what we will call "structural d-genes". The P.O.M. system is used as a tool for the description of instructions in both domains. The second issue is solved with the notion of regulatory and structural genes from the biological evolutionary model as described in the genetic experiments with the Drosophila melanogaster in Chapter 5.

We claim that the notions of regulatory and structural d-genes together with the P.O.M. system can provide us with a pragmatic rationale for our model.

This chapter is subdivided into four sections. Section 6.1 will introduce Tzonis' P.O.M. system, and will examine the system to see how it can contribute to the development of a model for the re-use of design precedents. Section 6.2 will try to work out the relations among the P.O.M. concepts and the biological concepts to form the basis of a provisory model for the re-use of design precedents; section 6.3 will provide a brief summary of the findings and the conclusions.

6.1. Introduction to the P.O.M. System

According to Tzonis, the P.O.M. system is intended to deal with the problem of representing architectural knowledge, the basic concepts and structures which capture information contained in precedents, principles, and rules of architecture. Tzonis made this knowledge fit into a reasoning mechanism that departs from a program of architectural needs, exploits knowledge and leads to design products (Tzonis 1992, p.147). Afterwards, he translated this reasoning mechanism into a framework, which aims to represent design explanation as well as design generation.

6.1.1. The Power of Description

"A core of an intelligent design system," wrote Tzonis, "should represent significant aspects of how artifacts are made out, how they work, what they do in respect to what has to be done, how they fit into the environment and how all these aspects relate to each other" (Tzonis 1992, p. 147). The P.O.M. system was developed to address those aspects.

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[2] i.e. the desired characteristics belong to a class of objects outside architecture.

The framework of the P.O.M. system relies on four main concepts, which are: "performance", "operation", "morphology", and "context". "Performance" refers to the conditions that a prospective building is intended to bring about, or the degree to which a scheme of building brings these conditions about (Tzonis & Heintz 1995).

"Morphology" is used to refer to the formal aspects of a building or an urban area (e.g., Steadman 1983; Tzonis 1992; Jeng 1995, p. 179). It refers to the artifact's attributes, its spatial composition and its material structure (Tzonis 1992, p. 147).

"Operation" refers to the process that comprises the use of a building, and the role of form in this process (Tzonis & Heintz 1995; Jeng 1995, p. 179). It refers to the way the morphology "controls, holds or channels people, objects and equipment associated with the activities planned for the building, i.e. in this sense, buildings contain operations (Tzonis 1992, p. 147)."

"Context" generally refers to the state in the external world. It is the whole situation, background, or environment relevant to a particular event (Jeng 1995, p. 188). According to Tzonis, "context" acts in such a way that "if a corridor has a specific shape X [morphology]; then people can safely evacuate the building [operation-performance]; unless the lighting conditions are of type Y [context]" (Tzonis 1992). However, the concept of context is not much further developed in this article.

"The kernel of the framework," wrote Hoang-Ell Jeng, "the performance[3], operation[4] and morphology[5], has been applied to examine architectural thinking (Zandi-Nia 1992; Fang 1993; Li 1993; Yu 1994) and architectural education" (Tzonis & Heintz 1995). Jeng used it as a tool for representing normative descriptions (Jeng 1995, p. 180), while we shall apply the P.O.M. system as a structure of knowledge due to its descriptive power in the expression of architectural thinking.

Design generation, "morphogenesis", seems to be the result of the interaction of these factors. According to Tzonis, it "starts with performance and terminates with form." Morphogenesis, wrote Tzonis, answers questions such as "if a building has to be highly safe (performance-norm), what kind of circulation of people has to occur (operation)? And if this circulation pattern has to take place, then, what kind of configuration the corridor needs to have (Form)?" (Tzonis 1992, p. 148).

The concept of "frames" as used in Artificial Intelligence (Minsky 1997) was used and expanded to represent design reasoning through these four concepts. "Frames," wrote Tzonis, "are a powerful data structure to capture standard cases,

[3] i.e. what the artefact does in respect to what has to be done.
[4] i.e. how the artefact works.
[5] Morphology is how the artefact is actually comprised.

and exploit law-like facts of architectural knowledge." Nodes and links, i.e. objects and the relations between them, compose the structure of frames. "These nodes and links," claimed Tzonis, "make up a kernel of design thinking which gets hold of constants, facts. Nodes and links spread out of this kernel to account for particular fact instances through slots, terminals which can receive specific values and keep track of differences and change" (Tzonis 1992, p. 149) (see Figure 1).

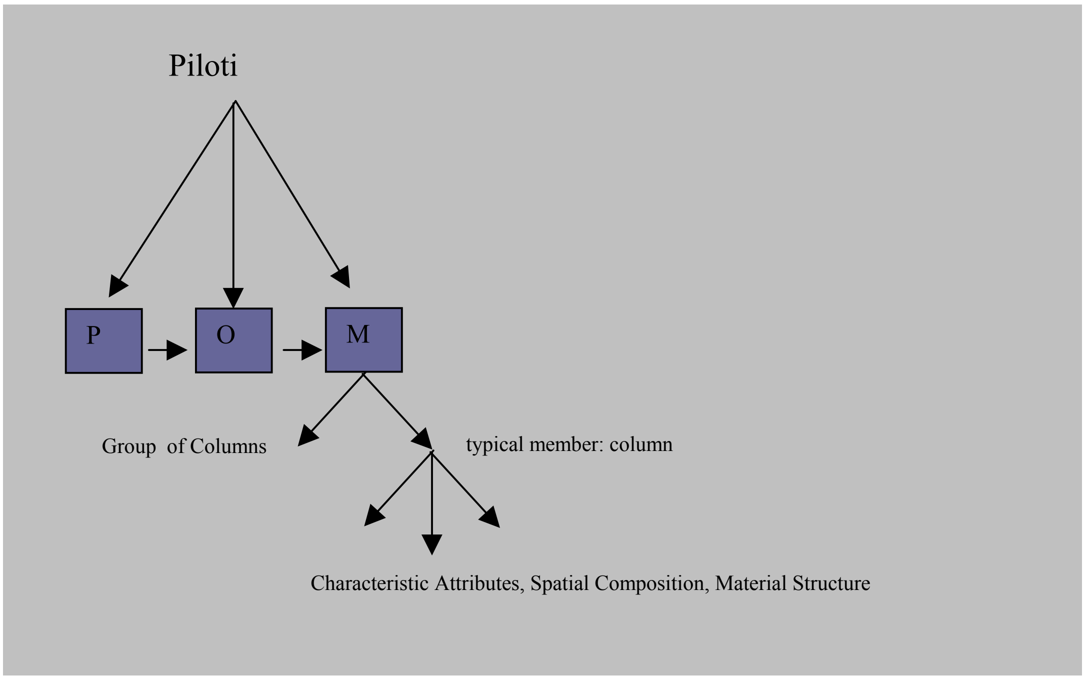


Figure 1: Nodes and links spread out of a kernel to account for particular fact through slots

Tzonis illustrated how this frame works based on the case of Le Corbusier's Unité d'Habitation. He claimed that Le Corbusier conceived the building's spatial concept, grasping from the outset "its fundamental aspects". Inventing a truly complex multi-functional unprecedented form, he synthesized out of and in analogy to a multitude of precedents[6], "recalling these precedents from memory, examining them, dissecting them, trying them and recombining them, putting old tools to new uses and old ones in new compositions (Tzonis 1992, p. 145)."

Would this P.O.M. system be effective within our model for the re-use of design precedents? What are the advantages and shortcomings of this system when applied in our model? The next sub-section will briefly evaluate the potential of the P.O.M. system in relation to its possible contribution to our model for the re-use of design precedents.

[6] Examples are the savage hut, the liner, the winebottlerack, the Greek temple, etc.

6.1.2. Examining the P.O.M. System

According to Tzonis, "The P.O.M. system is first intended to deal with the problem of representing architectural knowledge, the basic concepts and structures which capture information contained in precedents, principles, and rules of architecture" (Tzonis 1992, p. 147). Although proposed for design generation as well as to explain designs, the P.O.M. system remained on the level of description of parts.

Referring to the direct application of the P.O.M. system in our model, some problems were identified for the re-use and adaptation of design precedents:

1. It describes a set of actions, but does not start the process by itself.
2. It does not propose how the multitude of pieces of information will relate to each other – e.g. information about the overall performance of the building.
3. It approaches the problem of conflict in the integration of the recollected parts with the design in hand, but it does not solve it.
4. It does not approach the problems of adaptation and fitness to the environment.
5. It does not clarify the difference in the transference of element configurations and structural solutions, for example, in the case of Le Corbusier's piloti; it is presumably transferred from the "savage hut". But if people search for what was transferred, they will understand that it was its configuration and not its material, technique and scale.

Despite the above constraints, the Performance, Operation and Morphology reasoning system provides a good description of the features to be transferred, adapted, and/or recombined.

6.2. Toward a Model for the Re-Use of Precedents

Proceeding from the interaction between "regulatory d-genes" and the "structural d-genes"[7] and their potential for representing transference of design precedents from one artifact to another, a representation of the process of re-use of precedents will be explored. In this model, the P.O.M. reasoning system shall be applied as a descriptive device to make the instructions of the d-genes explicit.

Besides the commands to transfer and adapt features from one design to another, the "genetic" framework should contain good descriptions of the features

[7] To avoid misunderstandings in our use of the analogy, we refer to Chapter 2; we also refer to Chapter 5, which describes the similarities and differences between our use of genes in design (d-genes) and the action of genes in nature.

to be transferred and adapted. This section will describe the way that the Performance Operation and Morphology (P.O.M.) reasoning system is applied within our model for the re-use of design precedents. We claim that the P.O.M. system can link the main factors involved in the process of re-use of design precedents and, therefore, it seems a powerful method of description.

6.2.1 The Role of the Architectural "Genes"

When we say that a regulatory d-gene is being transferred, we mean that the general layout configuration of that feature is transferred. But there is also the transference of some measures giving the minimum and maximum ranges of the elements composing the feature; in particular those which, if not respected, will either disturb the good operation of the element or impede the feature to perform according to the requirements. For example, a piloti has to be at least one story high in order to support the circulation of people.

The structural d-genes are represented by databases that support the calculation for the specific size of the structure according to the configuration given by the regulatory d-genes, its material, technique, position and scale. In our model, structural d-genes may belong to related inventions like the Immeubles Villas and the Unité d' Habitation that will be described in the next chapter.

Without the structural d-gene, form could assume all sizes and connect all spans. The structural d-genes should take into account internal forces (for example: the weight of the object itself), external forces (for example wind), as well as site allocation (for example the slope of the terrain or the quality of the soil). It should contain all necessary knowledge concerning specific materials and techniques, such as construction methods using reinforced concrete.

In nature, "structural genes" will produce the fruit fly's eye and not the camera-like eye of the mouse even if the fruit fly's regulatory gene is substituted for that of a mouse (Maynard Smith 1998; Ridley 1999). In design, the instructions that a structural d-gene contains refer to materials, techniques, growth and the distribution of forces through materials bounded by different techniques and technologies. It refers to the physical context, such as site peculiarities and the endurance of the artifact to forces produced, for example, by the wind; or, in the particular case of bridges, when facing forces derived from cars moving on a bridge. As mentioned above, the structural d-genes are represented by databases integrated into a program which will generate the features conforming to the regulatory genes' descriptions. It seems logical that if such a d-gene is transferred then there will also be a transference of the feature's geometrical configuration that belongs to the regulatory d-genes; however, the functional configuration of the feature does not need to be transferred. The adaptation of a structural d-gene should be tested by a fitness function.

6.2.2. The P.O.M. System's Contribution to the Proposed Model

The P.O.M. system is our tool for the description of all d-genes. In the model for the re-use of design precedents, an artefact is described on two levels: the configurational and the structural. The configurational description provides facts about building element(s) according to its position, relation among them, minimum height, as well as intentional function (topology) and is contained in the regulatory d-gene. The structural description provides facts about the stability of the structure within the specified techniques and materials. It is contained in the regulatory d-genes and will probably be described in the form of databases.

The P.O.M. system is used as a tool for the description of the performance, operation and morphology of the architectural regulatory (or hox) genes. In other words, it is a tool to describe the general principles, position, maximum and minimum ranges and arrangements that are transferred from one design to another at a pre-parametrical stage. On the other hand, P.O.M. is used as a tool for the description of the architectural structural genes; as such, it is a tool for the description of the principles within a concrete design structure with its material and technical constraints at a parametrical stage. The performance of a structural d-gene is high when it helps to create a stable structure that satisfies the specified requests of the regulatory d-gene.

The P.O.M. system describes how some factors probably came about and how the designer (probably) reasoned when searching for solution(s) for new designs. It can also help in the recollection of a design precedent by specifying either performance or operation, as in the case: "I need performance 'x' in my design. Do I know any artefact that has this performance?" If the answer is yes, then it may be desirable to bring its form and operation to the design.

The case of Le Corbusier's "savage hut"[8], can be represented as the transference of the regulatory gene of the piloti into his designs. Some actions were necessary in the transference between the act of recognition and that of application.

1. First, it was necessary to indicate what was transferred and whether the structural d-gene was transferred as well. Was Le Corbusier planning to re-use the "piloti of the savage hut" in timber? If yes, which assemblage technique did he use? This was not the case; he used it in reinforced concrete.

[8] In the next chapter, we are going to see that the transference was not so direct or linear as it is pictured here; however, for the initial explanation of our framework, this information seems sufficient.

2. Second, the context, the real situation where the design precedent must be applied, imposes its constraints: be that of scale, or of plot irregularity or the dynamic forces to which the building is submitted, such as wind.
3. Thirdly, the elements of the feature must be integrated into the rest of the design.
4. Fourthly, an evaluation of structural fitness must take place, to check the integration and stability of the overall structure as well as to see whether the structure meets the requirements of the regulatory d-genes[9].
5. Fifthly, the fitness of this feature must be tested in relation to the whole design. In other words, to see whether the new feature will improve or diminish the overall performance.

However, not only can the regulatory d-genes be transferred, the structural d-genes can too. Being an instruction toward a structural solution[10], their transference is constrained by factors of the regulatory d-genes. They can be disconnected from its intentional function such as in the case of a bridge becoming a roof, but they certainly respond to the geometrical configuration of the architect.

Another kind of constraint refers to the integration of the parts. After the transference of the d-gene, it must fit into the new design; it must interrelate with the expression of other d-genes.

Next we explore the idea of linkages as a solution to face these constraints. Genes makes linkages in nature so that some characteristics appear in general together, such as the color of the eyes, skin and hair of an organism.

6.2.3. Gene Linkages

One may ask how, in a complex design, do the d-genes constrain one another or how are they linked to one another to form the total "organism?" In nature, there are regulatory genes that define the regions, the axes and the order of development. It goes also from the general to the specific. It is not our intention to set an order in the way a building must be created; however, regardless of how the architect proceeds, he/she must fit the parts to the whole.

To explain the necessity of a gene linkage representation in architecture, we introduce Le Corbusier's five points for modern architecture, which are: the piloti, the free plan, the free façade, ribbon windows, and the roof garden.

[9] A building can have a well-integrated and stable structure, yet fail to satisfy the users or the clients.
[10] Such as the use of arch and cables to suspend the deck of Santiago Calatrava's bridges or the use of the torsion box to deal with asymmetric forces acting on the deck of the bridge, such as in the cases of the Lusitania and Alamillo Bridges.

Far from presenting an extensive description of the d-genes of these features, we shall focus on their linkages, their dependencies and condition to favor the appearance of the other. We shall give just a rough description of the content of these "genes". But first we want to explain something about the nature of two of those architectural points: the free plan and free façades.

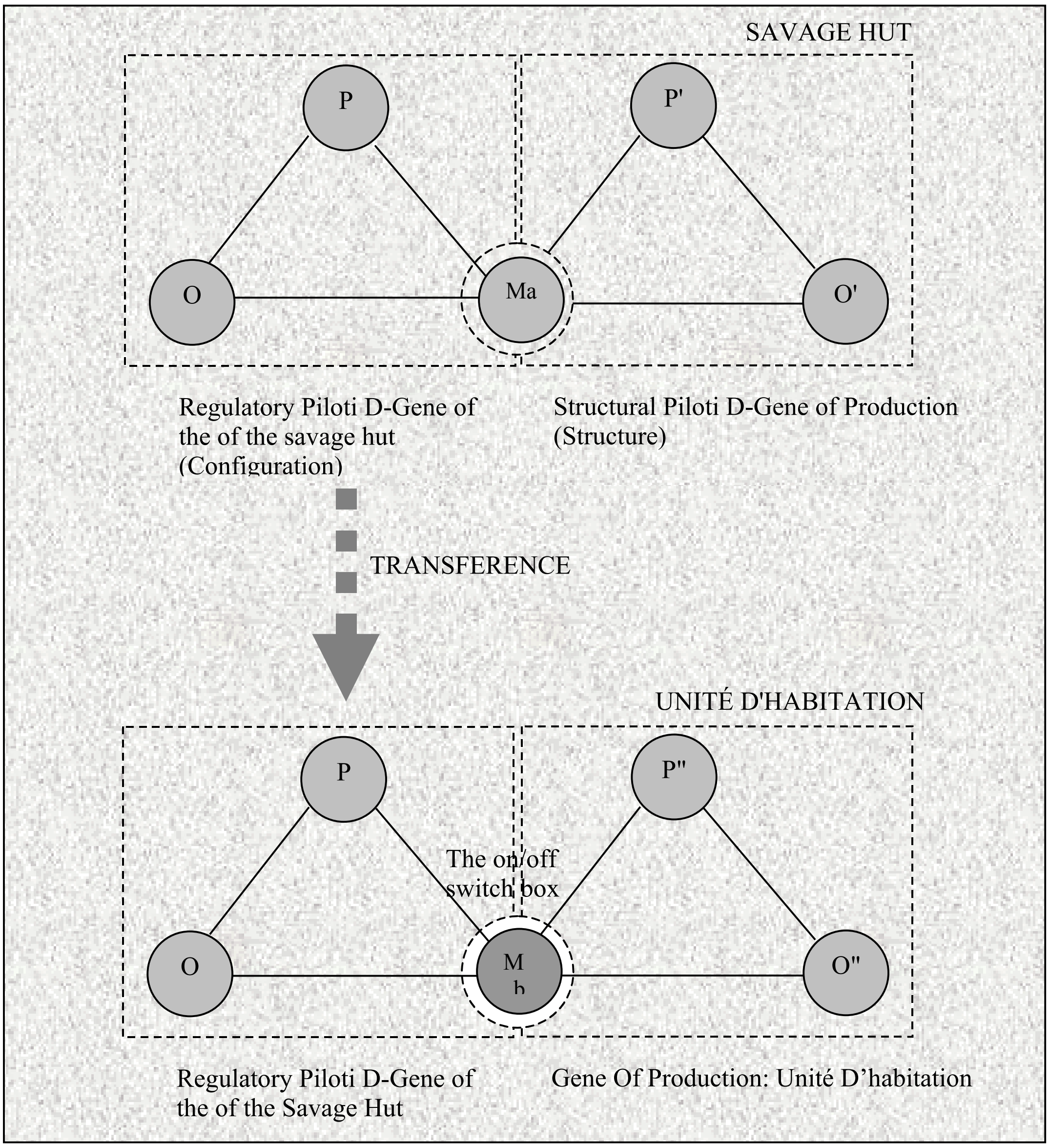


Figure 2: Transference of Regulatory Piloti D-Gene

Free Plan and Free Façades

One might wonder how one can call a "free-plan" a gene if the name of this principle implies that there are no rules, i.e. it is free. In his essay "Free Plan versus Free Façade, Villa Savoye and Villa Baizeau Revisited", Risselada asserted that the free plan and the free façade are organized according to their own laws, whereby the façade is coordinated by the abstract system of 'regulating lines' (Risselada 1988, pp. 55-63). The façade was freed from structural elements, but Le Corbusier made use of elements such as the brise-soleil and ribbon windows to compose it. Also, the plan layout of Le Corbusier's houses is free from most structural barriers, i.e. the spaces created are not contained between limiting bearing walls; however, his plans have a vocabulary. Le Corbusier used certain features that he recalled and adapted again and again to perform his "architectural promenade". These features were: the ramp, the bridge, the spiral staircase, scissor staircase, the double story height of the living rooms, and the curved wall of the solarium or of the bathrooms.

The Linkages of the Five Points for a Modern Architecture

Returning to the explanation of linkages, we note that the piloti, i.e. a column and beam (or slab) structure of Le Corbusier's Dom-Ino system, has a crucial role in constraining the appearance of the majority of those features.

Taking firstly the free façade, one can clearly see that the freedom of composition depends on positioning the structural elements in cantilever. In other words, bearing walls constrain freedom of composition but so do columns. Considering Le Corbusier's preference for a column-and-beams structure, whenever freedom was necessary in the composition, the piloti had to be placed in a plane parallel to the façade, on the internal side of the building and not within the plane of the façade itself.

Secondly, there is no free plan, if the design is constricted within a narrow framework of bearing walls. The freedom in layout was made possible by the use of a column and beam structure; i.e. the structure of the piloti.

Thirdly, in the same sense that there is no free façade where there are bearing elements within it, there will be no possibility of running a ribbon window on the whole extension of the façade, if structural elements are placed in the plane of the façade.

The roof garden is the exception. There is no direct pre-condition between the configurational use of the structure of a piloti and the design of a roof garden, except that the roof-garden depends then on a concrete structure to support it and on some technical innovations to keep the concrete moist as well as to drain the excess rainwater.

As in nature, it seems that some d-genes seem to work linked in their phenotypic expression.

6.3.Contribution to the Qualitative Model: Conclusion

This chapter has presented the dynamics of the re-use of design precedents based on a genetic structure of commands superimposed on the P.O.M. system.

In summary, we have seen that sometimes only a part of a precedent is used, such as the piloti of the "savage hut". We have also seen that not all information contained in the part transferred, such as in the case of the piloti, is carried forward to the new design. In this case, the regulatory d-gene refers to this transferred information. It switches the structural d-genes "on" and "off" in order to construct buildings on stilts, just as the small-eye hox gene of a mouse is responsible for the making of a perception organ in the embryo of the fruit fly, determining the time of development and the place. The structural gene determines the "material", "assemblage technique", and "technology" (see Fig. 3).

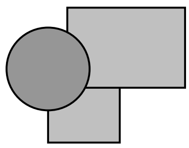
Regulatory D-Gene			Structural D-Gene	
Performance (P)	Operation (O)	Morphology (M)	Operation (O")	Performance (P")
User's Satisfaction; Architect's Satisfaction	Geometrical Configuration Topology (plan layout)		Distribution of Structural Forces (according to the selected technology)	Structural Stability Facilitate Topology

Figure 3: The Framework of the Regulatory and Structural D-Genes

In the aforesaid biological experiment, the "structural gene" of the fruit fly's eye was clearly different to that of the mouse. The fly therefore developed a perception organ in the time and place "ordered" by the regulatory gene; however, it resulted in the development of a perception organ which was typical of a fruit-fly (Maynard Smith 1998).

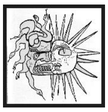
Gene linkages constrain one part of a feature in relation to other parts of the design. We argued that some d-genes constrain others. These constraints are often preserved by means of linkages[11], such as the position of the columns in relation to the façades in order to provide "free façades" or not. These linkages form clusters that represent inventions such as that of the Citrohan house.

In the next chapter, we will illustrate this qualitative model with the help of a case on the development of Le Corbusier's Unité d'Habitation. We will see how genetics and the P.O.M. system can represent the re-use of design precedents. Undoubtedly, it is not our intention to make a "recipe" for all the parts of a design. "Recipes" are only necessary for those parts that are mainly re-used.

[11] This became clear during the experiment with the Drosophila melanogaster.

CHAPTER 7

ILLUSTRATING ASPECTS OF THE EVOLUTIONARY DESIGN MODEL



The Case of Le Corbusier's Unité d'Habitation of Marseilles

At the end of Chapter 3 on J.J.P. Oud's social housing, we claimed that the evolutionary analogy could probably support the re-use of elements of design precedents in that new organisms "re-use" the genes of their ancestors. We explored the traditional and current use of the analogy, which is presented in Chapter 4; however, the analogies reviewed did not facilitate the description of the phenomenon of change through the re-use of design precedents. Therefore, we explored evolutionary biology, genetics and embryology. We decided to explore this reference because of the lack of architectural theories that could systematically help us to represent the process of re-use of design precedents carried out by architects over the years. The analogy serves as a heuristic device, and obviously, it would be of no help in developing the model if we had not found any fruitful similarities between the mechanisms of "re-use" in evolutionary biology and design.

Starting from our architectural questions, we explored concepts and rival theories that resulted in ten assumptions to help us in developing our model for the re-use of design precedents. After a long exploration in the field of biology, Chapter 6 provided the center of the proposed model; it showed how the concepts of genes, linkages and recombination could help in representing the architectural phenomenon. Chapter 6 also presented a system for the description of instructions, which can support re-use and will set the basis for our "architectural gene".

This present chapter presents our illustration case; it draws from the conception of Le Corbusier's Unité d'Habitation (U.H.) of Marseilles; it will show how our qualitative model is applied to represent the process of re-use of design precedents in architecture. The model does not attempt explain how architects think but represents the facts in a way to allow insights into this process.

The case study is carried out as follows: after a description of the Unité d'Habitation, we will explore three innovations, which we equate with species, and analyze their features and the presumable transference of those features from one innovation to the other. These innovations are:

1. Maison Dom-Ino 1915-1919
2. Citrohan Houses 1919-1927
3. Immeubles-Villas 1922-1928

It will be shown that certain features of these inventions are often re-used and that in this process, they are modified and recombined. Therefore, we take some of these features that we provisionally equate with architectural genes and verify their evolvement and linkages with the rest of the building. These features are:

1. The linkage: Bottle, Wine Bins and Bottleracks
2. Roof Gardens
3. Piloti

Proceeding from an analysis of the phylogeny and ontogeny[1] of the Unité d'Habitation, this chapter shows how the application of the ten assumptions helps in developing a model. In other words, armed with analogy between the process of re-use and the biological evolutionary models (Chapter 5) as well as with the structure of our architectural gene (Chapter 6), we shall illustrate aspects of the re-use of design precedents in Le Corbusier's designs, which may contribute to the production of an evolutionary design model. We will speculate on the ontogeny of the Unité d'Habitation of Marseilles; in particular, on the re-use and recombination of features derived from earlier projects or analogies; and on the actions necessary when re-using the features.

As explained in Chapter 2, we use the analogy between the process of re-use of design precedents and the biological evolutionary models as our heuristics. In other words, we think that the process of re-use of design precedents and their modification over the years can be described by structuring the process with some of the processes and the ordering of arguments of the evolutionary model and that this description can provide insights into the study of this architectural phenomenon. This chapter will present in its conclusions a set of these insights.

Next, section 7.1 will describe the Unité d'Habitation; section 7.2 will describe projects (organisms) of three specific innovations (species), which contributed to a great extent to the conception of the Unité d'Habitation; and section 7.3 will deal with the U.H. genome – in other words it will describe some architectural

[1] See Chapter 5 for definitions.

genes/principles that contributed to the invention of the Unité d'Habitation. In particular, it will describe their hypothetical origins, their use and adaptation as well as their linkages and recombination. Section 7.5 will (hypothetically) describe the ontogeny or development of the Unité d'Habitation. Finally, section 7.6 will provide the chapter conclusions.

7.1. Description of the Unité d'Habitation of Marseilles (1945 - 1950)

The Essential Joys: Sun, Space and Verdure

Le Corbusier's inventions combined innumerous concepts within a fascinating network that involved different levels and domains. General ideas were carefully translated into architectural elements, which very often evolved in combination with others, such as the elements that compose the five points for modern architecture or the elements of his architectural promenade. Le Corbusier had a very peculiar way of looking at the object of design; if, on the one hand he proceeded from extremely general concepts trying to provide solutions for the primary needs of lodging, work, cultivation of body and mind, and traffic, then on the other hand, he claimed to have proceeded from the concept of the kitchen as a modern hearth, from which the rest followed naturally.

The Unité d'Habitation is a fundamental part of Le Corbusier's "vertical Garden City" or La Ville Radieuse for the industrial society, which stood in contrast to Howard's "horizontal" Garden City. The idea behind his "vertical garden city" was to liberate soil for nature and public parks instead of developing a green city based on private gardens. The tall buildings in his plans were not a means for land speculation as it was in the United States; but, as William J. R. Curtis asserted in his *Le Corbusier: Ideas and Forms*, it was a means to free land for "the essential joys of light, space and greenery" that should be available to all (Curtis 1975).

Le Corbusier claimed that unités could be constructed to replace whole districts or even towns. Erected two to three hundred meters apart in grounds laid out as parks, they would be the realization of Le Corbusier's Green Town, La Ville Radieuse (LeCorbusier 1953, p. 58).

The first unité to be constructed was the Unité d'Habitation of Marseilles. It was, according to Robert Furneaux Jordan, the child of a 40-year gestation (Jordan 1972, p. 79)[2] .According to Le Corbusier in his *The Marseilles Block,* the allied

[2] Thus, the assertion in his The Marseilles Block that the unité started out with the concept of hearth and home (337 hearths, 337 homes) and that the rest followed naturally (LeCorbusier 1953, p. 42) did not necessarily mean that he created all the parts of the Unité d'Habitation either from

armies were already closing in on Berlin at the end of the Second World War when the first Minister of Reconstruction approached him to design one of his “omnibus houses” for the people of Marseilles. Le Corbusier accepted it on condition that he would be freed of all building regulations in force: a wish that was granted. Thus, from 1945 to 1950, Le Corbusier worked with his associates[3] to create a prototype, which was to be the “forerunner of all sorts of things” (Le Corbusier 1953, p. 7). Their project survived ten successive governments and seven different Ministers of Reconstruction. This building block was inaugurated in 1952.

According to Curtis, Le Corbusier’s unité, a *‘unité de grandeur conforme*’ (unité of proper size), was an abstract prototype containing an optimum number of people[4]; in the case of Marseilles, approximately **1,600** inhabitants. It would contain a variety of apartment sizes; a middle-level shopping street; and other communal facilities such as a common roof garden. Like Jordan, Curtis also claimed that the unité “reflected years of rumination on collective living. For example, the apartments were to have double-height living rooms linked to single-level bedrooms and kitchens by an overhanging gallery”; this arrangement, claimed Curtis, descends from the Immeubles villas[5] of 1922 (Curtis 1975, p. 169).

The first unité that was constructed was the Unité d’Habitation of Marseilles and it is the one that will be described further.

7.1.1. Context: Initial Settings and the Location of the Unité d’Habitation of Marseilles

Le Corbusier’s initial studies called for three separate buildings: the first with 218 apartments facing east, west and south to house 962 inhabitants; the second with 108 apartments facing south for 479 inhabitants; and the third, also facing south, with 32 apartments of an Immeuble Villa to accommodate 192 inhabitants. It would achieve a density around 600 inhabitants per hectare in a area of 2.65 hectares (L’Architecture 1947) and would stand at La Madraque near the Old Port; an area that, according to Curtis, was badly damaged by Nazi dynamiting and then later during the allied landings of 1944 (Curtis 1975, p. 169).

Eventually the Unité d’Habitation of Marseilles was located on the Boulevard Michelet and, instead of the three aforementioned blocks with residential units, only one was built. Some of the “Extensions of the Home” were not built, such as a school that was planned to be built separately nearby.

tabula rasa or even from a bottom up approach. He was probably referring to the whole design process that involved the creation of innumerable inventions until the unité.

[3] Le Corbusier often worked with one or more associates; for no other reason but conciseness, we only mention Le Corbusier.

[4] The unité d’habitation should house from 1200 to 1800 inhabitants – author’s note

[5] This building type and others will be described later in this chapter.

The Marseilles Block stands on 3.5 hectares or 8.65 acres (LeCorbusier 1953, p. 58); it has the density of 460 persons per hectare (185 persons per acre[6]); and as Jordan asserted in his *Le Corbusier*, its ground is a single green area, rather than dark courts or negligible little gardens (Jordan 1972, p. 81).

7.1.2. The Block

Including the roof garden, the Unité d'Habitation in Marseilles has eighteen stories on piloti; in addition, there is a small building on top of it that leads to the solarium (22nd floor). The block contains: 337 apartments in 23 variations of a prototype; communal services such as crèche, kindergarten, hotel, restaurant; shopping streets to facilitate daily needs; and recreation facilities such as a solarium, gymnasium, and a 300-meter running track (Figure 1).

Interesting features are:

1. Building orientation in relation to the sun: the flats face east, west and south; The north façade is blind.
2. Vertical circulation: three staircases and elevators.
3. Horizontal circulation: internal streets at every three floors.
4. Brise-soleil: to protect from glare and excessive sun in the summer as well as to welcome sun and light in the winter.
5. Sound insulation: the apartments, claimed Wogensky, "are constructed independently. Completely in themselves, they are so to speak inserted into the reinforced concrete framework without touching each other. Between their floors and the concrete beams which carry them are lead pads which absorb vibrations."
6. Ramps: from the seventeenth story to the roof garden connecting the kindergarten with the playgrounds.
7. Roof garden: the block has a roof garden which accommodates recreational activities for all inhabitants of the block and gives great views of the Marseilles landscape.
8. Piloti: The piloti are "high enough to give this area a very real feeling of unbroken space, visual and physical, right through the building (Jordan 1972, p. 82)."
9. The building's 'artificial ground level': according to Jordan, "The piloti carry an extra first floor – that is between the top of the piloti and the lowest layer of apartments – thick enough to contain a walk-way or tunnel, what Le Corbusier called the building's 'artificial ground level'. Within this walkway

[6] Jordan claimed a density of 139 inhabitants per acre; however, this would give us only 1200

are contained with great ease and simplicity all the services: water, electricity, heat, sink-waste and sewage. Aesthetically this service floor also gives a very strong plain line between the massive piloti and the grille-like façade of the building above" (Jordan 1972, p. 82).

7.1.3. The Apartments

The building block contains 337 apartments able to accommodate approximately 1,600 people. From the initial 51 types of dwelling, 23 types were realized that are able to house single people, childless couples, as well as families with one to eight children, and also small flats to accommodate guests (Figure 2). Jordan stated that these apartments are grouped as follows: 18 small flats, called *chambres d'hôtel*, for guests or tenants; 27 maisonettes (apartments with two floors) for single people or couples without children; 45 maisonettes for families with one or two children; 196 maisonettes for families with two to four children; and 35 maisonettes for families with four to eight children (Jordan 1972, pp. 83-4)[7].

Figure1: The Unité d'Habitation, Marseilles, 1952

instead of 1600 inhabitants on the 8.65 acres.

[7] Note: someone is approximating the data here. If one counts the number of apartments according to Jordan, only 321 apartments will be found.

Type E2 (Figure 3) has an area of 98 m^2 and can, in fact, be called the prototype, because it is contained in one module and has all the types of rooms: a kitchen, a double height living-room, a master bedroom, two children's bedrooms, toilet, bathrooms, and lobby with cupboards. These rooms can be grouped into: a) the kitchen with the living room; b) the master bedroom, which, according to Andre Wogensky, is provided with a large built-in wardrobe, and a bathroom, which is fitted with a bath, shower, wash-basin and bidet; and c.) children's rooms, which contain a wash-basin, cupboard and a corner for play or work and a balcony, and the lobby[8] with cupboards and shower. Each two adjacent children's bedrooms are separated by a sliding door which, when open, provides a large space for playing.

The prototype has two sub-variations: one has the kitchen on the mezzanine and the other together with the living room. From the interior street, one invariably enters the dwellings via the kitchen[9]; According to Wogensky, the kitchen is a little labor-saving laboratory, everything being within easy reach.

Le Corbusier asserted: "Everything depends on the value, the efficiency, and the integrity of the cell. When it comes to human housing - planning, whether of town or country, whether of streets, houses or blocks or flats, it is the cell which commands" (Le Corbusier 1953, p. 13). The cells are well studied and analyzed, but they are also invariable. With the exception of type B (for a single person), which has no double height living room, the internal plan-layout for each specific room hardly ever changes. The 23 variations are created by the addition or subtraction of rooms.

The "living-room (or rather a considerable part of it)," claimed Wogensky, "is two floors high, measuring 4.80 m to the ceiling. This gives a spaciousness that allows the family to gather together without feeling cramped." Accordingly he explained that the outer wall of the living room (3.66 m wide by 4.80 m high) was completely glazed, allowing light to penetrate into the kitchen from the tall window between the balcony and the living room. In addition, this window is divided into two parts; when the lower part (2.0 m high) is totally opened, the living room and balcony form one integrated space.

Wogensky asserted that "the balcony is designed to form a sun-screen (brise-soleil). That is to say, it allows sunshine to stream right into the apartment in winter while providing shade in summer. The kitchen together with the living room accommodate the essence of family life: i.e. the modern hearth" (Le Corbusier 1953, p. 20).

[8] The lobby in the center of the apartment is not a mere circulation leading to the shower, toilet and children's bedrooms. This lobby has innumerable cupboards for storage of, for example, linen and towels.
[9] With the obvious exception of the *chambre d'hôtel* which has no kitchen

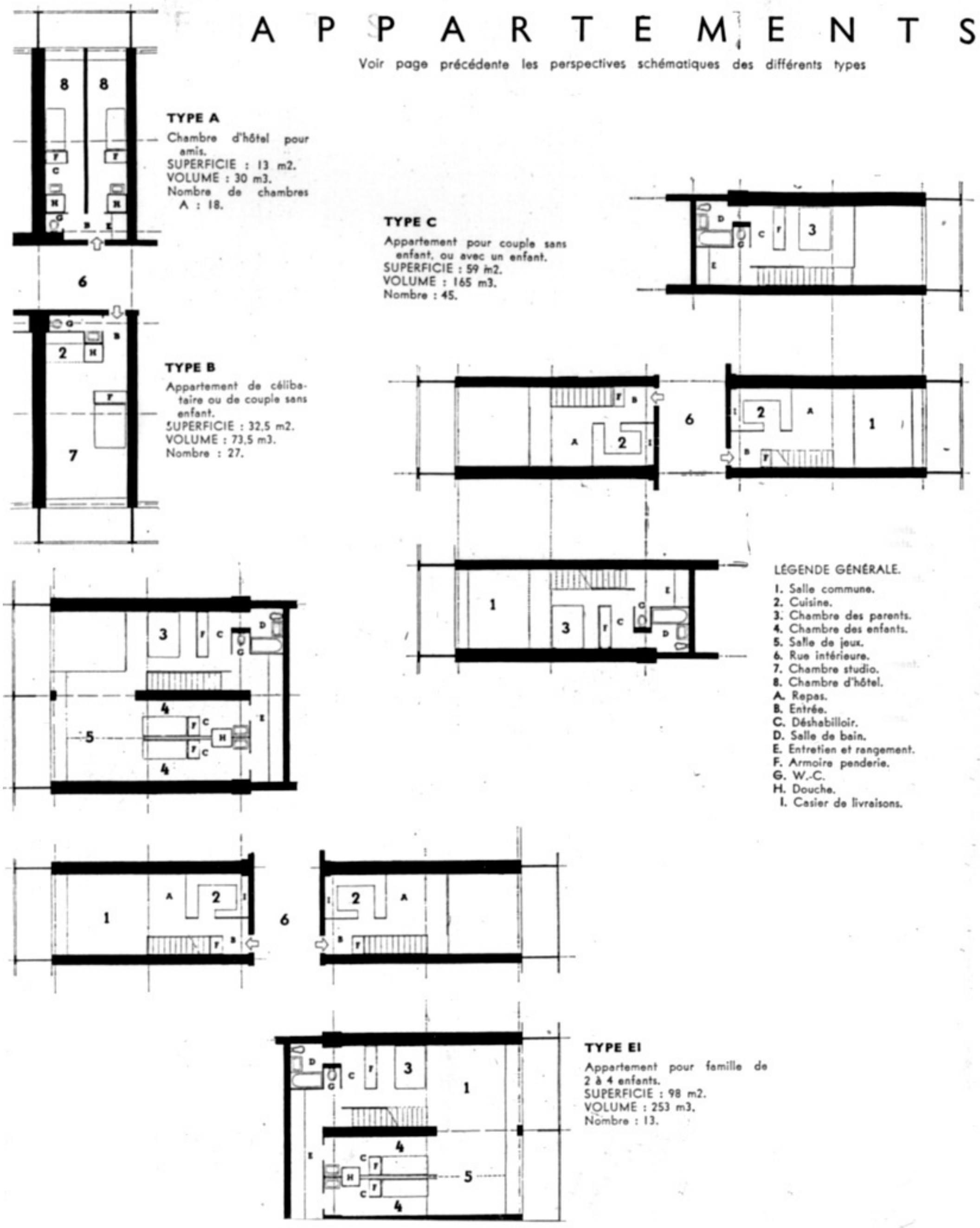


Figure 2: Unité d'Habitation, Marseilles, 1952, plan layout, some house types

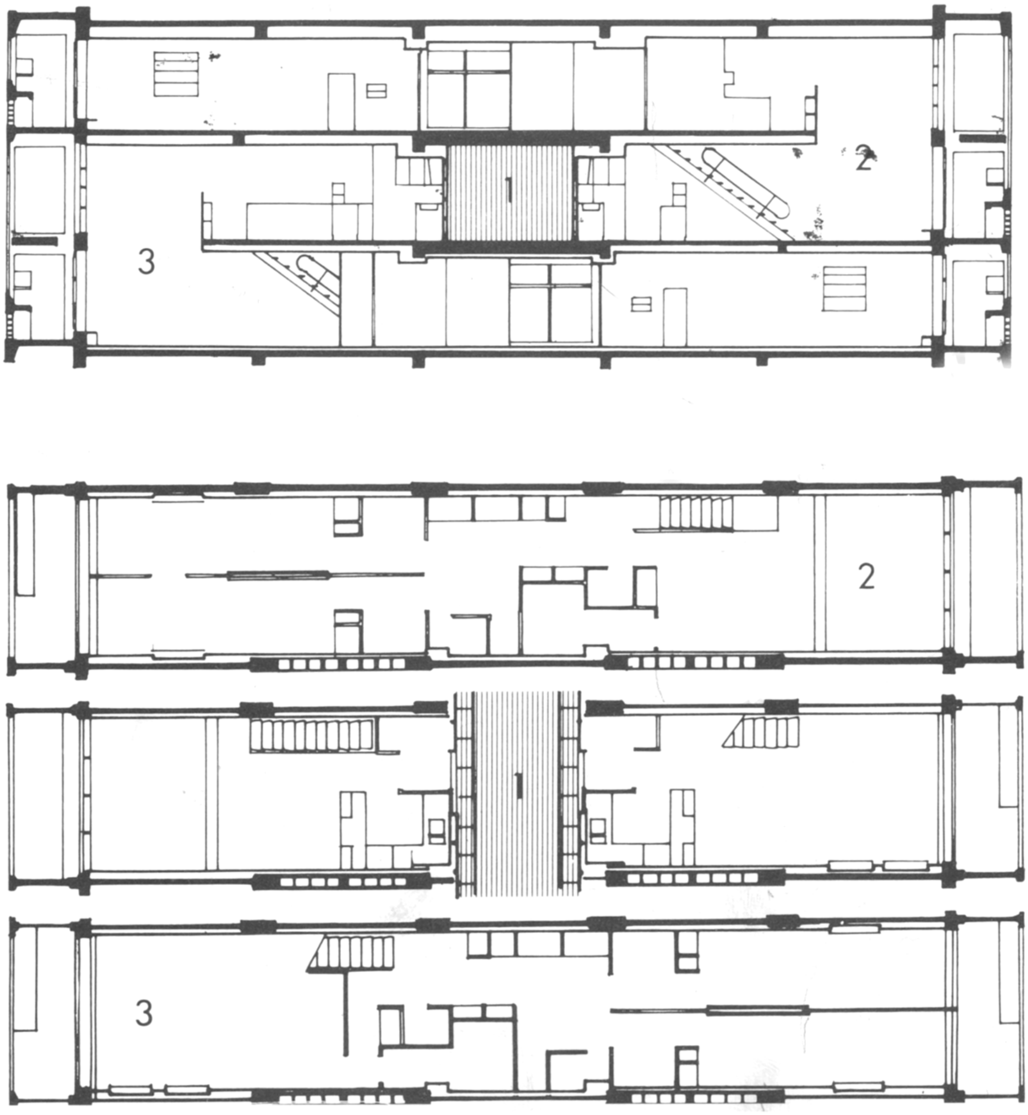


Figure 3: House Unit, Unité d'Habitation, Marseilles, 1952, plan layout, prototype

7.1.4. Communal Services and the Extensions of the Home

Shops, restaurants, and everything that the inhabitants of a traditional neighborhood or city need for their daily life Le Corbusier called "communal services". The seventh and eighth floors of the Unité contain a big co-operative store and a few individual shops to satisfy the daily needs of the inhabitants. A small restaurant and a hotel of 18 rooms (type A) are also provided.[10] Because this small hotel would provide rooms for guests, dwellings would not need guest rooms.

The facilities provided under the heading 'Extensions of the Home', asserted Wogensky, "demonstrate Le Corbusier's anxiety to provide, within easy reach of the home, all that may be necessary to supplement it" (Le Corbusier 1953). They were a crèche on the 16th floor; a kindergarten on the 17th floor, a swimming bath and playgrounds (connected by a ramp to the kindergarten) on the 18th, and the roof garden. Amenities for adults, such as a covered and open-air gymnasium and a 300-meter running track were also situated on the 18th floor; and finally, situated on an isolated building of the roof garden, a solarium (22nd floor) with music and pastis.

On the ground floor, there was to be a garage, swimming bath, tennis courts, sports ground and playing field. "To these," claimed Wogensky, "should be added schools and other things which could not be provided with the funds available" (Le Corbusier 1953, p. 58). These were facilities that could only be economically available to workers if they were shared within a large group.

7.1.5. Exploring the Unité d'Habitation of Marseilles

In the ontogeny of the Unité d'Habitation, we will find an intriguing conceptual network that will be described at the end of the chapter according to the ideas developed in chapters 5 and 6 on the re-use of design precedents. But first, we will present design precedents that may have contributed to the creation of the Unité, and try to specify what was indeed re-used. Next, we will present three inventions which, in our view, greatly contributed to the creation of the Unité as a recombination and adaptation of old patterns in a new context. Afterwards, we will present some of those re-used patterns in their history of evolution to hypothesize on how they (as kinds of selfish genes) evolved and how they are linked with others.

7.2. Three Main Inventions as Design Precedents

Proceeding from an evolving vocabulary (gene pool), Le Corbusier produced diverse and creative inventions (species) such as the Maison Dom-Ino, Maison Citrohan, the Immeubles Villas and the Unité d'Habitation. In the making of these inventions, analogies played a very important role such as the recognition of elements from other orders of classification, like bottles and bottle racks. This

[10] The 7th and 8th floors also contain type B flats for single people as well as flats for couples without children; and type C, the smallest unit with a double height living room, also for couples with no children.

section will show how Le Corbusier recombined architectural elements to form three main inventions; i.e. the Maison Dom-Ino (1915-1919), the Maison Citrohan (1919-1927) and the Immeubles Villas of 1922, which almost indisputably are design precedents (ancestors) of the Unité d'Habitation. While focusing on these inventions (species), other projects will eventually be approached due to their direct or indirect relation with these three inventions.

The objective of this section is to identify elements, whether recombined or not, which contributed to the creation of the Unité d'Habitation. We are most concerned with the identification of design precedents of the Unité d'Habitation, their chronological order as well as the way they evolved and how they most likely influenced the design of the Unité d'Habitation.

7.2.1. Maison Dom-Ino 1915-1919

Design precedents of the Maison Dom-Ino were possibly: the vernacular houses that Le Corbusier drew in his sketchbooks, in particular features like the roof garden and outer stairs; Perret's office on rue Franklin in Paris, in particular the structure; and Tony Garnier's projects, if we eliminate their cornices.

During his fifteen months training with Perret (1908-09), Le Corbusier had the opportunity to work in an extremely modern building: at Perret's office on rue Franklin in Paris. This building was certainly a remarkable precedent of Maison Dom-Ino, due to its structure, which is completely independent of the partition walls (Figure 4).

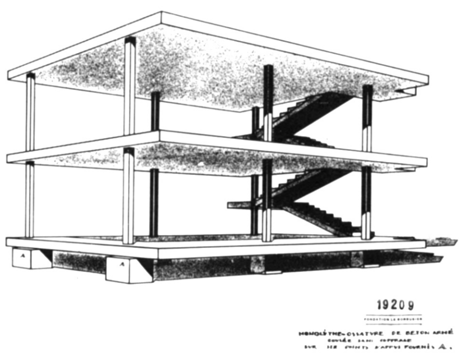


Figure 4: Maison Dom-Ino, 1915-1919, structure

According to H. Allen Brooks[11] in his *Le Corbusier's Formative Years*, from 1915 to 1919 Le Corbusier intensively experimented with a series of reinforced concrete systems that would result in the "Dom-Ino" system. The objective of this system was the rapid, low cost construction of extensible housing to meet the

[11] H. Allen Brooks is Professor Emeritus of Art History at the University of Toronto. He is, together with Prof. A. Tzonis, the General Editor of *The Le Corbusier Archive.*

demand in the post-war period (Brooks 1997, p. 381). The Dom-Ino system was developed together with Du Bois, who studied civil engineering at the Zurich Polytechnic under Prof. E. Morsch[12]. According to Geoffrey H. Baker, the 'Dom-Ino' idea, a system using Professor Mörsch's *monolythe* principles, began to develop when Jeanneret[13] and Du Bois met in October and November of 1914 (Baker and Le Corbusier 1996, p. 216). An early sketch by Jeanneret shows that it was the position of the columns in relation to the slab that first suggested the domino comparison, as well as the fact that houses so constructed could be placed next to each other like dominoes.

According to Baker, Du Bois worked out the structure, and tried to help Le Corbusier obtain a patent and finance when Le Corbusier was to design several houses using the system. It has been overly emphasized that the goal of this system was to provide a structure that could produce cheap dwellings at high speed after the First World War. We believe that this emphasis takes away much of the credit from Le Corbusier's efforts in providing a structure to facilitate the design of at least four structural house types as well as innumerous variations of them. Therefore we will describe the structural framework as well as the design concepts that it represented. In other words, we claim that Le Corbusier's focus was two-fold: on the one hand, he wanted to solve problems of standardization and industrialization to achieve affordable houses; and on the other hand, he focused on the development of a framework which could facilitate the design of houses of different sizes and forms.

According to Brooks, the structural frameworks had three salient traits. First, they employed "free-standing concrete piers in place of load-bearing walls and, second, constructing the reinforced concrete floor and ceiling slabs without the use of traditional wood formwork which required support from below, and, third, doing all this in such a manner that the slabs were flat and smooth on both sides and joined to the supporting piers at right angles." Brooks claimed that the second trait was very difficult to achieve from an engineering standpoint when in combination with the third trait (Brooks 1997, p. 384).

The elements of the structural framework were columns, slabs, base and stairs. Furthermore, According to Ng[14], the Dom-Ino system involved "prefabricated standardised elements which could be attached to one another or placed next to each other like dominos, permitting a great variety in the grouping of the houses. This was a completely new method of construction, one whereby windows could be attached to the structural frame and lined up with wall panels to form partitions. The Dom-Ino system implied the possibility of a complete reorganisation of the interior plan and exterior elevation" (Ng).

[12] Professor E. Morsch developed the monolythe constructional method, which made use of structures in reinforced concrete at Zurich Polytechnic (Baker 1996, p. 216)
[13] Charles-Edouard Jeanneret is the real name of Le Corbusier
[14] Les-lee Ng at http://fridge.arch.uwa.edu.au/courses/380/citrohan/

As mentioned above, the structure of the Dom-Ino houses proved to be of great value in its potential toward housing differentiation. The characteristics of the Dom-Ino structure were: in differentiation between levels such as the layout of the house and its structure; in the use of an architectural grid, which supported differentiation in the plan layout of the houses; in the development of structural types as well as housing types; and the subsequent plan layout variations.

1. The levels: drawing no. 30285 of the *Fondation Le Corbusier* (FLC) shows three levels (Figure 5) of abstractions in the Dom-Ino framework. Level one is the structure at the urban level. Level two is at allocation level. It shows how the structure could be subdivided to provide dwellings of diverse sizes and forms. Level three shows a sector analysis that culminates in four structural types.

2. The grid: Drawing no. 19177 of the *Fondation Le Corbusier* (FLC) shows us a grid based on 1.15 m. Between columns accommodating living rooms, Le Corbusier chose (either vertically or horizontally) 4 x 1.15 m from axis to axis. The slabs are often in cantilever, whereby 1.15 m is the distance between the axis of the column and the axis of the façades. Stairs are between columns with a width of 1.15 m or 2.30 m from axis to axis[15].

3. The structural types and house types: the aforementioned grid was tried out in order to provide four structural types. We wish to differentiate between structural type and house type because, as shown in drawings 19207 (Figure 6) and 19211 (Figure 7) of the FLC, structural type B or its mirror B' could be used to make flats stacking one dwelling on top of another, or maisonettes with bedrooms on the first floor.

4. Dwelling variation: in drawing no.19172 of the FLC, one can see that Le Corbusier also provided variations of the dwelling layout (Figure 8).

Besides the aforementioned characteristics of this Dom-Ino system, it also included seminal ideas that would evolve in the not-so-distant future. According to Max Risselada in his *Raumplan versus Plan Libre*, the well-known 1919 perspective seems in retrospect "to contain the potential of the 5 points for a new architecture" (Risselada 1988, p. 99). We add to this idea the following:

5. Roof garden: some projects show a roof garden with pergolas such as in sketch no. 19133 (Figure 9) of the FLC, while others only show a balcony at the first floor such as in perspective no. 19131 of the FLC, and others still show no balcony and no roof garden, such as perspective no. 19132.

6. Free façade: the Dom-Ino housing system shows an intensive training in designing façades, such as in perspective no. 30290 and in façade/sketch no. 30291, both in the FLC.

[15] Drawing 19166 of the FLC shows a grid based on 1.05m.

7. Free plan: if there was a certain internal layout freedom in the design of the dwellings, then the drawings presented in the archives were not yet a good example of this freedom as it would be by the time of the design of maison Cook, Villa Savoye, and so forth.

8. Piloti: the structure is made of columns and slabs, and as such makes possible the use of piloti. The notion of "piloti" as it will be described is not yet developed at this stage. This structure is closer to the column-beams structure of Perret's office of the rue Franklin, where the column and beam framework is enclosed by partition walls and façades.

After having exercised with the Dom-Ino structural framework and design scheme, the observation of a "savage hut" would probably call his attention to the potentialities of this framework: the use of "naked-piloti". The Schwob house (1917) already contained an independent structure, in which the use of four columns freed the central part of the house from partition walls (Jencks 1973, p. 43). However, the step towards a new esthetical expression would only be given during the development of the Monol and Citrohan houses. Indeed, Le Corbusier would only make use of the "naked-piloti" in the design of his second Citrohan house.

The Dom-Ino housing system was a fortunate invention that opened the possibility for other developments, in particular for the formulation of the five points of a modern architecture.

In general, researchers and historians talk about the Dom-Ino as a constructive system; our standpoint is that the columns and slabs in reinforced concrete were not so unique if we recall that Perret designed his office in 1905 also using an independent framework, and that Le Corbusier knew this building very well from his fifteen months training with Perret. What we find interesting is the combination of the structure and its grid with diverse types of dwellings and variants, allowing him to see the design from a bottom-up as well as from a top-down approach. It is this practice as well as the possibilities toward a new vocabulary that make this invention very special in Le Corbusier's oeuvre. Indeed, it made possible the development of the roof garden, the piloti, the free façade and the free plan.

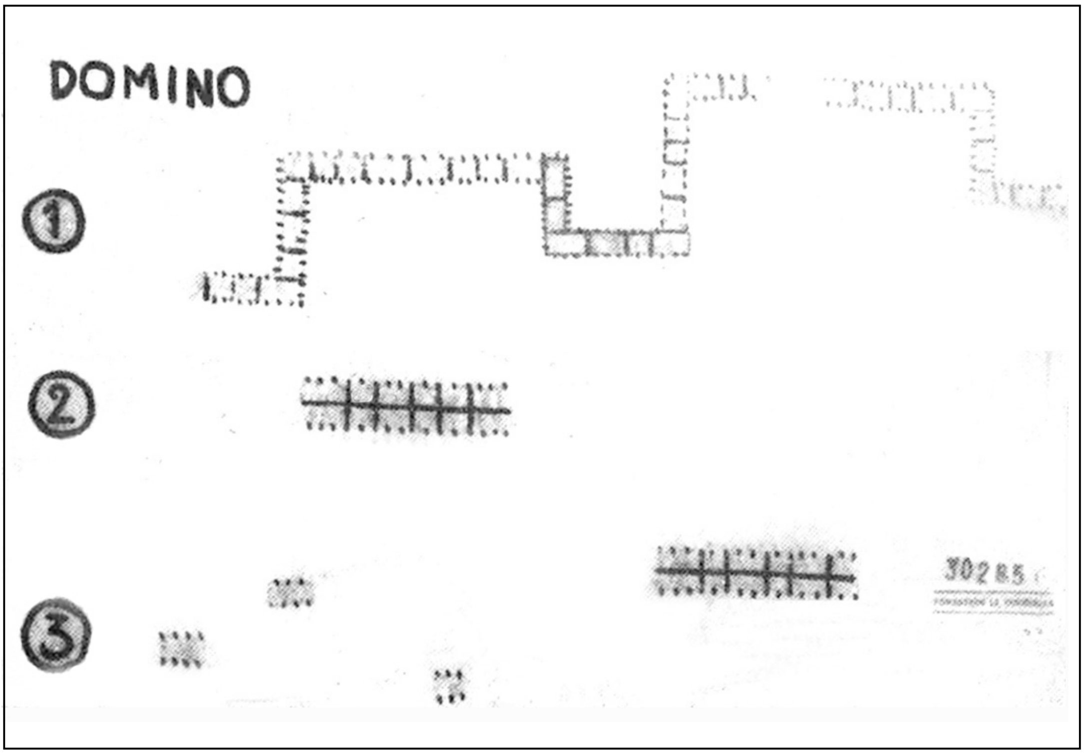


Figure 5: Maison Dom-Ino, 1915-1919, the levels

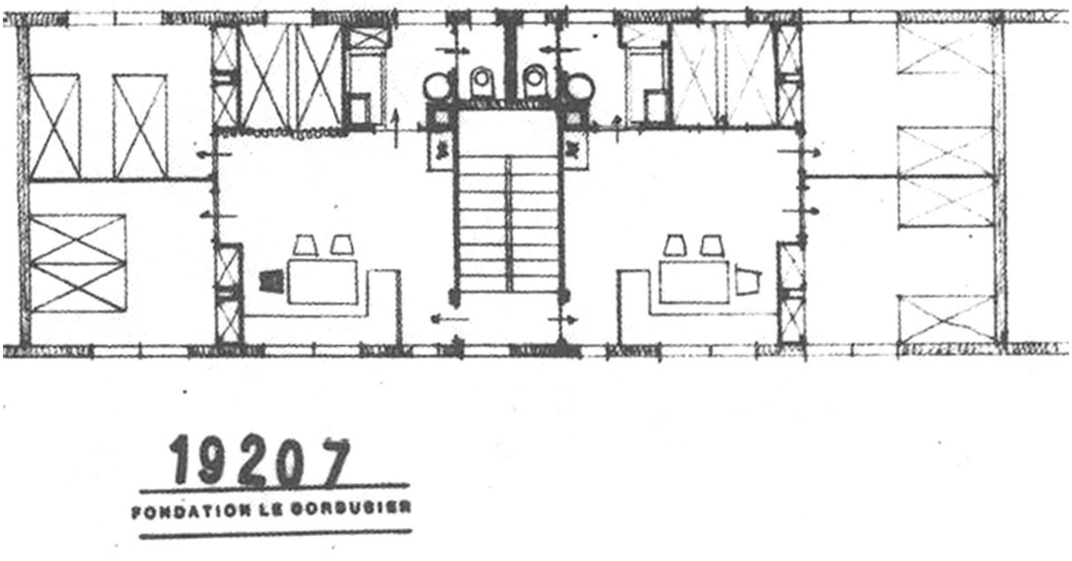


Figure 6: Maison Dom-Ino, 1915-1919, plan layout, stacked flats

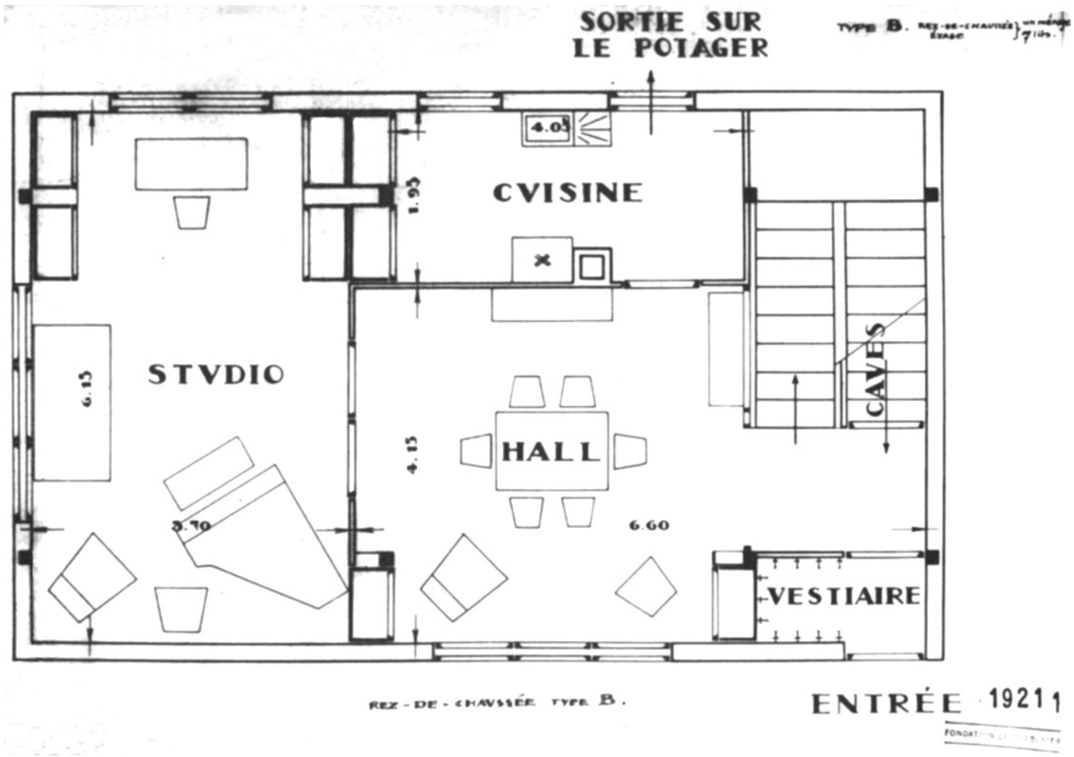


Figure7: Maison Dom-Ino, 1915-1919, plan layout, ground-floor, type B

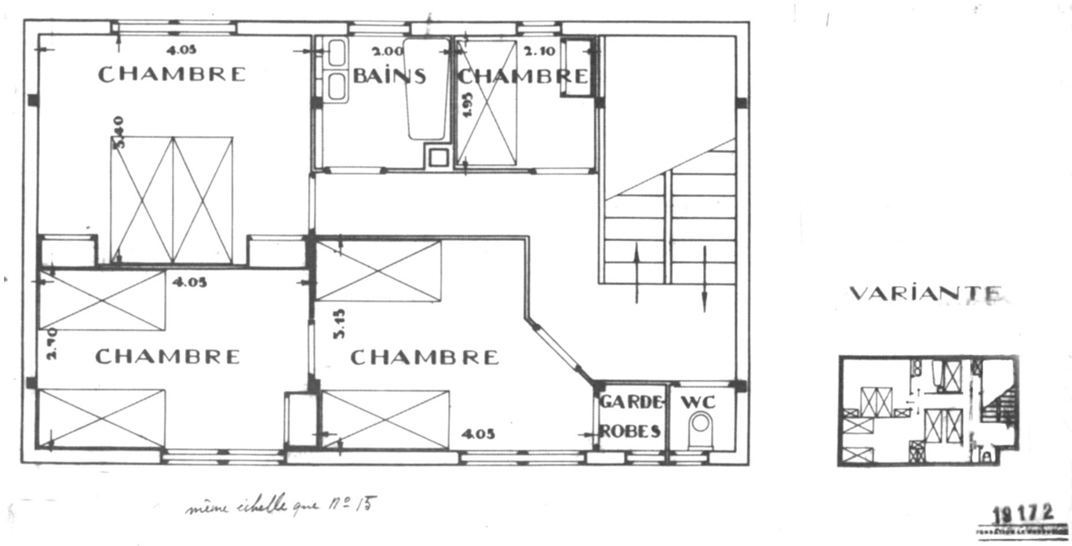


Figure 8: Maison Dom-Ino, 1915-1919, plan layout, variations of 1st floor

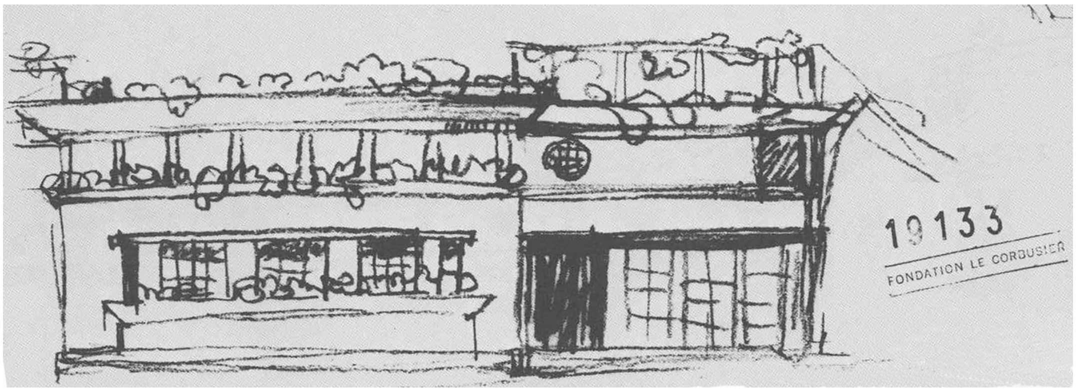


Figure 9: Roof Garden, Dom-Ino, 1915-1919, facade

7.2.2. Citrohan Houses 1919-1927

Le Corbusier's Citrohan houses seem to be based on several design precedents such as the "Haunted House"[16]; vernacular houses[17]; workers' housing of his Paris sketchbook, 1916-1922; the "savage hut" and the Maison Dom-Ino.

From 1919 and throughout the 1920s, Le Corbusier developed and experimented with what he called Citrohan houses. These houses showed a new aesthetical tendency: purism, and were meant to use the technological and architectural advances of the moment. Its name derived from the French Citroën car company that aroused great admiration in Le Corbusier due to its technology, functional line and use of standards (Le Corbusier 1986).

Le Corbusier claimed that a standard was necessary to put order into human effort, i.e. the efforts of industry as well as designers aiming at the development of "a recognized type conformable to its functions, with a maximum output and a minimum use of means, workmanship and material, words, forms, colours, sounds" (Le Corbusier 1986, pp. 135-7).

In Le Corbusier's eyes, cars, airplanes and ocean liners are machines which present great functionalism; they are composed of simple forms and made for mass production. He asserted: "If the problem of dwelling or the flat were studied in the same way that a chassis is, a speedy transformation and improvement would be seen in our houses. If houses were constructed by industrial mass-production, like a chassis, unexpected but sane and defensible forms would soon appear, and a new aesthetic would be formulated with astonishing precision" (Le Corbusier 1986, p. 133).

[16] The "Haunted House" was an old farmhouse owned by George Favre and situated across the valley from L.C.'s home. It was so called due to rumours that the house was haunted. This house was about to be demolished (Brooks 1997, p. 342; Baker 1996, pp. 213-214)
[17] Houses seen in the journey to the East with elevated terraces with a pergola.

It is during the creation of the Citrohan houses, claimed Brooks, that Le Corbusier coined “his famous saying, ‘a house is a machine for living in’, a catch phrase not necessarily aimed at the minimum housing since this house boasts a maid’s room and three W.C.’s” (Brooks 1997). Nonetheless, the systematic layout, the simple lines and the structural system of the Citrohan houses supported further developments in mass production.

Maison Citrohan seems to be an invention that evolved from previous experience. Indeed, according to Brooks, in the Haunted House of 1912 (Figure 10), which consisted of a clear rectangular cube, flat roof garden with pergola and outer staircase, perhaps lay the seeds of the Maison Citrohan of 1920 (Brooks 1997, p. 342). The Haunted House was one of the Jura houses so beloved by Le Corbusier that were put to demolition. Brooks emphasized the fact that, when Le Corbusier arrived at the site, this farmhouse was already without the pitched roof, which presumably made him remember the roof gardens of the vernacular houses of Istanbul (Figure 11).

With this, Brooks also referred to the external look of the Citrohan houses. However, it goes without saying that this Maison Citrohan contained many other concept-features. The first referred to the size of the rooms. The contrast between the size of the living room and the bedroom area is greater than in other contemporary designs; this contrast enhances what could be translated as the adaptation of the “reclusive (cell) versus collective (church) life” of Chartreuse d’Ema.

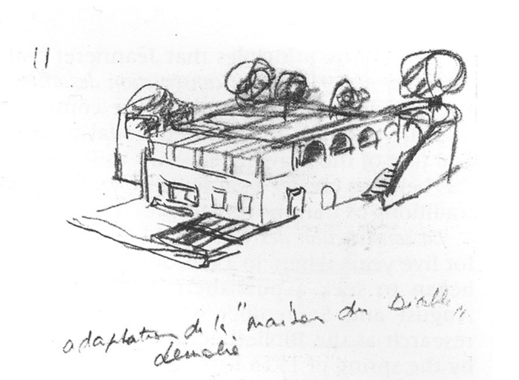


Figure10: Haunted House, 1912, perspective

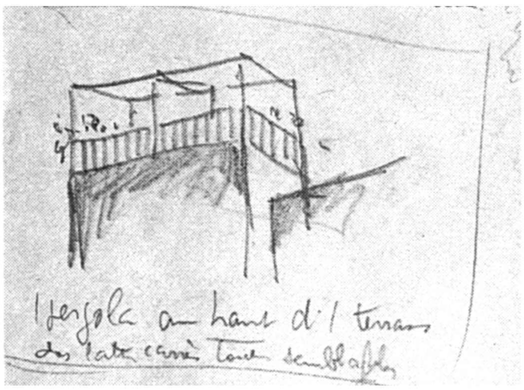


Figure 11: Vernacular Houses of Istanbul, schematic perspective

Secondly, the rooms of the plan layout are positioned in a metaphorical translation of what could be an automobile with its motor-service on one side, and the comfortable seats/living room on the opposite side.

Thirdly, Le Corbusier also experimented with what would be known as the architectural promenade, a “controlled sequence of space” (Jencks 1973), which “guided” the attention of the individual from one event to the other with the use of elements such as the stairs, the ramp, the bridge, the double height living room, the curved walls of the bathroom and/or of the solarium[18]. According to Jencks, "The spatial sequence is truly remarkable and remained a constant preoccupation of Le Corbusier." Jencks observed that Le Corbusier smashed his elements into and through each other to produce what Jencks called "compaction composition". These elements, claimed Jencks, are comparable to the **object-types** in a Purist painting used as "fixed words" in an abstract system of a Cartesian space (Jencks 1973, p. 87).

Finally there was the experiment with features that would later be called the five points for a modern architecture, which included the roof garden of the Haunted House, and which refer to more than the esthetics or visual quality of the space.

Le Corbusier designed several variations of the Maison Citrohan. However, authors writing on this particular invention often show a selection of houses that includes the first Citrohan House, example number 20707 of the Foundation Le Corbusier (FLC) shown in the Garland archives as well as the Citrohan of 1922 that introduced the piloti. However, The Citrohan example number 20719 (Le Corbusier and Corbusier 1984, pp. 333-341), although not fully expressed[19] and not so widely published elsewhere, seems very close to Le Corbusier's House 13 of the *Weissenhofsiedlung*; and Risselada in his *Raumplan versus Plan Libre* (Risselada 1988, p. 100) presented two instances of designs for the model estate exhibition of 1927 in Stuttgart as representations of a Citrohan house. House 13 is often called a Citrohan house and, in fact, the ultimate model of the Citrohan house.

Though developed very early in the phylogeny of Le Corbusier's designs, we claim that the Citrohan houses did evolve; and this is in accordance with Le Corbusier's own idea that "a good product should be developed in a cyclic process, perpetually enriched with the fruits of experience" (Risselada 1988, p. 98).[20] It seems that it evolved in a kind of punctuated equilibrium, which lasted about 10 years, through the addition and subtraction of features. In fact this invention seems to have directly influenced the Immeubles Villas.

Taking some examples of the Citrohan houses (see illustration), one can illustrate the phenomenon of change in design:

The first Maison Citrohan (1919) used two of Le Corbusier's five points for a modern architecture: the roof garden and ribbon windows (Figure 12). A remarkable characteristic was the vernacular outer stairs (Baker and Le Corbusier

[18] However, we are not claiming that all these elements were always present together at the same time in a design.
[19] It is missing two façades and some details of the layout-plan on the piloti level
[20] In fact, because it appears so early in L.C.'s oeuvre, Max Risselada argues that the Citrohan houses did not mature through experience, and therefore did not evolved in time.

1996, p. 221) and the pergolas (Baker and Le Corbusier 1996, pp. 164-5). As mentioned before, Le Corbusier had drawn several workers' houses with outside stairs in his Paris sketchbook of 1916-1922. The pergola seems to have been recollected from memory and from his sketches of the journey to the East, where he drew two houses at Psamatia (sketch nos. 2386 and 1813 of the FLC), both with pergolas on top of a terrace. It is interesting to note that the use of the pergola on the roof garden of his first Citrohan house made the volume become a complete cube.

A variant of this Citrohan (1920) retained the roof garden and the ribbon windows, but did not re-use the pergola or outer stairs. The latter is placed inside the building.

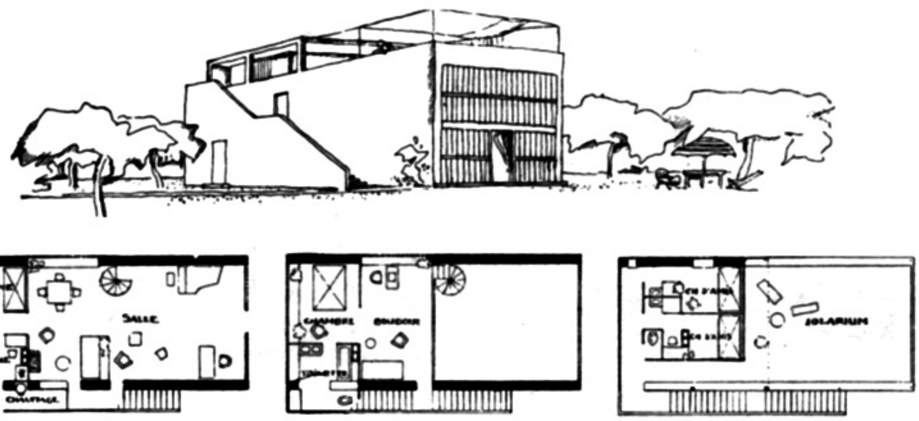


Figure 12: Maison Citrohan, 1919, perspective and plan layout

A Citrohan of 1922 shows one of the major modifications: the piloti (or the third point for a modern architecture). It was the first time that Le Corbusier used this element in his designs (Tzonis 2001, p. 42). The piloti was initially used due to economic reasons and because Le Corbusier wanted to free the house from humidity. Later in this chapter we will show that during its recollection and adaptation, the piloti notion was enriched and acquired more meanings[21].

According to William J.R. Curtis, for Pessac (1925), Le Corbusier "visualized variations on the Citrohan and Ribot prototypes laid out along tree-lined streets with gardens supplemented (in some cases) by roof terraces covered by pergolas" (Curtis 1975, p. 66). With these variations, Le Corbusier played with elements such as the outer open stairs that were used in some detached houses from the

[21] Here we could draw an analogy with the primordial development of the wings in birds. The first mutations towards the development of a wing were presumably favored by natural selection because they functioned to cool the bodies of the birds' ancestors down, and not because they were already a well-adapted "tool" to fly.

ground floor to the roof garden or only connecting the first floor with the roof garden. The piloti is not taken as a constant feature.

The project in Pessac is extensively discussed by Philippe Boudon in his *Lived-in Architecture, Le Corbusier's Pessac Revisited*. In this housing project, Le Corbusier tried to solve all kinds of problems. By standardizing the components of a house, the industrialization of construction could be achieved and subsequently costs could be kept low; by varying the position of his cells in the design of the house, sound isolation could be attained; and by varying the position of the houses in the urban plan, the distinct qualities of the individual and collective could be experienced in their right place (Boudon 1979, pp. 29-46). The extent to which this housing project became a success or not is discussed in detail by Boudon; it is not within the scope of this research to reanalyze the whole project.

In the *Weissenhofsiedlung* of 1927 in Stuttgart, two Citrohan variations were constructed[22]: one single house and the other a double house. As Curtis asserted, "Le Corbusier's Stuttgart houses demonstrated the principles of 'the five points of a New Architecture' that had been latent in the Dom-Ino skeleton, and gradually clarified in the villa designs of the mid-1920's" (Curtis 1975, p. 69). House 13 seems to be the ultimate Citrohan prototype. This house carries the famous "five features for a modern architecture":

1. It stands on columns (piloti) that permit the garden to grow under it, and permit the circulation of people and storage. Because there is ventilation through the piloti, the rooms were protected from humidity. According to Curtis, the "pilotis under the double house were made of slender steel stanchions and exaggerated in length to an almost preposterous degree" (Curtis 1975, p. 69).

2. It has a roof garden, which is assured by the use of reinforced concrete. As Curtis claimed, it "replaced land lost underneath the building with verdure open to sun, sky, trees and view" (Curtis 1975, p. 69).

3. It allows a free plan: the layout of the house could be free from load-bearing walls. According to Curtis, "the interiors of both houses opened up to become uncluttered space for daytime use which could be divided at night by partitions" (Curtis 1975, p. 69).

4. It allows the use of ribbon windows: they were meant as an esthetic device as well as a means to allow light in and have beautiful views.

5. It allows free façades. According to Curtis, they are a consequence of the use of the piloti, "as the exterior cladding was liberated from traditional weight bearing constraints, allowing openings to be arranged at will for light, view,

[22] One of the main requirements of the exhibition was the presentation of a low-cost house with an eye to the realities of mass production. Instead of aiming at the minimum house, Le Corbusier developed a house which had an architectural language capable of being industrially reproduced.

climate or compositional needs" (Curtis 1975, p. 69). Strangely enough, the façade along the stairs is completely free from columns; however, it is the façade where we can find the fewest openings. But even having the columns within a façade, the greater part of it is free for variation, at least, much more than in a bearing wall construction.

According to Le Corbusier, the free plan (resulting from the interior framework) and the free façade (increasing the available surface for lighting) were great architectural reforms arising from the then new technical possibilities of ferro-concrete and metal construction (Le Corbusier 1930).

We finish our description here of the Maison Citrohan with three claims:

1. Some features disappear in one Citrohan project only to reappear in a future design. This leads us to think that at this point of his career, he used a "piloti/no-piloti function" as if they were alleles genes, i.e. variations of a theme[23] (such as the hair, skin and eye-color of an animal);

2. The Citrohan houses enhanced the design of Le Corbusier's villas, but those villas also had a role in the phenomenon of change in the Citrohan series.

3. A great part of the Citrohan invention is transferred and adapted as units of the Immeubles Villas of 1922.

7.2 3. Immeubles Villas 1922-1928

As has already been mentioned, the Citrohan Houses are considered a direct precedent of this invention; similarly the Chartreuse d'Ema[24], in particular the organizational typology of this monastery that Le Corbusier visited in his journey to Italy in 1907.

[23] At that moment, it is unimportant what the reasons were, whether it was a concession due to economic or esthetical reasons, or if the need arose due to the particularities of the site. The fact is that the option was open.

[24] The Chartreuse d'Ema was located at Galluzo near Florence (sec. XVIII). L.C. visited the Carthusian monastery in September 1907 and once more in 1911. According to Baker, "The layout of the monastery, with its entrance courtyard separated by the church from the living quarters, resulted in a combination of privacy and communal interaction that became an obsessive preoccupation of Jeanneret throughout his life. He sketched the plan and section of a typical cell, being captivated by the way each monk could relate to the community at large by access from the courtyard, and to the external world by views from elevated gardens. The logic of this combination of a central zone for circulation (the courtyard) surrounded by individual private courts (the gardens), all based on a simple geometry, which ensured excellent lighting and views to each cell, was to evolve gradually in his own projects, appearing in many guises during his lifetime. In 1910 his design for a new Atelier d'Art had a similar centralized geometrical arrangement, with perimeter blocks also maximizing the admission of light, and with circulation and communal activities taking place at the centre. The elevated gardens of the monastery subsequently reappeared in his Immeuble Villas, which were exhibited at the Salon d'Automne in 1922 and were later reproduced in the Pavillon de L'Esprit Nouveau of 1925." - Baker, Geoffrey H. 1996. *Le Corbusier, The Creative Search*. London: Van Nostrand Reinhold. pp. 72-73

According to Jacques Sbriglio in *Le Corbusier, Architecte/Artiste,* "the Immeubles Villas project is Le Corbusier's first scheme for multiple housing. It appeared for the first time in the plan of a 'Cité Comtemporaine pour 3 millions d'habitants'. Presented in Paris at the 1922 Salon d'Automne, it is an alternative to the typical Parisian model of a rental propriety divided into apartments" (Sbriglio 1997).

According to Le Corbusier's description in *Towards a New Architecture*, "the drawings show the arrangement of a group of 100 maisonettes disposed in five storeys, each having two floors and its own garden. (…) Modern achievement, applied to so important an enterprise, replaces human labour by the machine and by good organization; constant hot water, central-heating, refrigerators, vacuum cleaners, pure water, etc." (Le Corbusier 1986, pp. 247-8). It was conceived as an alternative to the then current modes of living in an urban environment (Sbriglio 1997).

Le Corbusier was about to create certain services that he would later call the "extension of the home". However, he frequently offered them as an extra advantage. In other words, he claimed, "**Each maisonette** has its own **gymnasium and sports room**, but on the roof there is a **communal hall for sports** and a **300-yard track**. On the roof too is an **entertainment hall** for the use of the inhabitants" (Le Corbusier 1986, p. 249).

According to Le Corbusier, "The provision of food, whether cooked or not, is arranged by a special purchasing service, which makes for quality and economy. From **a vast kitchen** the food is supplied as required to be eaten, either privately or in the **communal restaurant**" (Le Corbusier 1986, pp. 248-9). Le Corbusier's proposal for a communal kitchen suggests that the concept of the kitchen as the modern hearth was not yet fully developed, for in the development of the Unité d'Habitation, he talked about 337 homes or 337 hearths, which are the essence of family life. In this new version, the kitchen is the modern hearth (Le Corbusier 1953, p. 20).

Further characteristics of the general block layout include the access, the courtyard and garages. Le Corbusier asserted: "The ordinary narrow entrance lobby of the house is replaced by a vast hall, and a porter is on duty day and night to receive visitors and show them to the lifts. There is the great covered court, on the roof of the underground garages, for tennis" (Le Corbusier 1986, pp. 247-9). Also, each duplex apartment (maisonette) is accessible by an external alleyway with a view of the court.

Sbriglio claimed that this rectangular five-double-story building block would have grocery stores and a communal laundry to facilitate the daily life of the inhabitants. For Sbriglio, an Immeuble villa "is a combination of the Citrohan house with a cell from the Chartreuse d'Ema and opens in the front onto a vast suspended garden" (**Sbriglio 1997**). Indeed, the building seems to be composed of stacked Citrohan houses (Figure 13). From this position, the most striking difference is the position of the hanging gardens. One could imagine a dialog in Le Corbusier's mind on how to group the units and still keep the privacy of the family when in their individual gardens.

A second striking difference is that the Maison Citrohan refers to the use of the piloti[25]. However, the first Immeuble villa was designed in 1922, the year in which Le Corbusier used the piloti for the first time on the Citrohan house[26].

According to L'Homme et L'Architecture (1947, p. 15), there was an evolutionary path from the Immeubles Villas (1922) to the Unité d'Habitation of Marseilles which covers buildings such as: the Pavillon de "L'Esprit Nouveau" of 1925; the Project Wanner, Geneva, of 1928; Immeuble "Clarte", Geneva, of 1930-1932; Immeuble Locatif in Zurich, 1932-1934; Immeuble Duvrier in Zurich, 1932-1934; the Project pour un Lotissement du Domain de Baradja, Algiers, 1932-1934; Habitation in Loyer du Chemin de Telembi, Algiers, 1932-1934; Maison Locative in Algiers; Lilot insalubre no. 6, type 'ville radieuse"; and the Unité d'Habitation in Bastion Kellermann. Due to the scope of this research, we shall limit ourselves to the inventions described above.

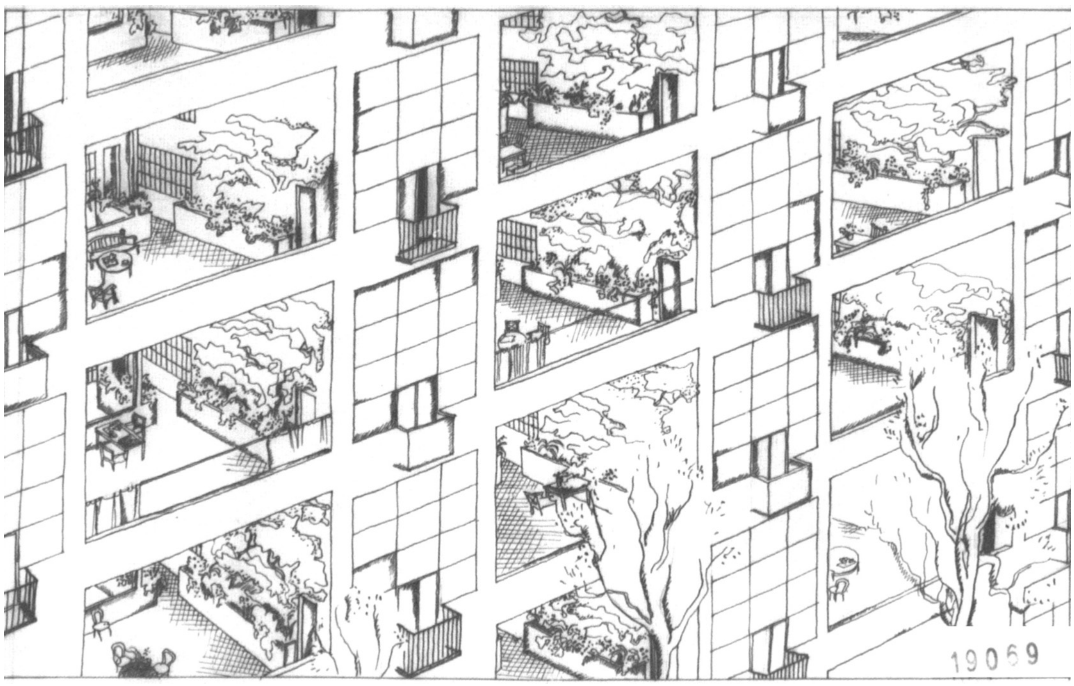


Figure 13: Immeubles-Villas, 1922-1928, perspective of the facade

[25] The first I.V. was designed in 1922, which is the year when Le Corbusier started to experiment with the idea of the piloti in the design of a Citrohan house.
[26] The first Citrohan house did not have the piloti.

7.2.4. A Broad View on the Phenomenon of Change

The three inventions that we have discussed up to now seem to have their influence in the development of the Unité d'Habitation. Some elements were transferred from one domain to another such as the roof garden and the piloti (table 1).

Domain / Inventions	Private: open spaces	Collective
Citrohan Houses	Dwelling • Cell/Bedroom • Services • Living room • Kitchen • **Roof garden** • **Piloti** (garden, garage, storage)	
Immeubles Villas	Dwelling • Cell/Bedrooms • Living room • Kitchen • WC • Bathroom • **"Roof" Garden** • **Sport room** • **Gymnasium** • Small Balcony	Reception Courtyard: Tennis Communal Services: • Groceries • Laundry Restaurant Under Court: Garage **Roof Garden:** • **Entertainment Hall** • **300-yard track** • **Communal sports hall**
Unité d'Habitation	Dwelling: • Kitchen + dining room • Double height living-room • Bedrooms • WC + Bathrooms • Lobby + cupboards • **Balconies**	Reception **Piloti**: Reception + parks **Roof Garden** Communal Services Extension of the home Interior streets Vertical circulation

Table 1: Private and Collective Domains of the Three Inventions

In the Unité d'Habitation, the individual garden disappeared, or rather, it was substituted for balconies and a garden for the recreational activities of the inhabitants of the whole building block. In the Unité d'Habitation of Marseilles, roof gardens and piloti would transcend the family/individual domain to the community domain. It is important to notice that piloti and roof gardens for the family/individual domain did not disappear from Le Corbusier's vocabulary. However, in a multi-familial building, the collective use of these features would be the main concern.

As a breeder, designers recall precedents by "artificial selection".

Assumption 2: Chapter 5

The mode of evolution

This "architectural evolution" does not follow a cladistic taxonomy, i.e. one species splitting in two and never returning to meet again. The designer tries to bring precedents from other designs into the one he wants to improve. D-genes are transferred from one design to another. The precedent will possibly need to be adapted to new materials, techniques and scale in use in the new situation.

The study of the three inventions showed many aspects such as that of the transference of features from one domain to another. These three inventions made it very clear that not the whole design precedent, but often only some features of each precedent are transferred. The next section will analyze more closely how certain features (presumably) evolved until their utilization in the Unité d'Habitation.

7.3. The Structure and Mutations of D-Genes

This section focuses on the description and presumable mutations of architectural genes (see Chapter 6 for definition), which evolved through time, as well as on an analysis of their linkages[27]. Subsequently, the section refers to the contribution of those changes in the genesis of new inventions. The objective of this section is to show how features were presumably transferred and adapted from one invention to another.

A final design representation expresses its phenotype, while its genotype is expressed by the design process.

Assumption 1: Chapter 5

In *Creation is a Patient Search,* Le Corbusier asserted that once a pictorial **impression** "has been recorded by the pencil, it stays for good, entered, registered, inscribed. The camera is a tool for idlers, who use a machine to do their seeing for

[27] Chapter 5 presented the study of mutant fruit flies that enabled biologists to understand the function and linkages of some genes.

them. To draw oneself, to trace the lines, handle the volumes, organize the surface… all this means first to look, and then to observe and finally perhaps to discover… and it is then that inspiration may come" (Le Corbusier 1960). Probably based on this statement, in the "Chapel of Ronchamp," Danièle Pauly claimed that Le Corbusier's sketches helped him to remember and to recollect them from memory when he was designing again (Pauly 1985, pp. 31-7). In other words, before Le Corbusier recollected any design precedents, he had recognized them in their potential to solve problems and sketched them to make his point(s) clear[28]; after processing the information from recognition to storage, they evolved due to their re-use. Le Corbusier saw (Le Corbusier 1960, p. 42)[29], recognized and stored certain intentionally chosen features of artifacts in his mind ready for future use and adaptation. This research focuses on the re-use and adaptation of genes already recognized. It refers to the storage of these "architectural genes" only with regard to what concerns their representation, since it will affect the way they may be re-used and recombined in different contexts.

A d-gene is not an element, but the instructions or recipe to develop this element; however, the following sub-sections will describe some of those elements (phenotype) and the history of their modification over time, in order to deduce their "architectural genes" and their possible "linkages".

7.3.1. Bottles, Wine Bins and Bottle Racks: 3 "linked genes"

This sub-section will first briefly present the ideas of the bottle, the bin and the bottle rack; second, it will indicate the modifications in re-use in relation to time; and finally, it will present some of its interdependency. The importance of the bottle, bin and bottle rack "d-genes" is to illustrate how one can represent linked d-genes/concepts and to show the important dependency among them.

Gene Linkage is the tendency of some features to appear often in combination with other features.

Assumption 6: Chapter 5

According to Le Corbusier, the metaphor "the house is a bottle" was first used by Perret (Brooks 1997, p. 162)[30]; however, this association would forever be inhabiting and evolving in the mind of Le Corbusier. The association started to play a role in Le Corbusier's thoughts during the design of Perret's La Saulot Hunting Lodge (Brooks 1997, pp. 161-5), and during the simultaneous

[28] According to Jordan (1972, p. 26), some of Le Corbusier's sketches were incomprehensible, others very beautiful, "and every one of them, presumably, done only to make a point."

[29] "*Others* stood indifferent - but *you saw!*" Le Corbusier. 1960. *Creation is a Patient Search.* New York: Frederick A. Praeger, Inc. p. 42

[30] Le Corbusier claimed, "une maison c'est une bouteille, est un mot de Peret, pas de moi." Quoted by Brooks (1997, p. 162) - from Le Corbusier's documentation on his own participation in the design of Perret's La Saulot,

development of Perret and Le Corbusier's Maison Bouteille[31]. The ground floor of the Maison Bouteille, claimed Brooks, "resembles an elongated octagon unencumbered by partitions; it rises two stories at the center with great window-walls facing both directions. At the upper level this space is overlooked by a transverse gallery that connects two lateral bedrooms at either end" (Brooks 1997, p. 166). It is exactly by looking at an elevation of the central space of both aforementioned designs that one can see the logic of Perret's association between the bottle and the house. With a few exceptions, these features reappeared eighth years later in Le Corbusier's Villa Schwob (Brooks 1997, p. 166)[32].

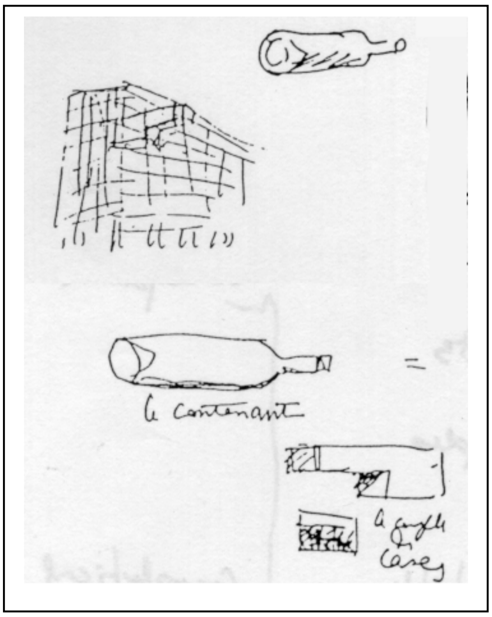


Figure 14: Analogies; the Bottle, the Wine Bin and the Bottle Rack

The concept of the bottle evolved. Disregarding the original central hollow space from which the association initially derived, the "bottle" notion became synonymous with "dwelling" in general. At a certain point, the bottle would mostly be represented as a bottle lying flat "somewhere", having its widest part representing the double-height living room. Indeed, in his book *The Marseilles Block*, Le Corbusier claimed: "having made our bottle, the dwelling, we can plump it down under an apple tree in Normandy or under a pine tree in Jura. We can equally well shove it into a pigeonhole, that is to say, into a space on the fifth or the seventeenth floor of a steel framework. It won't make any difference to the thing in itself or to the way we make it. Yes, we can put it anywhere we like in

[31] The analogy between the bottle and the house, like many analogies that Le Corbusier used, provoked certain shocked reactions, which made him justify some of its aspects: in Le Corbusier's words, "A bottle may contain champagne, Beaune, or just vin ordinaire, but the one we are talking about contains invariably a family. They may be rich or poor, but in any case they're just human beings (Le Corbusier 1953, p. 44)."

[32] Le Corbusier would indeed refer to the Maison Boteille as an important design precedent used during the development of Villa Schwob.

what we might call the supporting skeleton. Or more simply, a wine-bin" (Le Corbusier 1953, p. 44). The wine bin as mentioned above seems to suggest what he later called the bottle rack. Between the bottle and the bottle rack, Le Corbusier developed the idea of the case or bin: the bottle being the contained and the bin being the container, and the bottle rack as the support skeleton of them (Figure 14).

In other words, Le Corbusier expanded the bottle analogy to involve wine bins and bottle racks, which led him to produce a relatively independent structure for his Unité d'Habitation.

The bin most likely helped him to develop one of his most important inventions: the neutralizing walls (1929), which insulated the houses against possible noise from neighbors[33]. Another important contribution of the bottle and bin analogy seems to be the visualization of how to vary the size and form of the housing prototype according to the size of the families, and last but not least, how to group them (Figure 15).

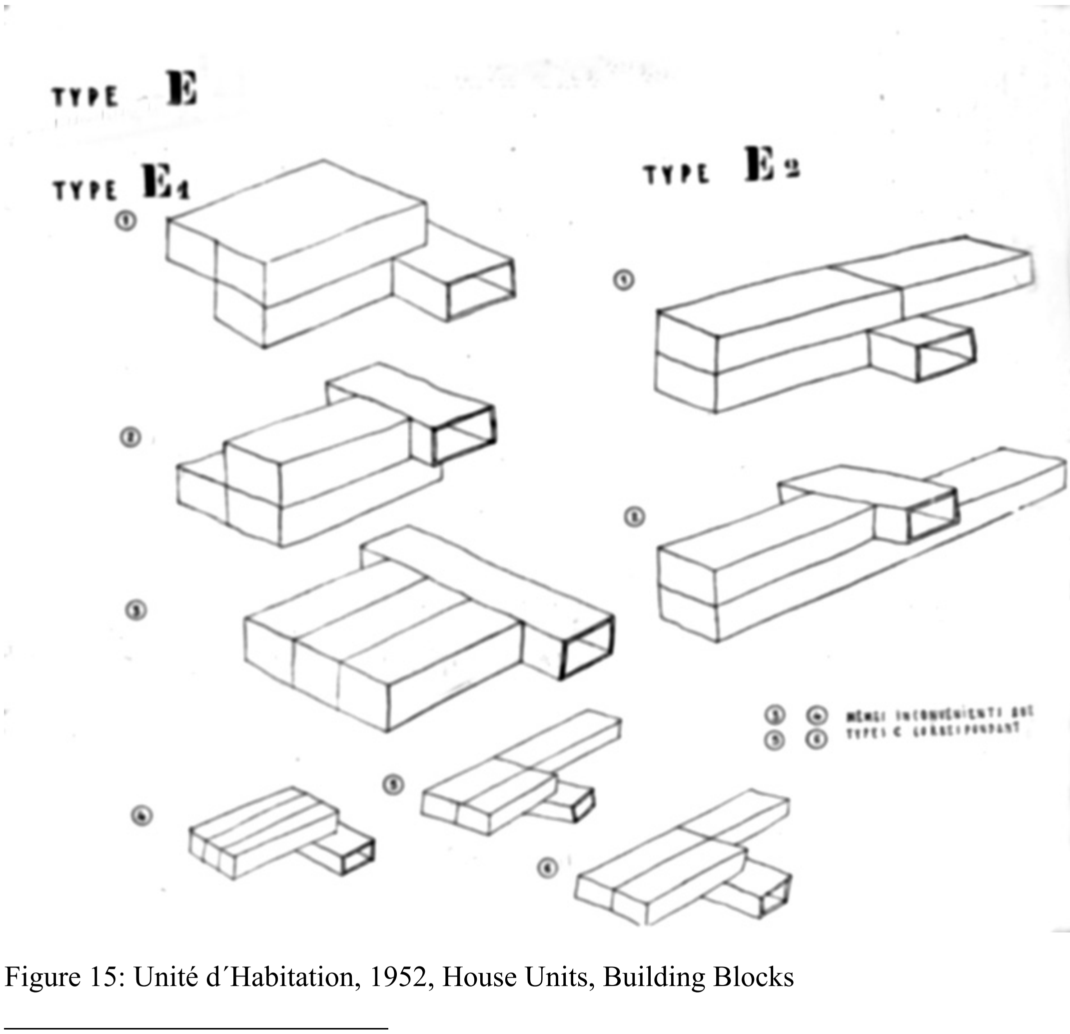


Figure 15: Unité d´Habitation, 1952, House Units, Building Blocks

[33] This invention increased the performance of Le Corbusier's concept of seclusion: the house as the cell of the Chartreuse d'Ema at Galluzo.

The bottle rack is the structural framework of reinforced concrete, which supports the weight of the bins and itself and transfers it to the piloti and the piloti to the foundation. The bottle rack helped the designer in stacking the dwellings (the vertical garden city) so that more ground would be made free for collective facilities and parks. Moreover, it was intended to favor the use of machines in the building site that would place complete units in the structure. An important feature of the columns and beams structure (the bottle rack) is that it exerts minimal interference on the internal layout of the dwellings.

These three features, the bottle, the bin and the bottle rack, supported flexibility in the size and form of the units and were used in an obviously linked mode: the bottles must fit into the bins and the bins must fit into the bottle racks (Figure 16). In the same way, the piloti must support the bottle rack structure that must carry the weight of the maisonettes, common services and roof garden.

7.3.2. Roof Gardens

The (hypothetical) origins of the roof garden will be traced by way of identifying its initial use, possible mutations and subsequent adaptations in the oeuvre of Le Corbusier.

As has already been mentioned, Le Corbusier worked for fifteen months in Perret’s office on rue Franklin in Paris between 1908 and 1909 (Brooks 1997, p. 183) and was quite impressed by this building. Brooks claimed that it has four of Le Corbusier’s five points for a modern architecture: roof garden, piloti[34], free façade and free plan. Due to its terrace on the top, it should be counted as a roof garden design precedent.

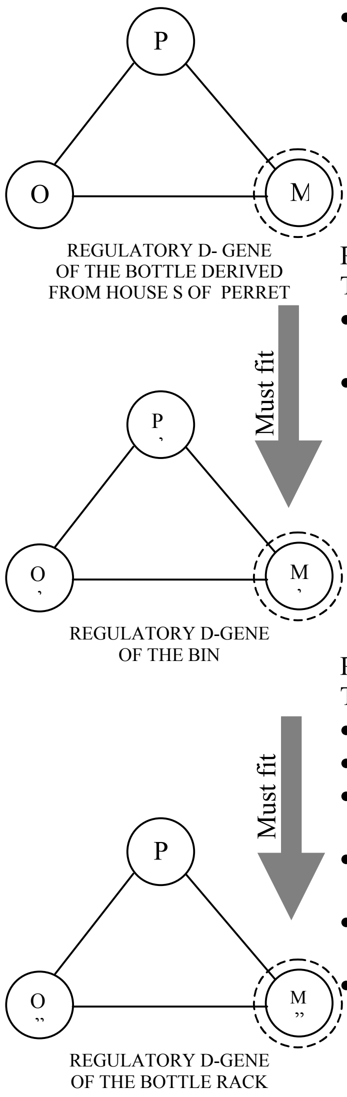
A second source of inspiration for the use of roof gardens is found among Le Corbusier’s sketches from his journey to the East of 1911, where one can find some houses with roof terraces and pergolas (Baker and Le Corbusier 1996, p. 160). These houses of Istanbul, claimed Baker, “with their cubic shapes, shallow pitched roofs, projecting bays, roof terraces and pergolas, were to inform his [Le Corbusier’s] domestic imagery for the next 20 years”.

[34] We would say that it would have the structure of reinforced concrete, using columns in place of bearing walls, which makes it possible to have a piloti. However, Le Corbusier's piloti is not only a structure, but also a (near) "naked" structure on the ground floor, and least one story high. Perret's office does not have piloti; it has a structural framework in reinforced concrete that makes the piloti possible.

BOTTLE

Operation
- The BOTTLE is provided with a functional layout;
- It has advanced household devices;
- It fits into the "bin" (M')

Performance
The BOTTLE must:
- Facilitate the activities of housewives
- Facilitate the circulation and functioning of the day-to-day actions of the inhabitants
- Favor health: air, light, sun, and nature



BIN

Operation:
- The bins are easily grouped;
- The bins let the architect visualize the variables of the prototype (size and form);
- They have neutralizing walls
- They fit into the bottle rack (M")

Performance
The BIN must:
- Facilitate grouping and variation of the dwellings
- Favor seclusion and silence

BOTTLE RACK

Operation:
- The framework supports grouped bins
- It transfers weight to the building foundation
- It gives flexibility in size of the dwellings and freedom to the plan layout and façades

Performance
The BOTTLERACK must:
- Facilitate free plan
- Facilitate free façade
- Facilitate the use of a roof garden
- Favor health: air, light, sun, nature
- Facilitate stacking of diverse sizes and formats of dwellings
- Facilitate the operation O'

Figure16: Linkage of D-Genes that develops the concept of the Bottle, Bin & Bottle Rack

Not long after this trip, Le Corbusier "applied" the roof garden in a hypothetical reform of Georges Favre's "Haunted House" (1912), a seventeenth-century farmhouse that was to be demolished. Brooks emphasized: "Jeanneret visited it after the roof and wooden superstructure were removed and only the masonry walls remained." It seems that the view of the farmhouse without the roof made him recall the houses of Istanbul; and it is possible that his knowledge on reinforced concrete acquired while working with Perret might have triggered his mind concerning the possibility of using of this feature even in his own country. Le Corbusier sketched, asserted Brooks, how the old structure might be re-used to create a modern villa and the flat roof was trellised to become a roof garden (Brooks 1997, p. 342).

Villa Schwob of 1917 was the first house built in his oeuvre to show this feature: a roof terrace with planter boxes (Brooks 1997, p. 431). From there on, this feature, a private terrace/solarium, reappeared on other houses such as the Dom-Ino houses; in all Citrohan houses, Maison Cook of 1926, Villa Stein-de Monzie of 1926-1927, and Villa Savoye of 1929. In the Immeubles Villas of 1922 and in the Unité d'Habitation, the roof garden was applied with modifications.

In the Immeubles Villas, his first multi-familial project, each unit had its own private garden. This idea is not only derived from the Maison Citrohan, but also from recalling the Chartreuse d'Ema. At this monastery, Le Corbusier recognized the value of "reclusive versus collective life": the cell-and-garden units of the monks of the Chartreuse d'Ema in contraposition to the courtyard, church and reception that had a collective character. This was a recognition, according to Brooks, that "individuality and community life could coexist – and in fact strengthen one another in the process" (Brooks 1997, p. 106). Cells, gardens and courtyards are elements that would be recalled and adapted to his Immeubles Villas.

On the one hand, from the building level, it was a hanging garden such as those of the other maisons: an elevated garden that belonged to the family and offered great views. On the other hand, from the dwelling level, the garden's position was atypical; it was not on the roof. It was placed at the "ground floor" of each house unit having a double story just like the adjacent living room.

This position in combination with the way Le Corbusier grouped the units granted more privacy to the inhabitants (Figure 17) than if the gardens were adjacent to each other on top of the units. In the Immeubles Villas, the use of individual "roof" gardens would present several disadvantages. Firstly, if each maisonette had three stories, the access to the above-stacked unit would be strenuous to say the least[35]. Secondly, if all the units were adjacent to each other, it would create a floor for the individual gardens; and if we would like to give this garden the same quality that the Citrohan roof garden had (filled with light and sun), then this floor would have

[35] Le Corbusier planned two elevators for the reception; however, staircases between the apartments suggests that the daily vertical circulation would be conducted via the stairs.

to have a double height. This solution would only worsen the problem of vertical access as mentioned above.

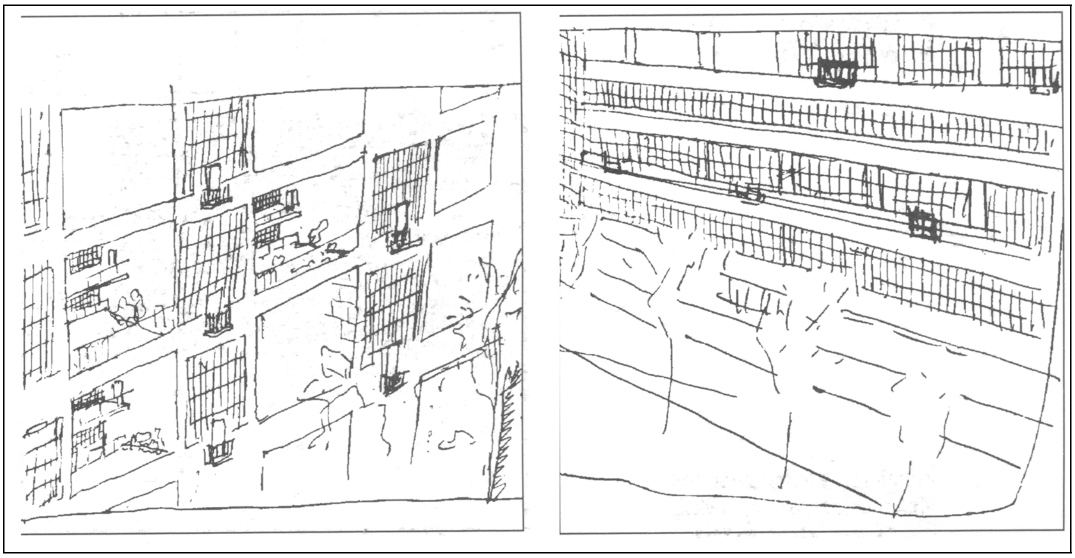


Figure 17: Designing the Gardens of the Immeubles-Villas, sketches

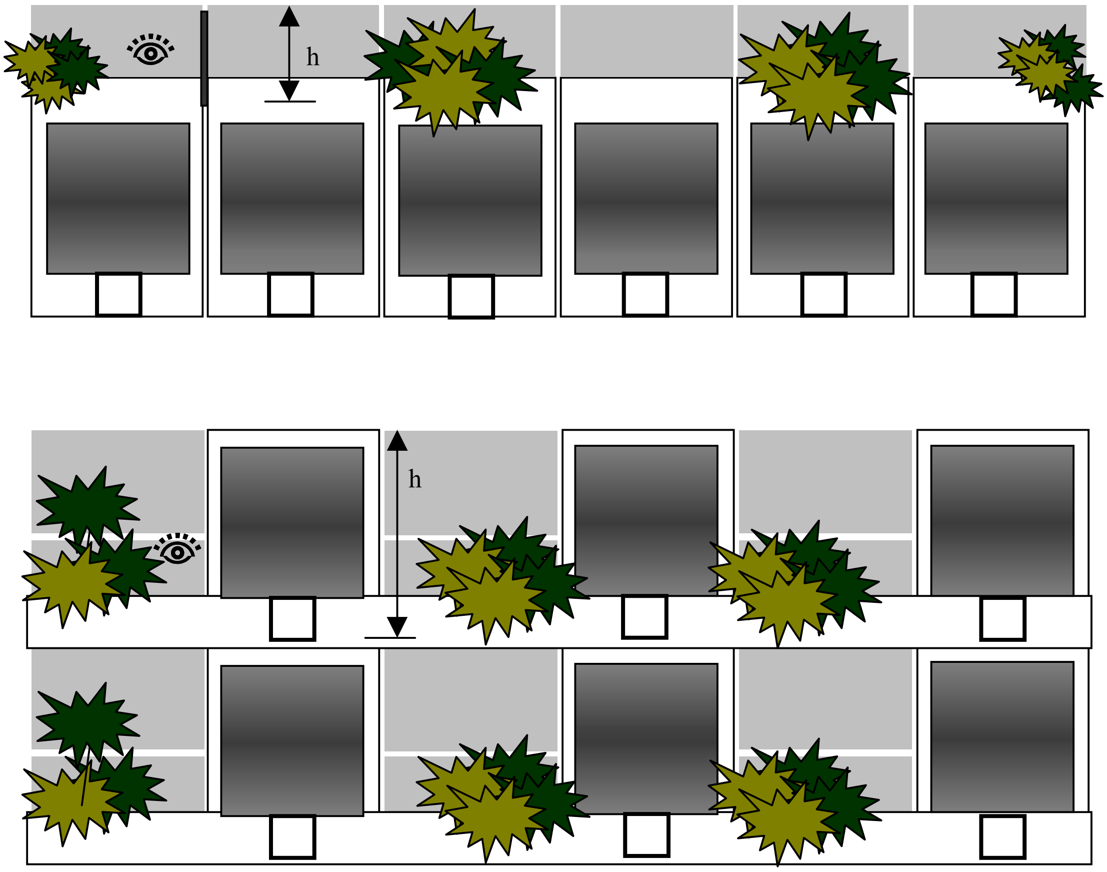


Figure 18: The Position and Characteristics of the Gardens of the Immeubles Villas

Placing the garden adjacent to the double-height living room (Figure 18), Le Corbusier created the possibility of making it at the same height, giving it plenty of light and protection from unwelcome views from the neighbors. With this solution, the hanging garden still had the most attractive quality of the roof garden: it was an open space for the recreation of the single-family; and in most cases, it was a hanging garden.

After this mutated application of the uni-familial roof garden in the Immeubles Villas (1922), the "normal" roof garden would often be used as before; i.e. a private terrace on top of the building (e.g. Villa Stein-de Monzie, 1926; Villa Savoye, Poissy-sur-Seine, 1929, and so forth).

However, Le Corbusier would bring another precedent of roof gardens to his design thinking: the deck of the Ocean Liner, which is a roof garden for all travelers. It belongs to the whole community, provides great views of the surrounding landscape as well as amusement for all passengers. Naturally, having seen the roof gardens of Istanbul houses as a main feature for his architecture, Le Corbusier then saw with ease that the deck of the Ocean Liner could significantly improve the fitness of new inventions such as the Unité d'Habitation (Figure 19). The roof garden of the Unité is not just a private terrace on top of a building or a private garden for each unit; it evolved to be a communal open space with facilities to suit all the inhabitants of the building: from a children's playground to a gymnasium (see table 2). Only the very rich could dream of pursuing such an audacious infrastructure. However, it fitted perfectly within this multi-familial building for the worker.

The initial variation of the roof garden did not die out; it continued to appear in other projects such as in the Vila Shodhan of 1956 in Ahmedabad, India.

Proceeding from the gene structure presented in Chapter 6, the generation of the roof garden on top of the Unité d'Habitation can be represented as follows: when applied to the Unité d'Habitation, the ocean liner deck would be read thus: "The views of Unité d'Habitation are enjoyable (P) <u>because</u> people can look from high up (O) <u>thanks to</u> its 'piazza' roof (M)." This corresponds to information at our regulatory d-gene level.

ROOF GARDENS DERIVED FROM HOUSE S OF ISTANBUL AND PERRET'S OFFICE

Roof Garden: Regulatory D-Gene of the Vernacular Houses of Istanbul

This roof garden was used in Citrohan houses and became part of Le Corbusier's five points for a modern architecture.

The Immeubles Villa had a slightly modified copy of this concept.

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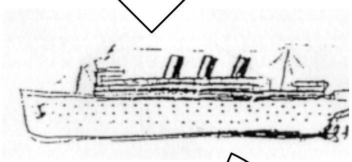


Roof Garden: Regulatory D-Gene of the Ocean Liner (O.L.)

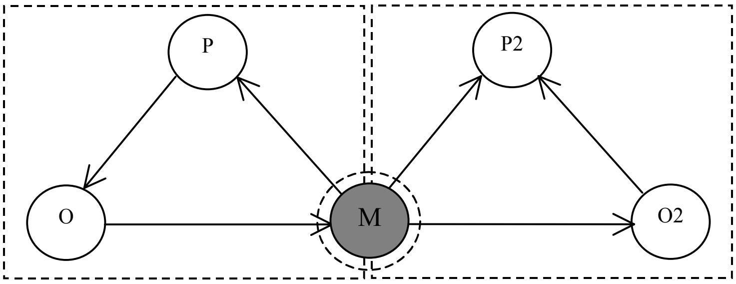
ADDED TO:

Performance (P):

Enjoyable views of its surrounding;

Healthy activities for the inhabitants

Structural Performance(P2):



Roof Garden: Adding the Regulatory D-Gene of the Ocean Liner to the Unité d'Habitation

REGULATORY D-GENE OF THE O.L.

STRUCTURAL D-GENE OF THE UNITÉ D'HABITATION

Operation (O):

People can look around from high up

People can join sportive activities on the roof garden

Morphology:

Deck roof: "the way the building comes up and terminates onto a public terrace." A "piazza" on the top of the building.

Struct. Operation (O2):

Rely on reinforced concrete, which can structurally support all activities.

Figure 19: D-Gene Mutation, Roof Garden

Examples of Elevated Gardens in Residential Projects		Characteristics
Design Precedents:	Perret’s office (1908).	Terrace on top of a building of reinforced concrete
	The houses of Istanbul (1911);	Terraces with pergolas on top of vernacular houses
	The Ocean Liner	
Re-use and Adaptation:	Farmhouse: Haunted House (1912);	Terrace on top of the building
	Maison Dom-Ino (1914-1919);	Terrace; reinforced concrete
	Villa Schwob (1916);	Terrace with planter boxes; reinforced concrete
	Maison Citrohan (1919-1927);	Roof garden and solarium Reinforced concrete
	Immeubles Villas (1922);	Each apartment had its own garden. Not on the top of the building; Not on the top of the unit. Reinforced concrete
	Maison Cook (1926);	Roof garden and solarium; Reinforced concrete
	Villa Stein de Monzie (1926/27);	
	Villa Savoye (1929);	
	Unité d’Habitation	Kindergarten, playground, covered and open-air gymnasium, 300m running track; swimming bath, high level solarium; lift shafts, water tank; ventilation shafts; Reinforced concrete Higher domain: the building community
	Villa Shodhan (1956); Ahmedabad, India	Ibid. Maison Citrohan

Table 2: Examples of Elevated Gardens in Residential Projects

According to Ng, “Traditional rooftops were convex because the house had been heated with stoves. With the implementation of central heating, it was appropriate for the roof to be flat. Reinforced concrete aided the realization of this homogeneous roof. However, reinforced concrete experienced a great deal of expansion and contraction, and intense movements of this sort could cause cracks in the structure. This problem was solved by having a constant humidity for concrete, which also assures a regulated temperature. The sand and roots of the garden terrace permitted a slow filtration of the water, thereby achieving the constant humidity and regulating temperature without the need for rapidly draining away the rainwater. Sand, a good form for protection, was covered by thick cement slabs with staggered joints which were seeded with grass. Besides its functional purpose, roof gardens also symbolized the idea of health-giving relaxation" (Ng).

One of the genes of production of the Unité d'Habitation would then read: if the "piazza" were to rely on reinforced concrete technology (according to the laws of mechanics) (O2), then the piazza could be structurally feasible (P2). A "piazza" roof on a framework of reinforced concrete will meet the requirement of enjoyable views and entertainment for all (regulatory d-gene) and is structurally feasible (structural gene).

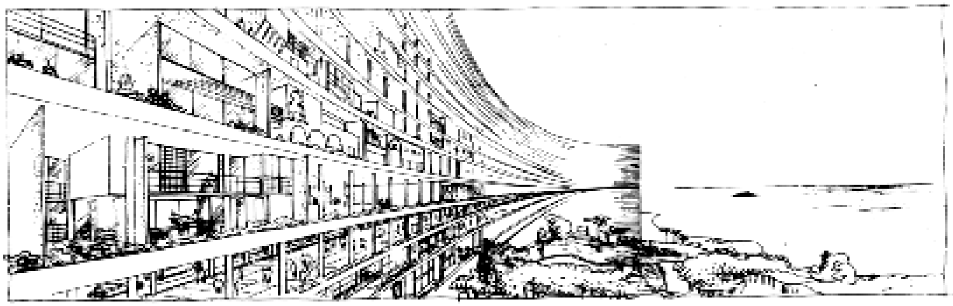
7.3.3. The Representation of the Piloti

In the Unité d'Habitation, not only the roof garden, but also the piloti and the free façade concepts changed their domain level: from the private (the dwelling) to the collective (the building). The free façade concept was initially tried out at the level of a Citrohan house as well as at the level of the unit, such as that of the theoretical multi-familial building (Figure 20), and then to a free façade at the level of the building block, where the façades of the units are standard but combined other parts to make the whole.

The first time that Le Corbusier used the piloti was during the design of his Citrohan house of 1922. Presumably, it was at this point that Le Corbusier[36] asked himself: "Do I know any products which do not disrupt the natural continuity of the terrain (Tzonis 1992)?" He searched through his memory to find a precedent that would fulfill his intention of not disrupting the continuity of the terrain and came up with the "savage hut" which, being supported by stilts, did not disrupt it. A process of recognition of characteristics of the stilts (piloti) took place. Further analysis of the element would suggest that the piloti could suit other purposes as well, such as that the piloti allowed air to circulate without obstruction under the buildings, thereby protecting it from humidity; for this reason it was also environmentally good[37]. This feature was then used in his Citrohan of 1922, stored in his memory and archives for later re-use in most projects.

[36] Tzonis asserted that the piloti of the savage hut was a direct precedent of the Unité. Because we are also studying the phylogeny of the genes here, we prefer to place the question much earlier, in 1922, when Le Corbusier used the piloti for the first time in his designs.

[37] Naturally, this is a hypothesis; the questioning did not need to be at a conscious level and also not in this order of facts; i.e. Le Corbusier could very well have searched for a solution which could free the construction from humidity.



Citrohan 1922

Free façade: from a free façade at the level of the unit such as that of the theoretical building above and that of a Citrohan house (left), to a relatively less free façade at the level of the building block.
Piloti: the concept of a naked structure functioning as a garden or garage under a private house (left) evolved into a naked structure functioning as a park /reception for all the inhabitants under the building block (below).

Unité d'Habitation of Marseilles

Figure 20: Change between domain levels

As Tzonis asserted in his article, Le Corbusier was selective in what he transferred. He was neither interested in the 'body' of the hut (room) nor in its 'top' (roof), only in its stilts. Looking deeper, we would claim that Le Corbusier was also not interested in all of the information of the piloti, but in the regulatory d-gene[38] of the piloti, i.e. in its pattern of arrangement. When challenged to find some precedent that did not disrupt the natural continuity of the terrain, he

[38] We recall, for example, (Chapter 5) that when one substitutes the small-eye hox gene of a mouse for that of a fruit fly, the fly will develop an eye but not a camera-like eye like that of the mouse (Maynard Smith 1998).

considered the overall configuration of the piloti and some of its operations. However, at that stage, he was not interested in measure, material, technique or technology; he was not interested in its structural gene (Figure 21). The transference of the piloti can be represented as a "genetic rescue" analogous to the example given by Maynard Smith of the hox gene of a mouse's eye being transferred as a substitute for the fruit-fly eye, if we think of the potential of Maison Dom-Ino in developing this structure.

During Le Corbusier's "40 years of gestation" of the Unité d' Habitation, the piloti first appeared in the Maison Citrohan and through re-use it changed from slender stilts to gargantuan columns; and from the individual domain to the collective domain.

Structurally, the piloti is a part of a building structural framework formed by columns and beams or slabs. While each story contains a set of columns mostly wrapped up by a "skin" (walls, glass etc.), the piloti is mostly exposed. It was produced in reinforced concrete but also in steel, e.g. in the double Maison Citrohan of Stuttgart, and distributed the structural forces to the building's foundation.

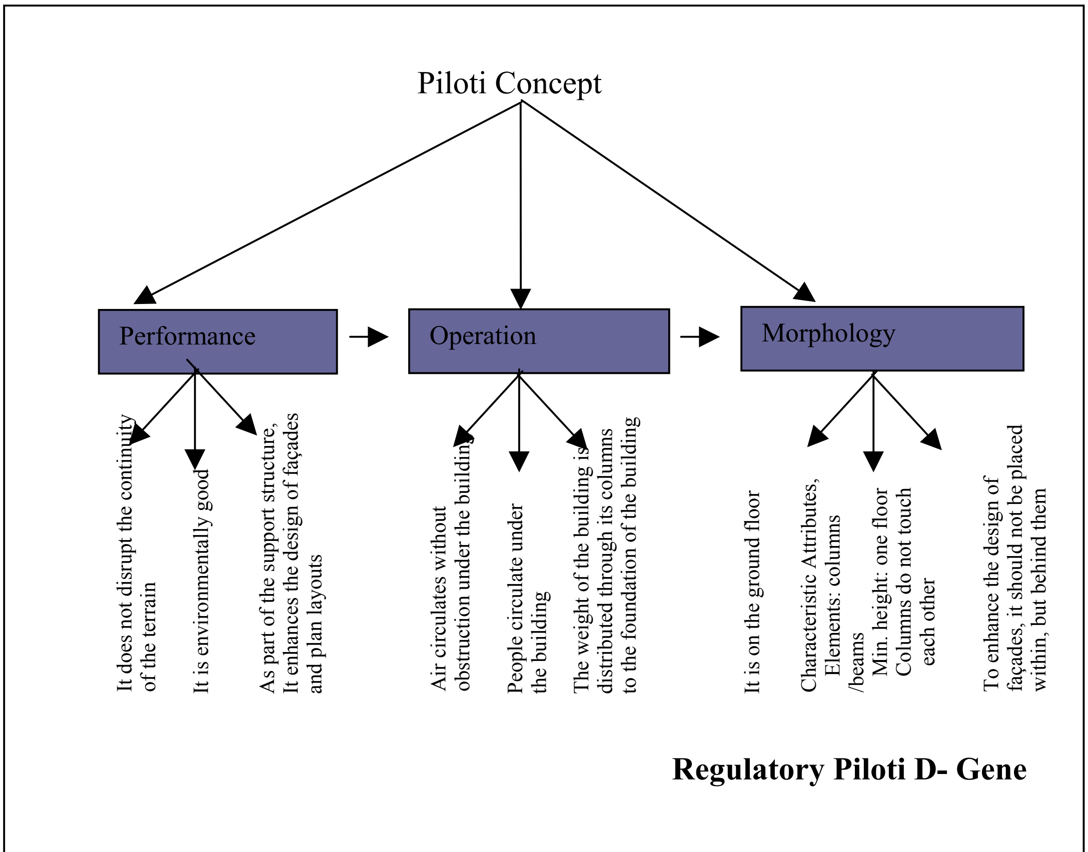


Figure 21: Regulatory Piloti D-Gene

The piloti is not just a set of columns; it is a set of columns at the ground floor, which in addition to supporting the artifact, should permit cross-ventilation to protect the building against humidity. Therefore, it should have none or only a few enclosure elements. Morphologically, it is composed of columns that do not touch each other; and it is at least one story high to permit the circulation of people. The space generated by the columns may function as access to the building as well as a garden, garage, and/or recreation area. In the Unité d'Habitation, the piloti was supposed to be used on a large scale (several buildings in an environment), and was intended to permit the view of an open landscape on the ground floor level and be used collectively; in other words, the notion of piloti evolved from the private domain to the collective, first because of its potential to meet other needs on a larger scale, and second because it was compatible with other innovations.

Together with the rest of the structure, it was intended to free façades and plan layouts. This formed a chain of links which could be read as the following: to enhance the design of façades, neither the piloti nor the columns of the framework should be placed within but behind the façades plane; to enhance a stable structure, the piloti needs to be linked to the total structural framework; and to enhance the design of free layout plans, the piloti and framework should allow partition walls to be freely placed in the layout, thereby freeing the layout of the units as well as permitting diverse house sizes (table 3).

7.3.4. Before Ontogeny

So far, this chapter has shown the contribution of precedents from invention to invention such as from the Maison Dom-Ino to the Maison Citrohan, and from that to the Immeubles Villas. This section has also described the modification of some features and illustrated how some individual features were possibly re-used and modified over the years.

One of the examples mentioned in this chapter was the "regulatory d-gene" of the roof garden, which seemed to have originally come from the vernacular houses of Istanbul, Turkey. Later, by a recombination with the "regulatory d-gene" of the deck of the ocean liner it evolved into the roof garden, which was used on the Unité d'Habitation. Another example given was that of the piloti (hypothetically). Seeking to protect the houses from humidity and seeking a structure that did not obstruct the continuity of the landscape, the piloti was transferred with modifications from the savage hut (through many of Le Corbusier's projects) to the Unité d'Habitation of Marseilles. It was translated into a colossal reinforced concrete piloti presumably to give the idea of a monumental artifact. This piloti did not belong to the individual /family domain, but to the building community, i.e. to the collective.

Regulatory Piloti D-Gene		
PERFORMANCES Looking for something that:	OPERATIONS Testing the precedent according to performance:	MORPHOLOGY Geometrical configuration and topology of the piloti
Must be environmentally good Must protect the building from humidity Must get plenty of light and fresh air Must not disrupt the continuity of the terrain	Air circulates without obstruction under the building Dwellings get more light and fresh air because they are lifted The view of the landscape is not disturbed The space may function as a garden, park, garage and/or services People circulate under the building	Piloti: the way the building rises on stilts. The piloti is on the ground floor. Its columns do not touch each other. The piloti is never totally enclosed by partition walls. If any, few partition walls. Its minimum height is one floor
Structural D-Gene (for a Unité D'habitation Around 1600 Inhab)		
The piloti ought to support the weight of the unité d'habitation of 1600 inhabitants (18 floors). It must transfer forces from the structural framework to its foundation	Option considered and tested: a structure of reinforced concrete can provide a stable framework	Piloti of reinforced concrete according to the recipe provided by the regulatory gene, stable and fitting the new project, in particular, fitting the linkages.
Linkages:		
Together with the rest of the structure, it should free façades and plan layouts.	To enhance a stable structure, the piloti needs to be linked to the total structural framework. To enhance the design of façades, piloti and framework should not be placed within but behind the façades plane. To enhance the design of free layout plans, the piloti should allow partition walls to be freely placed in the layout.	In combination with the framework, it is placed backwards to provide (a relative) independency of its façades. In combination with the framework, it does not contain bearing walls. Therefore, it frees the layout of the units, permitting diverse house sizes.

Table 3: Piloti D-Gene

These mutations and re-uses seem to have depended on the following factors: first, on the need for “change” setting Le Corbusier’s mind in the search for solutions; second, on the transference of features, for example, the deck of the ocean liner (and not the whole ship) to the Unité; and third, on the adaptation of this design precedent which must fit the Unité’s overall structure.

Curtis also made clear that Le Corbusier transferred what we call regulatory genes and structural genes from one design to another with the following assertion: “As Le Corbusier proceeded from one design to the next, he added new discoveries to his stock of inventions. Some of these were simply variations on type solutions, such as novel ways of joining pilotis to slabs. Others were schematic arrangements for plans and sections, such as contrasting curved partitions with grids, using opaque street façades and transparent rear façades, or placing small rooms low down houses and larger ones higher. Taken together these all constituted the elements and rules of combination of an evolving personal style, and after 1925 the architect had a clearer understanding of the implication of his forms.” (Curtis 1975, p. 76).The next section will illustrate how the ontogeny of the Unité could hypothetically have happened.

7.4. Ontogeny of the Unité d’Habitation

In nature, the development of the embryo begins when the regulatory genes are activated by fertilization. Cells then multiply and, because each cell knows where it is and because each cell has all the information on how the organism should be “built”, they proceed with defining symmetries, subdividing and differentiating patterns, which will result in the formation of various parts of the body, and finally the whole organism, without needing a central organization. However, the cell itself has a central organization containing a “grand plan”, and the instructions of this grand plan are given by regulatory genes.

> Like in nature, the design is generated by a set of instructions that guide its development from zygote to organism, from sketch to the detailed project.

Assumption 3: Chapter 5

One of the interesting regulatory genes was the hox gene, which is organized in clusters within chromosomes. They are placed in order: from the head of the organism to its tail, and they execute the plan by switching other genes on and off. Mice and humans have four clusters containing the same “recipe”[39], while fruit flies (Drosophila melanogaster) have only one. Therefore if, during development, a

[39] However, some clusters seem to miss some hox genes here and there.

genetic engineer makes a gene of a fruit fly collapse[40], or changes its position within the cluster, a certain feature will be lacking, or will grow at another position. The work of hox genes seems to be realized hierarchically from head to tail and from the general to the particular.

Proceeding from this analogy, this section will present aspects of the "ontogeny" of the Unité d'Habitation of Marseilles. The section refers to the evolutionary model as presented in Chapter 5, the architectural gene description as presented in Chapter 6, and the descriptions of the precedents as presented earlier in this chapter.

7.4.1. The Grand Plan: D-Genes and Linkages in the Unité d'Habitation

As has already been mentioned in this chapter, Le Corbusier claimed that the Unité d'Habitation was the result of "40 years gestation". This research suggests that this "gestation" was not a question of development (ontogeny) but of lineage (phylogeny). However, this chapter has illustrated the fact that the creation of the Unité was not the result of a consecutive combination of two design precedents or, in other words, a direct descent, from two parents to offspring, through the generations.[41] The creation of the Unité seems to be the result of the re-use and modification of specific elements, often in small chains of linkages such as Le Corbusier's five points of a modern architecture, or his bottle, bin and bottle rack "linked d-genes". He had at that moment a huge gene pool at his disposal, ready to be used.

D-genes may be transferred from one design to another, even if they belong to other species.

Assumption 5: Chapter 5

In designing the Unité, Le Corbusier's task was to provide a housing scheme for workers in the situation after the Second World War. His solution grouped 330 units to house a community of roughly 1600 inhabitants in an 18-storey building providing extensive services to the community. This was a unique opportunity to put all his ideas concerning multi-familial housing schemes into practice. He had already developed the three inventions described earlier, as well as many other concepts at the city planning level such as the concept of the vertical garden city. The Unité d'Habitation for the workers of Marseilles was the result of all these studies. In designing the Unité, he recalled many of those concepts; some of a

[40] In mammals such as mice and humans the prejudice seems to be minimized because they have four clusters with the "grand plan".

[41] This also seems to be the case of other designs carried out in architectural practice.

general order (light, sun, greenery) but also others that could be translated into architectural elements (the piloti, the roof garden, the free façades, and so forth).

Many parts of this building block were already developed in detail through experiments in other designs. But first he needed to have an overall framework. Le Corbusier had to assemble the right features into a whole to match the new desired configuration. In his world full of metaphors, he placed bottles (dwellings) into the bins (neutralizing walls) and the bins into the bottle rack (structural framework); a collective roof garden on top of the structure with activities for all inhabitants and a piloti freeing the whole block from the humid ground, providing the whole community with parks, schools and other extensions of the home.

As shown earlier in this chapter, it was not only a question of assembling the existent elements, i.e. recalling them and putting them together. They needed to be adapted to the new constraints. By constraints, we mean the particularities of a commission such as the budget available; the particularities of the site such as its landscape and climate; and also the selected technology and materials. Due to these constraints, mutations occurred[42].

Some “d-genes” changed their physical expression, i.e. their pattern or structural configuration changed such as the change of the slender piloti of the houses of the 1920s to the gargantuan piloti of the Unité. Other d-genes changed domain, meaning that the resultant element acquired uses different to the original one, such as the roof garden that was originally a family garden; after its recombination with the deck of the ocean liner, it became the square, the club, the gymnasium of the building block community. As mentioned above, some of the linked “five points of a modern architecture” from 1927[43] were used in a mutated form. In other words, **the initial linkage was broken; some genes mutated, and were recombined and re-used in the Unité** (Figure 22).

As an independent structure, the bottle rack allowed the creation of maisonettes of 23 different sizes and shapes to house[44] different types of families as well as the creation of a whole infrastructure of services for the block community. Elements such as the roof garden, bottle rack and piloti, gave the general structure of the Unité (Figure 23).

[42] However, Le Corbusier’s gene pool retained not only the modified genes, but also the “original” ones.
[43] When Le Corbusier designed House 13 of Stuttgart
[44] The variation of the maisonettes was, however, based on the addition or subtraction of cells (rooms) of a prototype (Type E). The cells did not vary in size or layout.

In the work of Le Corbusier, the d-genes (instructions pertaining to the making of elements) are units of selection like the selfish genes of Richard Dawkins[45]; they are recalled or selected via artificial selection (see Chapter 5), or, in other words, by their phenotype. They evolve by recombination, by adaptation to the new context imposed by their new sets of constraints. The combination of a series of regulatory genes as well as a recombination of their linkages supports the development of a new kind of "organism" or invention. Structurally, the resultant building should become a stable structure. Le Corbusier[46] differentiated his structure dimensionally, searching for the ideal proportion.

There are three units of selection:

1. The genes: not as Dawkins proposed, but we will consider the selection of the expression of genes. In other words, the selection of features (phenotypes) by the designer carries with itself the genetic instructions.
2. The organism: selection of a project.
3. The group: selection of prototype.

Assumption 7: Chapter 5

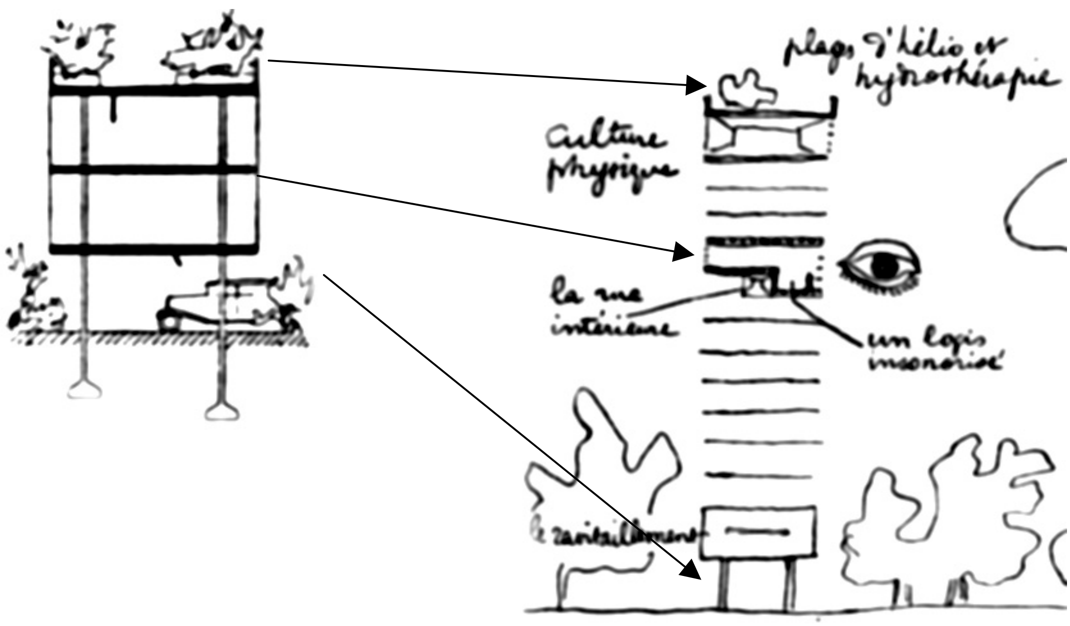


Figure: 22: The Mutated "Five Points of a Modern Architecture"

[45] Therefore, they are units of selection.
[46] If he was not the master of reinforced concrete!

7.4.2. The Grand Plan: between Standardization, Proportions and Structural Forces

The building should also show good proportions. To acquire them, Le Corbusier used another of his inventions, the "Modulor". This was a three-dimensional system to support standardization and the finding of satisfactory proportions for artifacts. At this point, we could ask ourselves: "was the development of the Unité constrained by the Modulor?" This sub-section will briefly speculate in this field, focusing on the size and width of the piloti of the Unité. An entire thesis would probably be necessary to argue and test the hypothesis put forth here. However, because of the great importance of this tool in his designs, we cannot avoid mentioning it here. The Modulor was developed between 1940 and 1955, but the greater part of it was conceived during the Second World War. Elise Maillart, of the Museum Cluny and author of *Du Nombre ed'Or*, contributed to the development of this tool, as did her student Hanning, "who had worked assiduously on the problem for three years and had secretly crossed the Savoy frontier line to see Le Corbusier" (Jordan 1972, p. 108). The Modulor makes use of the Golden Section, Fibonacci numbers, and of the physical dimensions of the average human. In fact, the formula creates an infinite number of Golden Rectangles. Le Corbusier described the developing process and his findings in his *The Modulor* (Le Corbusier 1954).

he objective of Le Corbusier in using the Modulor was to bring order to design and to support industrialization. A "common measure capable of ordering the dimensions of that which contains and that which is contained: capable, in other words, of offering a solid pledge of satisfaction to supply and demand" (Le Corbusier 1954). It was a system of measurement to: a) support architects and designers in producing artifacts with the right proportions; and b) to support industry, in particular the building industry, with a basis for universal standardization.

The Modulor was first used on the Unité d'Habitation and, according to Le Corbusier, made use of only seventeen measurements. In fact, claimed Jordan, "All the buildings that Le Corbusier designed in the twenties bore witness to his then rather rudimentary conception of an architecture based upon some sort of proportional system" (Jordan 1972, p. 123); "Le Corbusier used his system," claimed Jordan, "to fix all the dimensions of the Unité d'Habitation: its total form and shape, its volumes as well as its planes, its spaces as well as its solids" (Jordan 1972, p. 123); this leads us to the thought that the system could influence the size of the structure and composition of the building.[47]

[47] Le Corbusier later came to agree that his Modulor could not help all architects in producing good designs; there were terrible results arising from it.

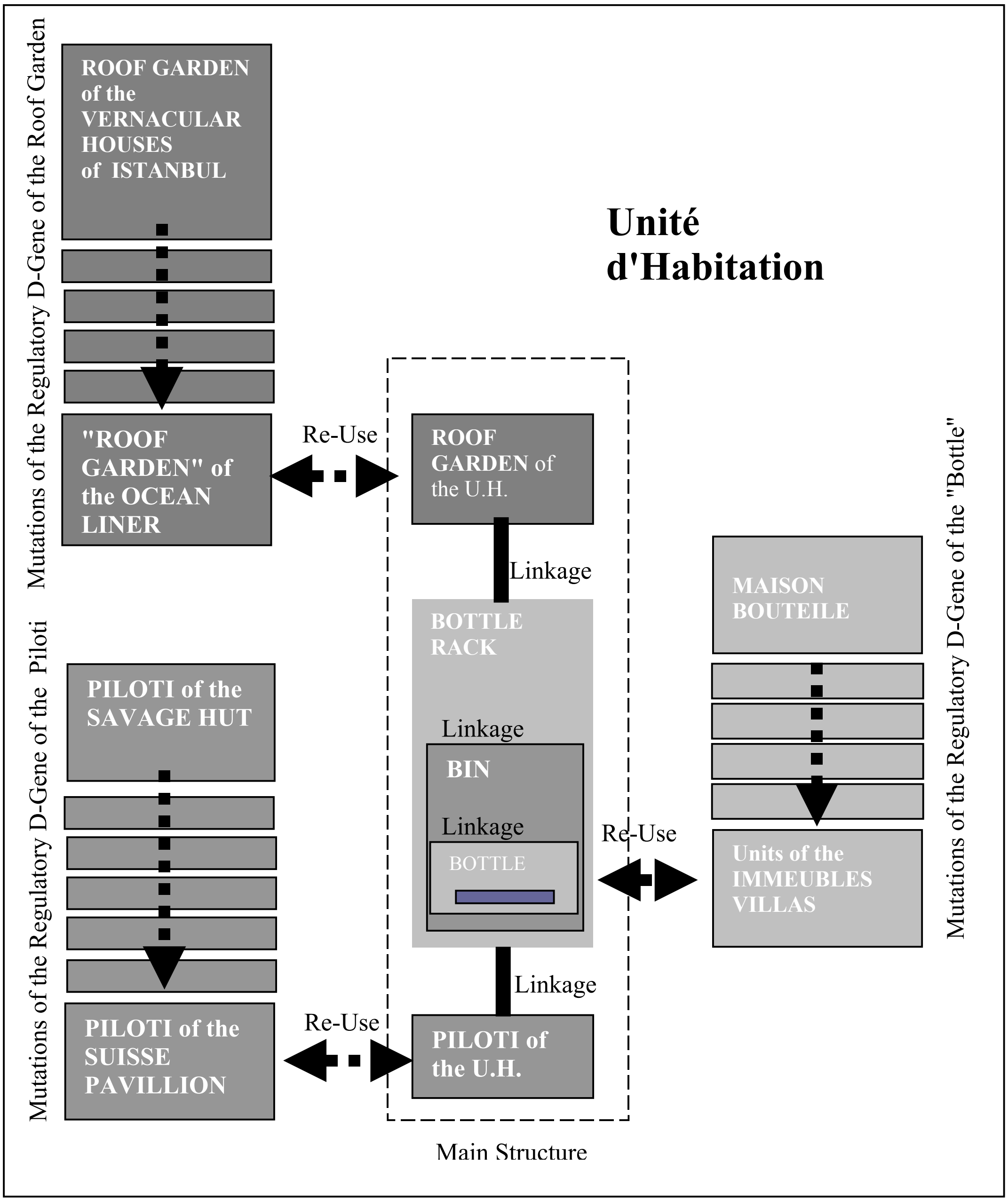


Figure 23: Main Structure of the Unité d'Habitation and the Re-Use of Design Precedents

Taking the example of the gargantuan columns that make the piloti, we may ask whether they were esthetically necessary or whether they were a result of this system of proportions; in other words, if an analysis of the structural forces of the building was neglected because the attention was focused entirely on defining the proportions according to the Modulor. According to Jordan, with this system, heights, widths and volumes could be infinitely varied in size, but not infinitely varied in proportion: “Size is unlimited, proportion is controlled; you have variety but not chaos” (Jordan 1972, p. 107).

Were his proportions constrained by the forces at work on the structure? According to D’Arcy Thompson (Chapter 5), heights, widths and volumes cannot be infinitely varied in size without consequences for the stability of the whole structure. As D’Arcy Thompson claimed, “it often happens that of the forces in action in a system some vary as one power and some as another, of the masses, distances or other magnitudes involved” (Thompson 1992, p. 25). This is due to Galileo’s principle of similitude or dynamical similarity. Esthetic proportions alone will not make the structure fit.

Were then the height and width of the piloti intentional or a result of the use of the Modulor? It could be a rewarding experience to explore this system to see to what degree structural forces were considered, even if not consciously. In order to bring the idea of intention into such an analysis, we would have to compare the sizes of the piloti of the Unité with other buildings such as the Pavilion Suisse to evaluate how far the gargantuan piloti was intentionally designed to give rise to a monumental character of the whole; whether it was due to structural forces or a consequence of the use of the Modulor. However, the study of the influence of the Modulor in Le Corbusier’s designs is beyond the scope of this research and we must leave it outside this thesis.

7.5. The Phenomenon of Change: Conclusions

By relying on Alexander Tzonis’ P.O.M. reasoning system as described in his article “Huts, Ships and Bottleracks: Design by Analogy for Architects and/or Machines” to describe the architectural gene, we have applied the ten assumptions from Chapter 5 and explored Le Corbusier’s design precedents such as the savage hut, the ocean liner, and the wine bottle rack.

The chapter has described the process of re-use of design precedents over the years. Some architectural features were recombined and adapted at various moments to form inventions such as the Dom-Ino and Citrohan houses as well as the Immeubles Villas. In describing the five points for a modern architecture, as well as their adaptation to different conditions, we observed that some features also changed domains: from the private to the collective. For example, the assertion of Perret, “the house is a bottle”, played a role in Le Corbusier’s thinking for the rest of his life. Salut, the hunting lodge of Perret, was designed at the same time as Le Corbusier and Perret’s Maison Bouteille. In both cases, as well as in the design of Maison Schwob, one can see in cross section what Perret meant. In the course of Le Corbusier’s career, he begun to design houses, which were not organized from around their center as the houses above; the new houses followed a zone system. However, the bottle would still represent the dwelling: the bottle would “lay down" to represent the Citrohan houses. Le Corbusier would claim that he could place this bottle anywhere, even in a pigeonhole; and with this statement he meant that the dwelling was now "siteless". If bottles could be placed in pigeonholes, why not place them in a (less bizarre) bottle rack? This leap in thought would bring about an independent structure that would permit not only one type of bottle/dwelling, but also a series of possibilities in a variety of sizes and shapes.

Some of the important regulatory d-genes transferred to the Unité d'Habitation of Marseilles were: the roof garden, bottle rack, bin, bottle, piloti, and the elements of the architectural promenade. Our proposed model describes how they were used and recombined over the years and during the design of the Unité d'Habitation in a way that resulted in a new invention.

Proceeding from the case study of Le Corbusier's Unité, one can say that this building did not appear from the successive crossing of two designs, and that through it, genes were passed on from one generation to another. Instead, it seems to have been a more direct action: d-genes of the most interesting facts were often re-used in various designs over the years.

In this case study, a series of actions were identified in re-using features as design precedents. Our proposed model could describe these actions and make them more evident. By using this qualitative model we could observe that:

First, in Le Corbusier's oeuvre, when a feature mutated, its original often remained in the gene pool and was available in the future, i.e. it was not a question of progress (improvement in a general sense), but of fitness. The private roof garden was in use at the same time that the "ocean liner" roof garden was being applied for high-rise buildings.

Second, Le Corbusier re-used "conceptual precedents" (or principles). The roof garden originated from the architect's analysis of the vernacular houses of Istanbul that had to be adapted to the climate of Switzerland to avoid critical expansions and contractions of the reinforced concrete. However, it became a point for a modern architecture losing its initial roots with reference to the original vernacular houses.

Third, "conceptual precedents" were also modified and recombined. The roof garden was modified through interaction with the deck of the Ocean Liner from its individual use into a square for the recreation of all inhabitants of a building moving from the private to a semi-public domain.

Fourth, some precedents often appeared together. They had an obvious linkage either to represent a new esthetic or because they were structurally dependent. The genes of those linkages also evolved; however, their evolution required a more complicated action. If one of the d-genes is modified, the linkage is broken. It may be recombined again like the case of the five points for a modern architecture, which had three points changing in their action from the individual domain to the collective domain.

Fifth, precedents were not only used as an overall rule. In the event that they were used, they could be a mere repetition of the former, they could be adapted to a new situation or recombined within a different linkage.

An analysis of the conception of the Unité d'Habitation as well as of the buildings that preceded it is surely not enough to explain the process of the re-use of design precedents in general because Le Corbusier's use of precedents has particularities that could not easily be generalized, and therefore another case follows this one to test the potential of our model to be used to represent the same process carried out by other designers. The evolutionary model is, then, a way to show the similarities between the re-use of design precedents among the designers and a way to explain aspects of the process.

In the next chapter we will introduce the third case study, which is composed of designs of the architect Santiago Calatrava, to examine whether the proposed model can be generalized to represent the process of the re-use of design precedents by another architect.

CHAPTER 8

TESTING THE EVOLUTIONARY MODEL, THE STRUCTURES OF SANTIAGO CALATRAVA

A case study to test the concepts of the theoretical model for the re-use and adaptation of design precedents

In the last chapter we applied our model on Le Corbusier's process of re-use of design precedents that gave origin to the Unité d'Habitation; a process that started not at the moment of the commission, but very early in his career. Our model provided insights into this process due to its systematic way of representing the precedents and the modification and recombination that they went through over the years.

In this chapter, we shall carry out our third case study to test whether the theoretical model can be sustained when generalized; subsequently, we shall test whether the process of re-use of design precedents in the work of Santiago Calatrava can be pictured with the help of our qualitative model as applied in the second case (Chapter 7).

We should reiterate that by modeling the phenomenon of change through the re-use of design precedents, we are not trying to explain the designer's mind processes. When architects find a precedent, modify it and adapt it, they do so according to their mind processes. The model does not imitate the architect's mind processes. The model pictures the process according to its own rationale, i.e. by describing the precedent, the kind of precedent-component that is transferred to the new design, its modification and adaptation over the years.

The main objective of this chapter is to verify whether the aspects of the design evolutionary model already developed and illustrated with Le Corbusier's Unité d'Habitation can be generalized to picture the process of re-use of design precedents in the work of another architect. Our model is applied to one feature only. Consequently, it limits itself in testing the representation of the phenomenon and it is not our objective to provide evidence that the feature led to the production of innovation, in view of the fact that the two earlier cases show that innovations involved numerous features that were transferred, adapted and/or recombined, and not by one feature only. It can only indicate an innovative use of the feature.

Particular to this case is that we shall not focus on the phenomenon of change due to the transference of regulatory d-genes (topology and geometric configurations), but on the phenomenon of change due to the transference of structural solutions. Consequently, we concentrate on how the forces are distributed through chosen designs and on what the most important linkages are among their elements to make these structures safe. Therefore, the case study provides first a description of two "through arch bridges"[1], in particular a description of the main forces working on the structures and the solutions found to keep the bridges stable and in equilibrium. The bridges are:

1. The Lusitania Bridge of 1988-1991 in Mérida, Spain;
2. The Puerto Bridge of 1989-1995 in Ondarroa, Spain.

In both cases, the arch is the main support element and it suspends the carriageway of the bridges with its hangers. However, these arches are positioned in different ways. The arch of the Lusitania Bridge is positioned symmetrically, while the arch of the Puerto Bridge is positioned asymmetrically in relation to their latitudinal cross sections.

By applying the description of the bridges within the "genetic framework", the chapter introduces the example of the "arch d-gene". It thereby tests whether the representation can be generalized to represent the phenomenon of change through the re-use of design precedents in the work of Santiago Calatrava.

Describing some differences and similarities between these bridges and other projects in regard to the use of the arch, one can observe a kind of phylogeny underlining Calatrava's projects that shows when some features were re-used and adapted into new designs. The chapter shows the kind of the variation of the arch in designing new bridges (e.g. the Gentil bridge and the La Devesa Footbridge) and the recombination of the arch when applied to designs of other orders such as the Velodrome football stadium, the Tenerife exhibition center, and the Jahn Olympic sports complex.

[1] Arches can be placed above the roadway, the so-called "through arch", such as in the case of the Lusitania Bridge (Mérida, Spain) and the Oudry-Mesly Footbridge. They can also be constructed with the deck at some intermediate level, the so-called "half-through" arches; as well as constructed under the roadway, the so called "deck arch" bridge (Romeijn 2002) [1], such as at Kronprinzen Bridge (Berlin, Germany). Romeijn, A. 2002. "Arch Bridges" in *CT5125 Steel Bridges: part 2*. Delft: Civiel Techniek, TU Delft. pp. 160-196

This chapter is subdivided into five parts. Section 8.1 presents Tzonis and Lefaivre's account of Santiago Calatrava's creative process and its relation to this research. Section 8.2 presents a description and analysis of two bridges of Santiago Calatrava, in particular concerning how he used the main support: the arch. The section will present the functional layout of the projects as well as their structural analysis. Section 8.3 re-defines the structure of bridges according to our "genetic framework". Section 8.4 provides an example of the structure of a structural d-gene in the making of these bridges. It presents the similarities and differences in regard to the use of this d-gene between bridges and buildings of Santiago Calatrava. Section 8.5 presents the conclusions. It analyzes the adequacy of the proposed model representing the process of re-use of design precedents, and it speculates on the effectiveness of the representation in modeling changes in a series of designs of Santiago Calatrava.

8.1. Santiago Calatrava's Creative Process

Proceeding from ideas developed in the forthcoming work of Tzonis' *The Designing Mind, Creativity in Architecture* (Tzonis, Forthcoming), Tzonis and Lefaivre posit a methodological hypothesis in the introduction of the two volumes of *Santiago Calatrava's Creative Process*. The hypothesis states that "there are two poles in creative thinking: the analytical problem solving and the analogical *dreamwork*" (Tzonis 2001). They assert that both analysis and analogy are a necessary condition for creativity, each being insufficient on its own. They are complementary. They posit that analogy and analysis are not so much parallel forms of thinking as intersecting ones that are characterized by feedback (Tzonis and Lefaivre 2001).

As they assert, the conception of this dual publication relies on a twin model of how the creative mind works beyond individual or institutional biases (Tzonis and Lefaivre 2001). Characteristically, the first volume is dedicated to Calatrava's analytical reasoning – the English translation of Calatrava's doctoral dissertation, while the second is dedicated to Calatrava's analogical reasoning – three of his sketchbooks (Tzonis and Lefaivre 2001).

To explain Calatrava's analogical reasoning, Tzonis and Lefaivre recalled Freud's concept of daydreaming, meaning "creating a world of fantasy"; a world that the person (in Freud's case, the poet) takes very seriously. For Freud, "the roots of poetic creation and adult daydreaming went back to early childhood play" (Lefaivre, 2001). Tzonis and Lefaivre pursued Freud's idea that daydreaming is rule-based, that it consists of "refashioning… ready-made material", or in other words, that it consists of rearranging "the things of his world and ordering them in a new way". They assert that indeed, by looking "through the sketches in Calatrava's notebooks and the strange forms of his projects, Calatrava appears to confirm Freud's claim that the creative imagination is quite incapable of inventing anything, it can only combine components that are strange to one another." Freud's interpretation of creative thinking already diverged from the "romantic, heroic view inherited from history that holds creative design as an incomprehensible miracle defying any explication"(Tzonis 2001). One could think that Freud's model - initially developed to explain "how that strange thing, a poet, comes by his material", would also explain how creative minds work in architecture. However, according to Tzonis and Lefaivre, creative thinking is also composed of a complementary analytical reasoning.

Tzonis illustrated this analytical reasoning by an in-depth look at the creative process of Santiago Calatrava. He asserted: "The ease and freedom with which creative designers produce has to do with the potential energy and knowledge structure with which they are already endowed." According to Tzonis, Calatrava's dissertation "was part of an effort to construct a framework that would enhance and sustain his design creativity. […] His dissertation explains the creative force and richness of his subsequent output and also sheds light onto a major aspect of creative design, the role of analysis" (Tzonis 2001).

Until now, with the transference of regulatory d-genes from one artifact to another in Le Corbusier's oeuvre, we have only applied analogical reasoning. This case will concentrate on the transference of "structural d-genes" which, we believe, are part of or are the objects themselves of Calatrava's analytical reasoning.

8.2. A Description of Two Bridges of Santiago Calatrava

Calatrava subdivides his bridges into three types: the cable-stayed bridge with pylon[2], arched bridge, and the cantilevered bridge (column and beams). This section describes two arched bridges.

In designing a**n "arched bridge",** Calatrava claimed: "The relative position of the arch and the connection with the roadway are of decisive importance for the expression of the bridge." The arched bridges suspend the roadway via hangers that transfer the dead and sometimes live loads from the deck to the arch. The position of these hangers is highly dependent on the structural forces acting on the arch; it may give equilibrium to the arch and help in preventing buckling.

[2] In Calatrava's bridgework, the pylon, the main support element of the **cable-stayed bridge**, can be symmetrically (Medoc Swing Bridge, Bordeaux, France, 1991) as well as asymmetrically placed in relation to the longitudinal section; the asymmetric pylon may or may not have return anchorage cables, for example in the Alamillo Bridge, the weight and slanted pylon maintain a mutual balance with the deck of the bridge (pedestrian path and motorway), thus making the return anchoring unnecessary, at least as regards the dead loads.

In Calatrava's oeuvre, the arches suspending the bridge are often placed asymmetrically in relation to the latitudinal section. The arch is then either vertical such as in the case of the Puerto Bridge (Ondarroa, Spain), which has cables on the same plane as the arch and slanted blades; or it is rotated; i.e. forming an angle with the deck such as in the case of the La Devesa Footbridge (Ripoll, Spain) and Alameda Bridge (Valencia, Spain), which have blades on the same plane as the arch or the Alcoy Bridge (Alcoy, Spain) and the Campo Volantin Footbridge (Bilbao, Spain), which have cables running in two rows to give the appropriate balance to the arch.

Calatrava's cable-stayed bridges and arched bridges have a four-level structural hierarchy; i.e. the live and dead loads of the deck are transferred to a girder that transfers them to the hangers that transfers them to the arch or pylon that transfers them to the abutments[3].

In the following two sub-sections, two bridges will be functionally and structurally described; later in this chapter, we will verify whether one of their features, the arches and hangers, can be represented by our genetic framework, like the features of the Unité d'Habitation of Marseilles.

8.2.1. The Lusitania Bridge of 1988-1991, Mérida, Spain

The Lusitania Bridge was designed in 1988 and connects the old center of Mérida to the newly developed area of Poligono on the northern side of the Guadiana River in Mérida, Spain. Its construction freed a 2000-year-old Roman Bridge[4] of vehicular traffic (Frampton, Webster et al. 1996, p. 87).

The Lusitania is a motor and pedestrian bridge that functions at the regional level. The total length of the bridge is 465 meters and the largest deck span is situated in the middle of the bridge, where a symmetric 34-meter deep arch is used to suspend the bridge over 189 meters. The arched section of the bridge will be the focus of this description (Figure 1).

[3] Possible horizontal components of the loads are transferred via the girder to the abutments.
[4] The Roman Bridge is located about 600 meters from the Lusitania and now functions as a footbridge (Frampton, Webster and Tischhauser 1996, p. 87)

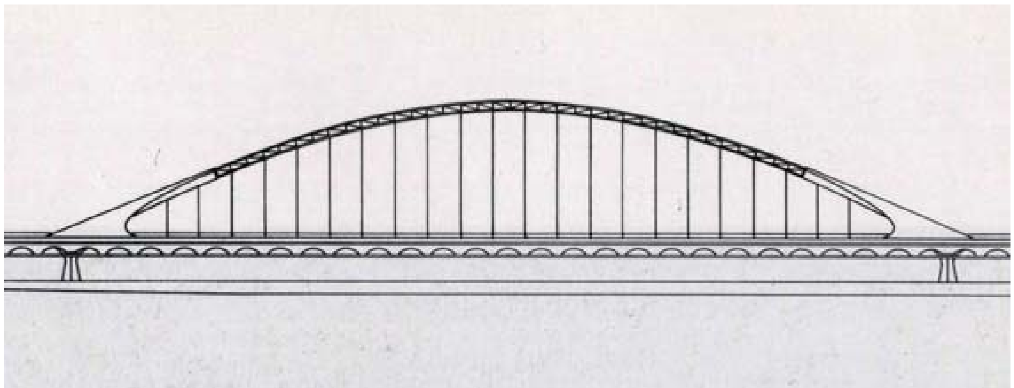


Figure 1: Longitudinal Facade

The pedestrian path (5.5 meters wide) is located on top of the central girder (torsion box) and is completely isolated from the vehicle traffic due to its position 1.5 meters higher than the two adjacent motorways (El Croquis 1992, p. 146). In addition to safety, the elevated position of the pedestrian path provides pedestrians with an opportunity to enjoy a view of the landscape. The walkway has its space defined by two railings running along the edge parallel to the roadways and 23 pairs of hangers (in this case, steel cables) that suspend the torsion box (Figure 2).

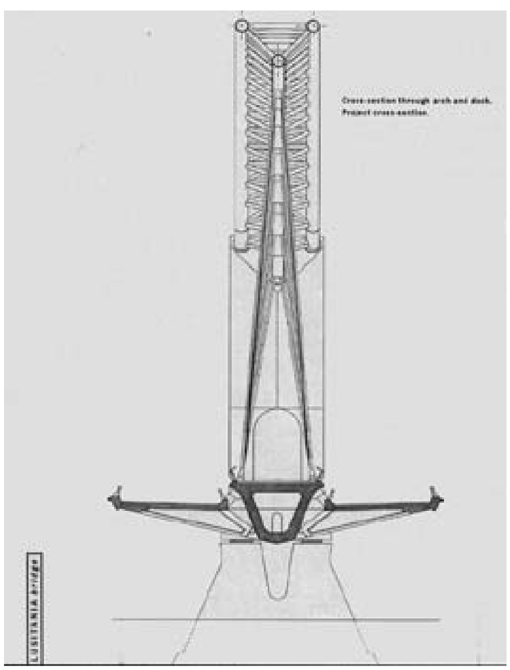


Figure 2: Section

The 34-meter deep arch is composed of two bases in reinforced concrete and, connecting these bases, three braced steel-arches. The steel arches are connected by linear rigid elements forming a truss, thus taking material out the center to give the whole a certain rigidity that prevents the arch from buckling as a consequence of, for example, wind load working on the structure (Figure 3). The cables are brought in pairs into an element pinned in the lowest of the three steel arches of the truss[5].

Like most Calatrava bridges, this bridge also presents a four-level structural hierarchy: dead and sometimes live loads carried by the roadways are transferred to the cables. These 23 pairs of steel cables transfer the loads to the arch, and thereafter the loads are transferred via the truss-like arch to its bases in reinforced concrete, and finally, to the abutments (Figure 4).

According to Frampton et al., the central load-bearing element of the bridge – the box girder or torque tube – is constructed from post-tensioned, pre-cast concrete elements (Frampton, Webster et al. 1996, p. 87). This is Calatrava's solution for dealing with the horizontal forces originating from the arch in the direction of the banks of the Guadiana River. In other words, the cables crossing the girder longitudinally generate a horizontal force opposed to that of the arch preventing the arch from collapsing.

Post-tensioned concrete wings supporting the road decks cantilever from the 4.45 meter-deep concrete box girder (Frampton, Webster et al. 1996, p. 87), i.e. there are cables crossing the box girder to connect each pair of opposed concrete wings.

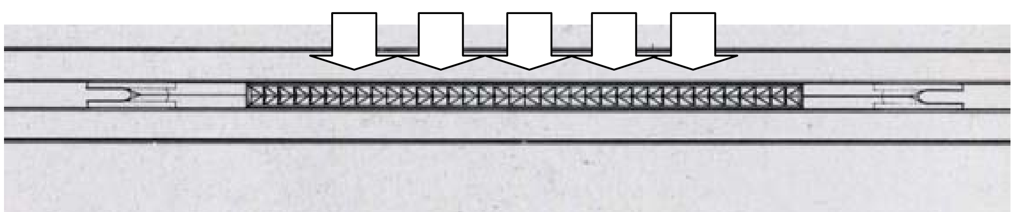


Figure 3: Truss Supporting Wind Forces

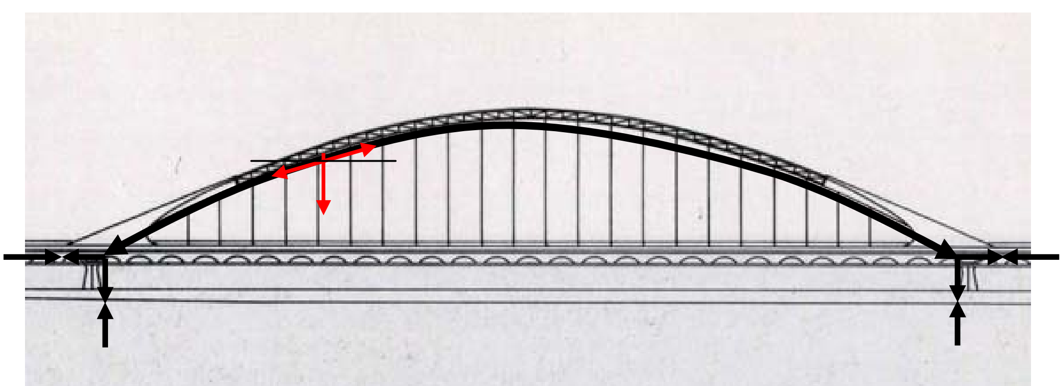


Figure 4: Diagram of Forces

[5] The first and the last pair are fastened inside the reinforced concrete basis.

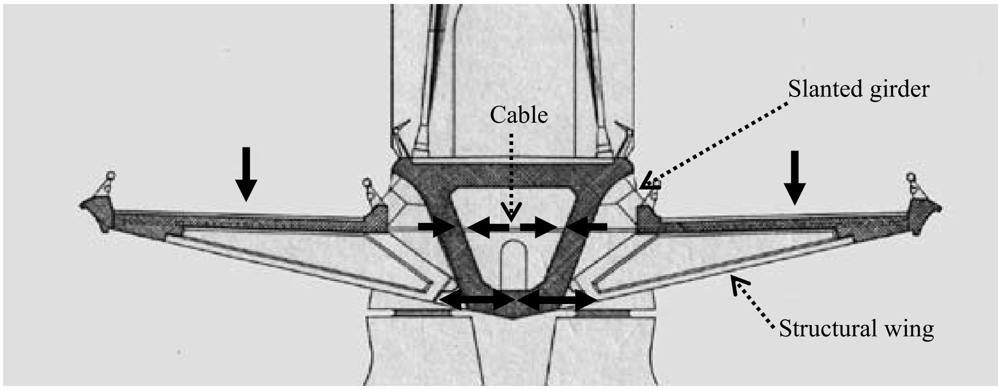


Figure 5: Symmetric Load Case

The motorways on top of the wings are not directly in contact with the torsion box; they transfer the symmetric loads (Figure 5) to the structural wings. Horizontal components of the live and dead loads acting on both decks and transferred through each pair of wings counter-balance each other via cables because the forces are similar at both sides of the girder. Vertical components of these forces are transferred through the cables to the arch (see illustration).

The asymmetric loads (Figure 6) – loads that are only applied on one of the decks due to potential traffic on one side of the torsion box – are solved by adding another set of slanted beams that suspends the motorway transferring forces also to the top of the torsion box. These beams are placed between the torsion box and each roadway at regular intervals (see illustration). The same elements also seem to prevent the whole from excessive vibrations generated by the friction of the wheels of the vehicles in the direction of their movement (Figure 7).

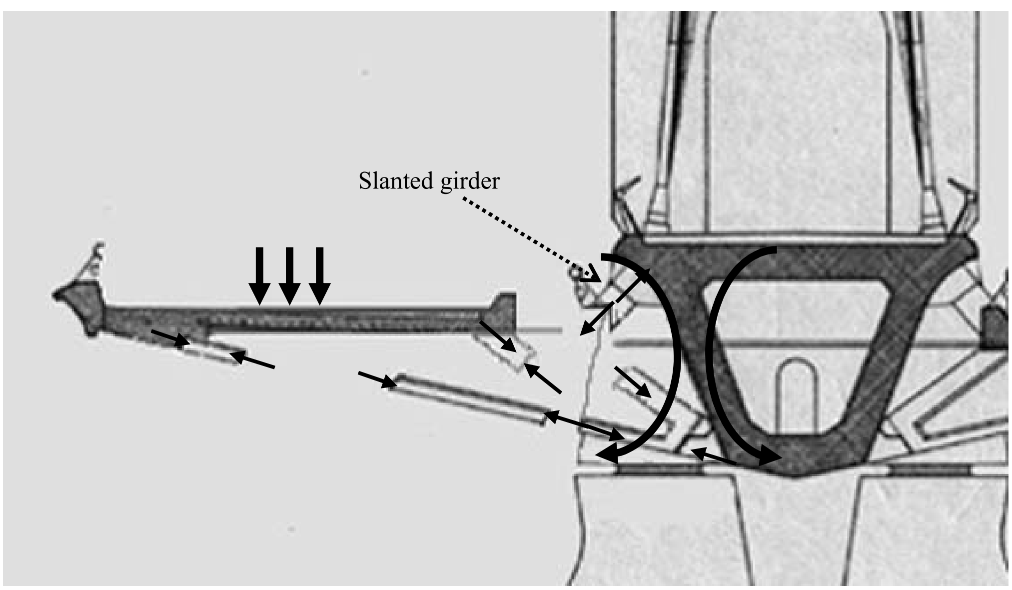


Figure 6: Asymmetric Load Case: torsion box comes to action

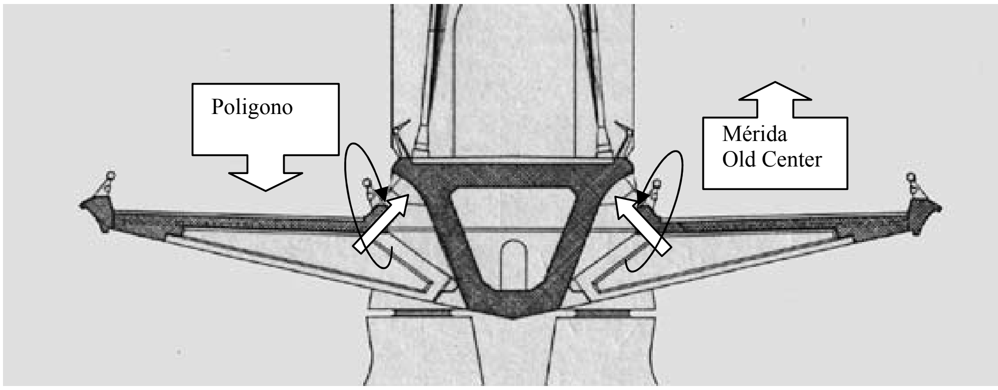


Figure 7: Vibration due to the friction of the wheels taken by the diagonal beams

8.2.2. The Puerto Bridge of 1989-1995, Ondarroa, Spain

The Puerto Bridge was designed and constructed between 1989 and 1995 and crosses the Artibay River with an arch spanning 71 meters over the port of Ondarroa, Spain (Figure 8). The bridge has two 4.5 meter-wide pedestrian paths, one at each side of the 7 meter-wide two-way motorway (Tzonis and Calatrava 1999, p. 140). With its arched form, the pedestrian seaside path becomes much more than a mere circulation; it becomes a communal balcony where people are invited to contemplate the sea. This pedestrian path is separated from the rest of the bridge physically – by a separation of the decks – and visually – by the 15-meter-deep vertical asymmetric arch and its cables.

Its asymmetric steel arch suspends the deck with the help of tensioned stayed cables that are at the same plane as the arch, and inclined blades that connect the vertical arch to the curved and cantilevered pedestrian path (Figure 9).

On one side of the arch, there is an arched pedestrian path, and on the other side there are a linear two-directional motor road and a second linear pedestrian path (Figure 10). One can say that the bridge must constantly endure asymmetric loads**,** because the seaside pedestrian path could not compensate for the 11.5 meter carriageway on the other side, particularly when we consider the movable loads on the wider side of the bridge. This brings us to the most ingenious part of the composition. The asymmetric loads would generate a rotation of the deck if it were not for the work of the slanted blades connecting the vertical steel arch with the almost horizontal shallow arch of the pedestrian path. The slanted blades transfer the horizontal component of the force producing rotation, since this horizontal component of the force cannot be transferred to the foundations by the cables and arch correlation. Therefore, the initially inconspicuous curved pedestrian path seems to be structurally essential for the balance of the bridge. It receives the horizontal component of the force through the blades and transfers it to the abutments. The vertical arch is rather thick, seemingly because it must resist the same horizontal forces.

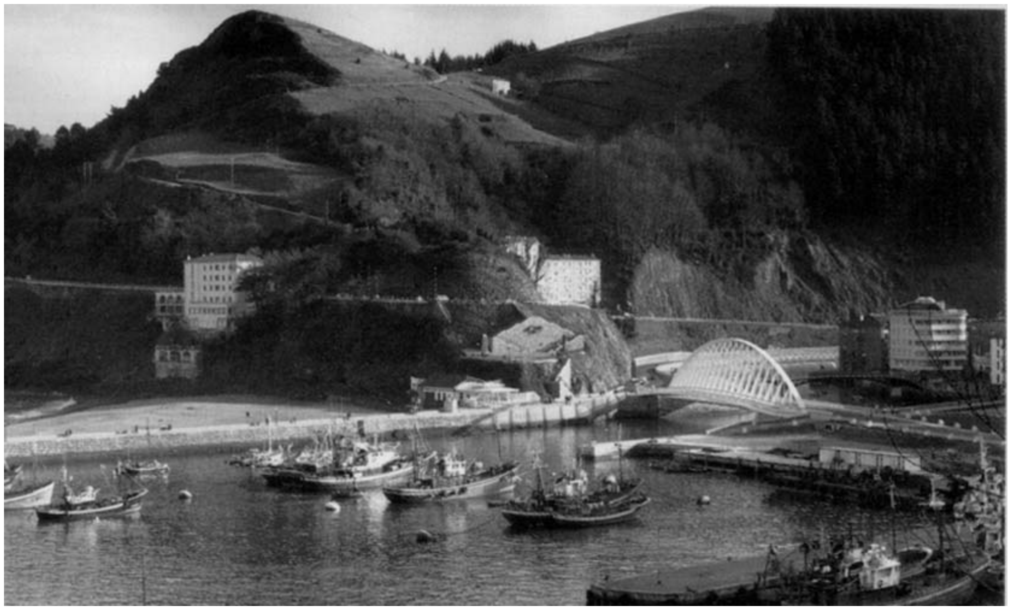


Figure 8: Puerto Bridge, view

Deck girders and hangers (blades and cables) form a triangle that presumably prevents lateral distortions. Providing lateral bracing to the vertical arch, the blades also prevent the arch from buckling.

Besides equilibrium, a bridge needs some stiffness; in this case, it is given by the deck structure that works as a girder that rests on both sides of the river. Longitudinally**,** the deck structure also has an important contribution. Asymmetric forces generated by the movable loads, for example at the beginning of the bridge, could cause distress on the arch unless the arch is made thicker. This seems to be avoided, in a Maillartian fashion, by developing a deck structure that can work as a girder that transfers the longitudinal asymmetric loads to the abutments.

What one can see in this description is that by allowing several elements to conduct the forces, Calatrava was able to make a slender, dynamic structure.

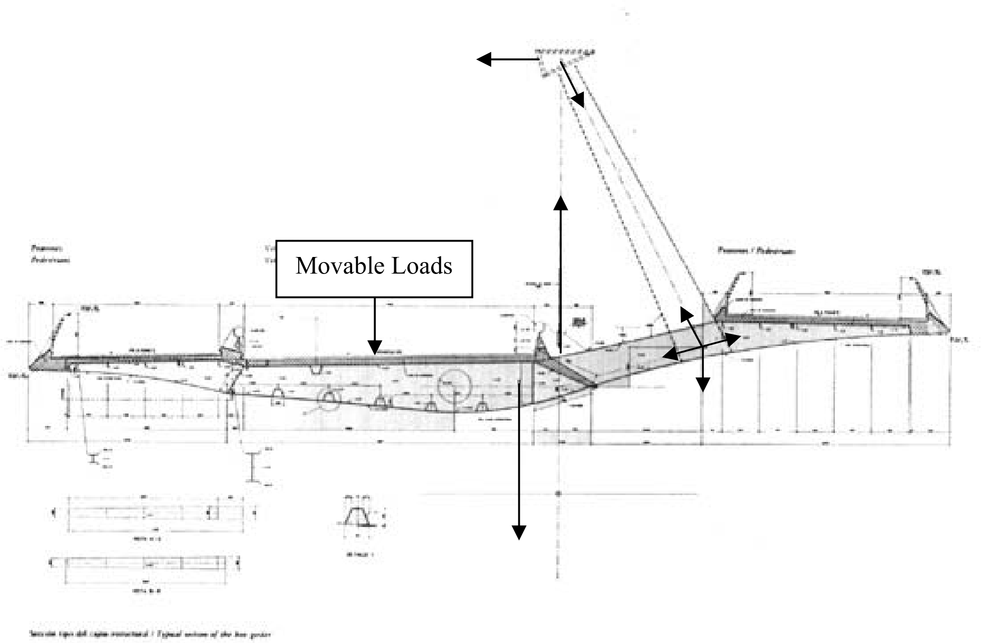


Figure 9: Puerto Bridge, Latitudinal Section

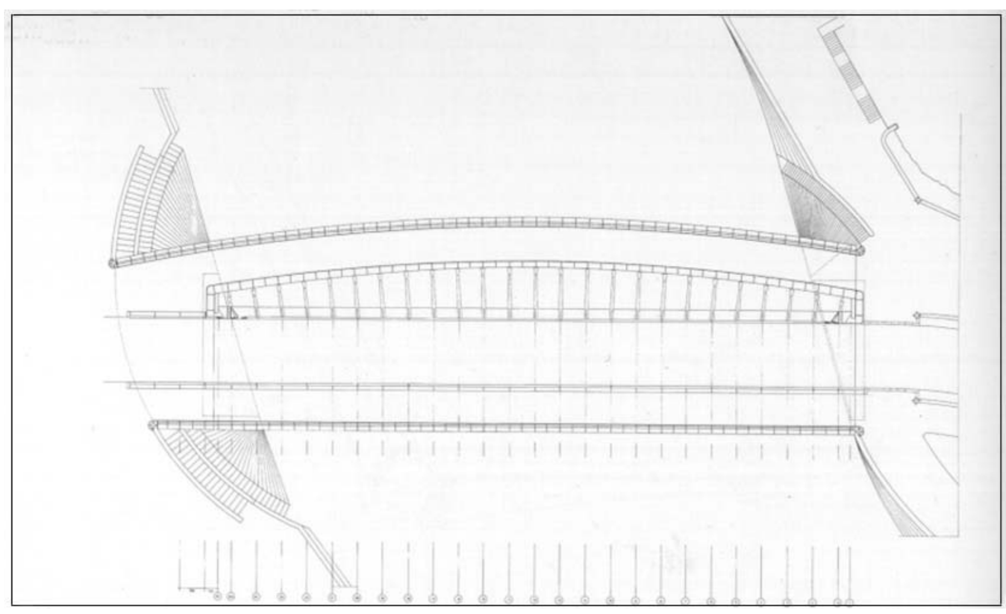


Figure 10: Puerto Bridge, Plan Layout

8.3. The Qualitative Model: Representing Bridges

Having described the bridges, this section will test aspects of the theoretical model by trying to describe bridges in general in the “genetic framework”. As already mentioned, the genetic scheme is composed of “regulatory d-genes”, “structural d-genes”, and “linkages” that are defined according to the Performance, Operation and Morphology reasoning system as explained in Chapter 6 (Figure 11).

Regulatory d-gene			Structural d-gene	
Performance (P)	Operation (O)	Morphology (M)	Operation (O”)	Performance (P”)
User’s Satisfaction; Architect’s Satisfaction	Connection of two or more places Geometrical Configuration Topology (plan layout)		Distribution of Structural Forces (according to the selected materials and technology)	Structural equilibrium and Stability Facilitates Topology

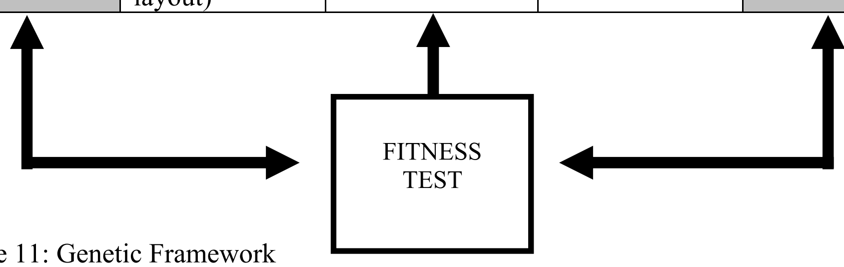


Figure 11: Genetic Framework

As we can observe from the above table, the performance in a regulatory d-gene refers to functions that a bridge should satisfy in order to serve as a utilitarian construction in society, while the performance in a structural d-gene refers to the structural equilibrium and stability that the artifact should have as a condition for its existence.

The regulatory d-gene’s operation aspect deals with the position and arrangement of the parts as well as with its minimum and maximum ranges in a pre-parametric stage. The operation within the structural d-gene deals otherwise with structural forces such as those of compression, tension, bending, buckling and torsion that are acting on the structure in a parametric stage. By analyzing these forces and distributing them through the structure and selecting the proper materials and techniques, the design reaches structural equilibrium and stability.

If we try to put the descriptions of the bridges within our genetic framework (regulatory d-genes and structural d-genes), we will have the following:

8.3.1.Performance and Operation of Regulatory D-Genes

"Born of necessity," asserted Calatrava, "a bridge becomes predominant, and must have its own identity. While being independent of local design, it should harmonize with, transform and complement its setting" (Calatrava 1996). A required performance of any bridge is to facilitate the transfer of people, animals, and/or vehicles from one side to the other by crossing over a certain obstacle. Traffic safety is a priority, and for architects the esthetic expression of the bridge is a priority as well (Schodek 1980, p. 81), in particular for Santiago Calatrava.

The main operation of a bridge is the connection of (at least) two points to facilitate the transit of people, vehicles and goods. A second important operation refers to its plan layout and traffic safety: the more types of transport a bridge needs to accommodate, the more differentiated roads will be required such as pedestrian and bicycle paths and two-directional motor-roads.

8.3.2. Performance and Operation of Structural D-Genes

Within the framework of the structural d-gene, structural equilibrium and stability is a main requirement for all bridges. In other words, the bridge should not deform so as to cause distress such as cracking or buckling.

Thus the performance of the structure of a bridge is high when:

1. It allows the performance and operations of the regulatory d-gene
2. The bridge can be considered "acceptable on safety grounds".

The bridge should be able to support static forces; i.e. its own weight (dead loads) and the movable loads (live loads); it should also support dynamic loads; i.e. continuous forces such as wind forces, and forces due to impact. Therefore, design precedents derived, for example, from Santiago Calatrava's sculptures, must be re-evaluated and the scale problem considered.

A second criterion for the performance of a structure is what Schodek called efficiency and we could call parsimony[6], which refers to the relative economy with which a structure achieves its design objective (Schodek 1980, p. 81). In other words, two possible solutions may be equally "serviceable", but one may require less material or can be assembled in such a way that time, labor or material will probably be saved (Schodek 1980, 81). However, subjects such as costs and construction methods are not within the scope of this research.

Besides accommodating a plan layout, another essential task of the designer is to avoid excessive deformations. As Schodek asserted, "Deformations are

[6] As George C. Williams asserted in his essay "Excerpts from Adaptation and Natural Selection", the principle of parsimony "demands that we recognize adaptation at the level necessitated by the facts and no higher" (Sober 1995, p. 123).

controlled by varying the stiffness of a structure. Stiffness depends largely on the type, amount, and distribution of material in a structure. Often it is necessary to use a larger member to achieve necessary stiffness than is required to achieve the necessary structural strength" (Schodek 1980). Calatrava's approach, however, is often that of differentiation[7] and finding rigidity/stability through the connection of the elements in a way to form trusses (e.g. the arch of Lusitania Bridge). In other words, a fit and elegant solution can also be found by selecting other materials, varying the aforementioned measures, or differentiating the structure.

A long span will favor differentiation of its elements into smaller ones such as an arch in reinforced concrete transformed into a truss, as in the case of the Lusitania Bridge. The deck can also be differentiated in a structural framework including carriageway, box girders and trusses.

8.3.3. Morphology, the Expression of D-Genes

According to Santiago Calatrava, building a bridge is a symbolic gesture, linked to the needs of the people crossing, and the surmounting of an obstacle. He tries to create bridges that have a "straightforward appearance"; he uses concrete and steel and applies modern construction techniques. Calatrava devotes special attention to the integration of technology and esthetics (Calatrava 1996).

In the proposed model, morphology is the result of the performance and operation of regulatory d-genes that refer to function and esthetics (principles concerning geometrical and topological configurations), and structural d-genes. The latter refers to a technology that enables the designer to build a stable and safe structure that, in turn, makes the geometrical configuration and topology possible and/or opens the possibility to create new geometrical configurations. The result, morphology, may be shown by just indicating the representation of the bridges or the built bridges.

8.3.4. Implication

One can say that, firstly, not only the functional performance (regulatory d-gene), but also the structural performance (structural d-gene) constrains the design results. Secondly, not only the geometric configuration (O), but also the play of the structural forces acting on the artifact (O") can induce change and therefore the possibility to innovate in design. In other words, form is not only influenced by topology and geometric configuration but by the search for solutions leading to structural equilibrium and stability, which determines the possibility of its construction.

[7] Differentiation: the modification of one element into a network of smaller and possibly slighter elements.

Next we shall describe one of the main features used in the design of the bridges of section 8.2: the arch. In other words, the following section will introduce a potential gene: the arch d-gene; and it will show how it was possibly re-used and what changes or mutations can be recognized in this process. We will see that some mutations are due to a change in the topology of the new artifact and others will be structural due to the search for a new morphological expression and/or a response to the site constraints.

8.4. The Arch D-Gene in the Phylogeny of Calatrava's Designs

In this section, we shall deal with only one feature of the arched bridges, to test whether the "genetic" framework is robust enough to model the phenomenon of change that occurred with the re-use of this feature over time. The choice of dealing with one feature only would not be wise if we were trying to find a design innovation in the mode of Le Corbusier's Unité d'Habitation, which presented a recombination of numerous features. As has already been mentioned at the beginning of this chapter, the test of the proposed model only refers to the model's potential in representing the phenomenon of change. The feature selected for further representation and analysis is the arch with its respective hangers.

Arched bridges have proved to be not only good structural solutions, but also depending on their form, size, position and order of elements, a good design statement vis-à-vis the environment; some being proper regional bridges, i.e. monumental arches with a landmark character such as in the case of the Lusitania Bridge and others very successfully applied in historical places and integrated within the built environment. We shall focus on the arches of *through arch bridges*. To be operational, these arches always have hangers to suspend the roadway. This is the reason for considering the combination of these elements – which are used again and again and are as much esthetical solutions as they are structural – as a d-gene.

In our genetic structure, the d-gene is then further subdivided into the regulatory arch d-gene, the structural arch d-gene, and their linkages.

8.4.1. The Regulatory Arch D-Gene

Essential in Calatrava's bridges, it would seem, is the performance related to the environment as well as performances related to a dynamic and technological expression, the feeling of protection, and the idea of a place where people stop to view the landscape, instead of a mere transit path.

In our hypothetical reconstruction, we claim that Calatrava expressed the desire to produce a dynamic technological structure (Performance). This sub-section describes an example of the contribution of the arch d-gene in achieving this performance.

Symmetric cantilever solutions could replace most of Calatrava's bridges. However, from the beginning, it seems that in his search for a dynamic form, he brings an asymmetry with a certain configuration of elements that when necessary, can help him with the peculiarities of the site. From this point of departure, he solves the problems of equilibrium, buckling and bending of the bridge derived from live and dead forces working on the structure.

Identifying Change in the Geometric Configuration

In finding similarities and differences in the use of the arch d-gene, we must consider their morphology and hypothesize about how the parts operate to meet a desired performance. The following questions seem to be relevant in this investigation:

What was the geometric configuration?

1. How many arches does the bridge have?
2. Are their latitudinal sections symmetric or asymmetric?
3. Are they rotated?
4. Are there cables, blades or both?

During the search and analysis of the precedents, one solution will probably appear more effective than others. For example, examining the potentials of the arch, one may realize that:

1. Asymmetrical structures, either rotated (e.g. the Alameda Bridges) or not rotated (e.g. the Puerto Bridge), could convey the dynamic technological expression and the idea of movement.
2. Differentiation of elements such as steel arches braced as trusses instead of "heavy" concrete structures (e.g. the Lusitania Bridge) could make a more rigid bridge and could contribute to the technological expression of the bridge.
3. Space could be created by "covering" the deck of the bridge with cables (the Bach de Roda and Lusitania Bridges), which could contribute to the feeling of protection and the idea of "place".

These operations refer to Calatrava's patterns of geometrical configuration related to principles, concepts or desired performances. These simple operations show how performances were translated into the new desired solution, or morphology (see table). To achieve a dynamic and technological expression, Calatrava's designs show a tendency in:

1. Reducing the number of arches;
2. Designing asymmetric and rotated arched bridges;
3. Keeping symmetric structures only when dealing with very long spans.

In particular, the use of the rotated asymmetric arch seems to contribute to the expression of a "dynamic technological structure" (Table 1). However, the symmetric bridges and the bridges with more arches are not eliminated from Calatrava's "d-gene pool".

The expression of the bridge:		
REGULATORY ARCH D-GENE: composed of **ARCH and HANGERS**		
PERFORMANCES	OPERATIONS (Considering and testing the arch d-gene to fulfill the performances)	MORPHOLOGY
The feeling of movement The feeling of protection The feeling of a place to enjoy the view Structures showing a dynamic and technological look	Steel arches in combination with hangers can give the artifact a dynamic and technological look. Arches and hangers may have a position that reinforces the feeling of protection and may have been composed with such a form and size that will produce the sensation of movement, protection and "place". Rules of thumb: Range between the minimum and maximum height of the arch(es) for a certain span; Range between a minimum and maximum number of hangers.	Geometric configuration: The way in which position, rotation and the number of arches determine the dynamic technological look; The way cables "covering" pedestrians give the idea of shelter.
There is a linkage between the arch d-gene and what could be called a Topology-gene. There should be a rule that the arch position could not be an obstacle for the plan layout of the bridge.		

Table 1: The Expression of Calatrava's Bridges

8.4.2. The Structural Arch D-Gene

Chapter 7 explored "regulatory d-genes" found in Le Corbusier's designs. This section shall now focus on "structural d-genes", in particular the "structural arch d-gene" of Calatrava's bridges. In other words, we will take his projects as a result of his principles and explore the notion of the "structural d-gene". More specifically, taking his projects as they are – the result of environmental, economic and cultural constraints, as well as topology and geometrical configurations – we shall describe the structurally fit solutions (built projects) by using the proposed evolutionary model.

Identifying Changes in Structural Solutions: the Role of the Structural Arch D-Gene

The main performance of the structural d-genes is to make a stable structure that facilitates the "grand plan" of regulatory d-genes. In other words, it is not enough to produce a stable structure; it should facilitate the topology (plan layout) and the geometric configuration as described by the regulatory d-genes.

To find the re-use and modifications of the design precedents, we will check similarities and differences among the given bridges in what concerns structural solutions, focusing in particular on the structural arch d-gene. In searching for similar attributes, one should ask questions such as:

1. How is the problem of rotation solved?
2. How is the problem of buckling related to asymmetric live and dead loads solved?
3. How is the deck suspended?
4. Are there similar answers to the above questions?
5. When did feature "x" appear for the first time? Were there changes?
6. If yes, did the modified feature replace the older version or coexist with it?

Contrary to the use of types, which permits only variation, we are trying to see how a feature passes from one design into another.

As Schodek claimed, span length is unquestionably a crucial determinant in selecting a structural response for a given situation, since some structural systems are more appropriate for certain span ranges than for others (Schodek 1980, p. 438). A primitive tree-trunk, obviously limited in length by tree heights in nature, would not solve many of today's problems, not only because of its deficiency in accommodating several types of traffic, but due to its impossibility of crossing great spans. Proceeding from the span length, the designer will search for a technology and materials that may match his esthetical needs and available budget. Naturally, the total length of a bridge can be subdivided into several spans.

The performance of a structural d-gene is always to produce a stable artifact according to the desired configuration as stated by the regulatory d-gene. In other words, the most important task of structural d-genes is, in fact, the translation of the regulatory d-gene into a stable and safe structure within an appropriate technology and materials. This must follow some criteria with regard to the distribution of forces through the artifact to verify its stability. Each action of the designer in modifying the elements of the bridge, and hence also the arch and hangers, will modify the distribution of the forces within the structure. Some of these actions are[8]:

- Arch height: a rule of thumb reads that for each six meters of the total span, the arch should be about a meter high. This rule prevents, for example, the arch from being either extremely shallow – increasing the risk of collapse due to the weight of the deck – or too high and therefore increasing the risk of buckling. Naturally, there is a range between these extremes where the bridge arch could be built without provoking much distress; in general, height variation is possible due to stiffening of the arch itself or the use of linked elements, such as blades. The stiffening of the deck, which then works as a beam, avoids arch bending. This bending could result from the asymmetric live forces conducted by the roadway in its longitudinal direction due to its movable loads.
- Number of arches: the number of arches is a consideration that has an impact on the expression of the bridge (geometrical configuration) and also on the distribution of load. To date, all Calatrava bridges with more than one arch have been symmetric bridges.
- Arch position and/or rotation on the section: this has an impact on the expression of the bridge and on its topology (plan layout) as well as on the distribution of loads. If asymmetric, the arch will require either a particular position of hangers (e.g. the Puerto Bridge) or a rotation of its center (e.g. the Alcoy Bridge and the Campo Volantin Footbridge).
- Arch stiffening or arch differentiation: stiffening the arch may prevent collapse or buckling. However, the differentiation of a concrete arch into a truss composed of braced smaller steel arches can solve the problem of buckling. For example, in the case of the Lusitania Bridge, the arch is further differentiated and transformed into smaller arches braced by rigid elements forming a truss. In this way, by taking material from the center, the arch becomes more rigid and thus supports the dynamic forces acting on the structure to a greater degree.
- Position of hangers in relation to the arch(es): hangers suspend the deck and their directions may help in making the arch stable. In Calatrava's designs, hangers often appear in the same plane of the arch and vertically parallel to

[8] We are not implying any order or hierarchy in these actions

each other. However, on asymmetric bridges that only use cables, they may appear in sets divided into two rows (or curves). The latter may also be suspended in a divergent arrangement such as in the Alcoy Bridge and the Campo Volantin Footbridge instead of vertically parallel to each other.

- Number of hangers: the more hangers an arch has, the more effective the loads can be distributed through the arch, hence avoiding, for example, the bending of the arch.

These criteria refer to the structural arch d-gene (Table 2), but they would not be enough to bring stability to the whole bridge. There is a need to see the correlation of the parts, hence a need to analyze the d-gene linkages.

STRUCTURAL ARCH D-GENE		
Performance	Operation	Morphology
To contribute to translating regulatory d-genes into a stable and safe structure	An analysis of the distribution of forces through the artifact is necessary to verify whether the bridge is stable. Points considered in the analysis: Arch binding with foundation; Number and Position of the arch(es) (position in the section); Arch stiffening or arch differentiation; Rotation of the arch(es); Position of hangers in relation to the arch(es) and deck structure; Height of the arch(es) for a certain span; Number of hangers; Hanger's linkages; Cable linkages.	The physical result. Materials: steel arches, steel cables and trusses. Linkages in steel but also often in concrete. Technological configuration: according to the regulatory d-gene but adjusted to perform well as a structural d-gene; i.e. the technological look should correspond to its structural effectiveness. The way that the deck loads are transferred via tensioned stayed-cables to the arch and from the arch to the pylons or foundation piers without causing crashing, buckling, bending or torsion that would make the bridge collapse.

Table 2: Structural Arch D-Gene

8.4.3. Linkages of the Arch D-Gene

Though essential for the expression and support of the bridge, the arch depends on the integration and co-operation of itself with the other parts of the bridge. Proceeding, for example, from an asymmetry, Calatrava would initiate a "dialog" with the forces involved in the whole bridge until he could make the whole stable and in equilibrium.

Structural d-genes make the instructions of the regulatory d-genes feasible by rendering them stable and safe. However, one d-gene alone cannot make the whole structure safe. The performance generated by the expression of one particular d-gene may be very high and precisely because of it, the overall performance of the structure will be very poor. Using linkages among the d-genes may help in producing stable structures.

Proceeding from our arch d-gene, we could consider the following linkages:

- Arch anchorage: the arch transfers the thrust to the abutments. The connection may form a close system or work with forces outside the span in question. According to A. Romeijn, there are three main types of anchorage. First, the "basic arch bridge with a predominating arch and with the thrust transmitted directly to the foundation. Therefore, the elongation effect of the roadway-supporting structure is assumed to be absent. The arch is subject to bending, shear forces and axial forces." The second is the "basic tied arch bridge. The arch still dominates, but the thrust is resisted by tying the ends of the arch through the deck system." The third is the "tied arch bridge with stiffening girder. A predominating stiffening girder is subjected to bending moments and axial forces induced by the arch. The arch itself is mainly loaded in compression. Because of the stiffening girder, the hangers are more uniformly loaded" (Romeijn 2002).
- Arch linkages with other arches: when using more than one arch, Calatrava often braces them in pairs. This stiffens the bridge when under wind loading.
- Link of hangers with the structure of the deck: To suspend the deck and transmit the loads to the arches, the cables must be fixed to the deck structure so that (the vertical component of) dead and sometimes live loads can be transferred from the deck structure through the hangers to the arch(es).

As we demonstrated in Chapter 7, "d-genes" form linkages that benefit certain natural selected performances. However, these linkages make "changes" (meaning mutations and not variations) less probable, because one change would involve many other changes. In the case of the "five points for a modern architecture" of Le Corbusier, two of these features changed from the private to the communal domain, favoring the creation of the Unité d'Habitation.

In the case of Calatrava, the modification of one structural d-gene can make the whole artifact unstable if the other parts are not reconsidered. They are highly constrained, although not invariable. In the Black Hall Place Bridge in Dublin of 1999-2001, one can see that there is no linkage between the arches. Bracing arches is a way of correlating parts of the bridge giving it stability; it is a feature that is possible to mutate. It seems that by changing the linkages a designer may probably move towards innovative designs.

It is not within the scope of this research to provide a deep description of these bridges; therefore, we are going to illustrate them with some examples, focusing briefly on the solutions found by Calatrava in answering two of the aforementioned questions.

Solving the Problem of Buckling and Bending

In solving the problem of buckling that resulted from (dynamic) forces such as the wind (in its latitudinal section), or bending due to the asymmetric live loads on the suspended deck (in its longitudinal section), Calatrava showed several solutions which sometimes (but not necessarily) work together in the same design:

1. Bracing arches (using trusses) to give some rigidity to the structure making it resist the forces of the wind.
2. Using blades in asymmetric arched bridges such as the Puerto Bridge can prevent the arch from buckling as well as from bending in all the rotated asymmetric arched bridges.
3. Using Maillart's solution with a stiffened deck girder (Billington 1979, p. 93), which provides elegant structures while preventing the arch from bending.

Solving the Problem of Rotation of the Carriageway

Calatrava often solves problems concerning rotation with several types of elements; this approach has helped him to make elegant and light constructions. Some of the solutions are given below:

1. The design of symmetric (braced) structures, in particular when there is more than one arch (such as the Oudry-Mesly and Cascine Footbridges);
2. The use of a torsion box to assimilate the asymmetric loads (such as in the Lusitania Bridge);
3. The use of slanted blades to transfer the horizontal forces applied on the arch by the wind to the deck structure, such as in the case of the Puerto Bridge.
4. The rotation of the arch (particularly in asymmetric bridges)

Calatrava provokes a certain visual imbalance/tension in some elements and solves it with the support of other ones. This play of forces is his way of producing dynamic structures. For example, instead of solving all main problems of a straightforward bridge, he provokes an asymmetry with the position of the arch that would generate a rotation or a buckling if there were no other elements to receive and transfer the forces to the foundations. So, "distortions" produced on the arch due to its asymmetric position were solved, for example, by switching cables for blades, and by the form of the structure of the deck (Linkages). Each of these solutions compensates for the initial distortion, which was meant to create a dynamic expression of the bridge (Table 3).

Some LINKAGES of the Arch D-Gene: (In order to make a stable structure the arch d-gene must be linked to other d-genes)		
PERFORMANCE	OPERATIONS	MORPHOLOGY
Arch anchorage	The arch must transfer the vertical forces to the abutments and the horizontal forces must be counter-balanced with the forces generated in the structure of the deck.	The way an arch is fixed on the abutments and has its forces transferred to them and to the deck girder. In the case of the Lusitania Bridge, it is an open system, which has several spans connected by a post-tensioned pre-cast concrete girder. In this way, the horizontal component of the forces derived from the arch is stabilized by a counter-force outside of the scheme.
Arch linkages with other arches.	An arch must have a certain rigidity to support the wind load acting on the bridge. This rigidity can be provided by bracing two arches with rigid elements.	The way rigid elements brace arches forming a truss such as in the case of the Oudry-Mesly Footbridge. The way an arch is differentiated in smaller braced steel arches such as in the case of the Lusitania Bridge.
Cable linkages with the deck structure	To suspend the deck and transmit the loads to the arches, the cables must be fixed to the deck structure: the vertical components of the dead and sometimes live loads must be transferred through the deck structure to the cables. The direction of the cables may help in giving the arch stability.	The way hangers are linked to the deck structure.

Table 3: Linkages of the Arch D-Gene

The creation of a structure involves the plan layout, with the span to be covered, the loads that it will support as well as the architect's artistic expression or design statement. It seems that once Calatrava achieved a determined performance by using a slightly modified version of a precedent, he would often use this solution in future designs.

8.4.4. Mutations and Transference of the Arch D-Gene in the Phylogeny of Calatrava's Designs

Proceeding from a list of Calatrava's designs in chronological order, this section first shows examples of transference of the arch d-gene, its "mutations" and adaptations from one bridge to another. Second, it shows an example of transference of the same d-gene to a building (Tenerife Exhibition Center). The objective of this section is to describe and explain the modification that occurred to the arch d-genes in their re-use through time. Modifications will be shown that are related to regulatory and structural d-genes.

An Example of the Transference of the Arch D-Gene among Through Arch Bridges

This sub-section shows the adaptation of the arch in a set of Calatrava's bridges that uses only one arch to suspend the carriageway. It shows the adaptation of the arch structural d-gene when Santiago Calatrava introduces an asymmetry in the structure, modifying the distribution of the forces in the whole (Figure 12). The solution is achieved with a play of forces and form; and its optimalization is achieved in part, as Tzonis asserts, "by following two major design strategies: profiling elements of structure, and differentiating elements into specialized function and materials" (Tzonis and Calatrava 1999, p. 31).

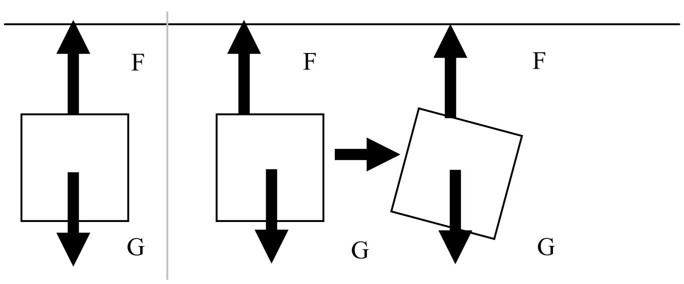


Figure 12: Asymetric Distribution of Forces

The bridges are: the Lusitania Bridge, the Gentil Bridge, the Miraflores Bridge, the Puerto Bridge (already described), the La Devesa Footbridge, the Uribitarte Footbridge, the Alameda Bridge, the Alcoy Bridge, and the Campo Volantin Footbridge. The position of one of the arches of these bridges in relation to the carriageway is symmetric (Lusitania Bridge); the others are asymmetric. Among the asymmetric, there are: first, the arch of the Puerto Bridge that is asymmetric but not rotated; second, the arches of a the Gentil Bridge, Miraflores Bridge, La

Devesa Footbridge, Alameda Bridge and Alcoy Bridge that form an obtuse angle with the largest part of the carriageway; and third, the arches of the Urbirtarte Footbridge and the Campo Volantin Footbridge that form an acute angle with the widest part of the carriageway (Figure 13).

The esthetical expressions of these bridges are inseparable from their structural solutions. The Gentil Bridge, the Miraflores Bridge, the La Devesa Footbridge, and the Alameda Bridge are asymmetric bridges that have one arch rotated and instead of cables they have blades, which could not be just substituted by cables. Their slanted blades, like those of the Puerto Bridge, serve to transfer the horizontal forces created by the rotated arch to the girder; these blades are also used with the intention of resisting the bending of the arch.

If we make diagrams of forces considering the three main variations of the position of the arch in relation to the carriageway (latitudinal cross section), we shall see the main constraints related to the rotation of the arch with regard to equilibrium and solutions to resist the rotation of the deck. Any variation of the rotation of the arch will require variation of the position and the kind of hanger that should be used. In the event that the position of the hangers does not contribute to the equilibrium of the whole, then a linkage with other features will be necessary, such as a linkage of the arch d-gene with a torsion box or box girder gene so that the structure may resist the tendency of the deck to rotate (Figure 14).

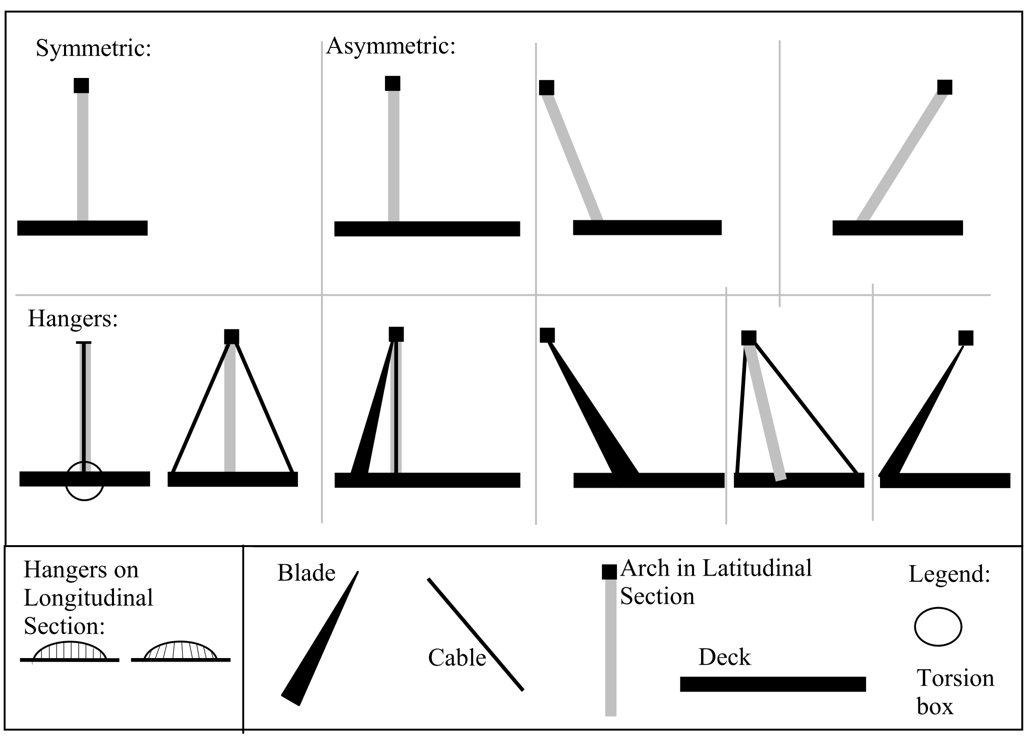


Figure 13: Arched Bridge Configuration

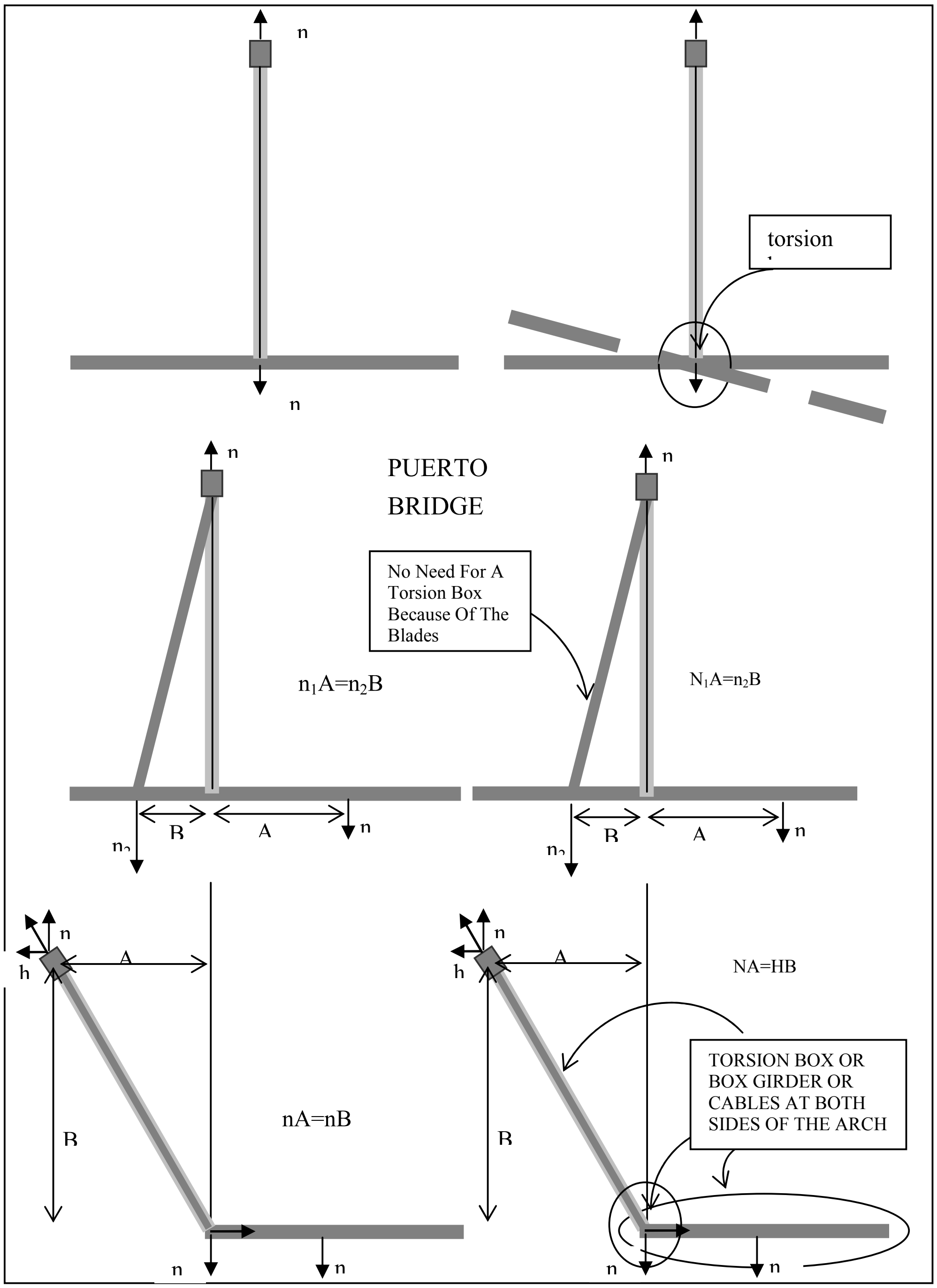


Figure 14: Diagram of Forces: Equilibrium (only dead loads considered) and Torsion

For example, if the designer does not want blades but only cables on a bridge with an asymmetric rotated arch such as in the Alcoy Bridge and the Campo Volantin Bridge, then the designer might be driven to create two rows of cables which are not in the same plane as the arch. In the case of the Alcoy and Campo Volantin bridges, the divergent position of the hangers of each row seems to reinforce this adaptation of the arch to conform with requirements vis-à-vis the stability and equilibrium of the whole, so that the flattened parabolic arch and their non parallel cables can safely suspend the carriageway and provide a peculiar sense of lightness to the observer. In the cases above, the use of blades and/or cables show the esthetical and structural quality.

Tenerife Exhibition Center, Tenerife, 1992

The arch of the bridges shows many similarities with that suspending the roof of Calatrava's Tenerife Exhibition Center of 1992 (Figure 15), in such a way that we could say that the structural arch d-gene of Calatrava's bridges was transferred to this building (Figure 16; Figure 17).

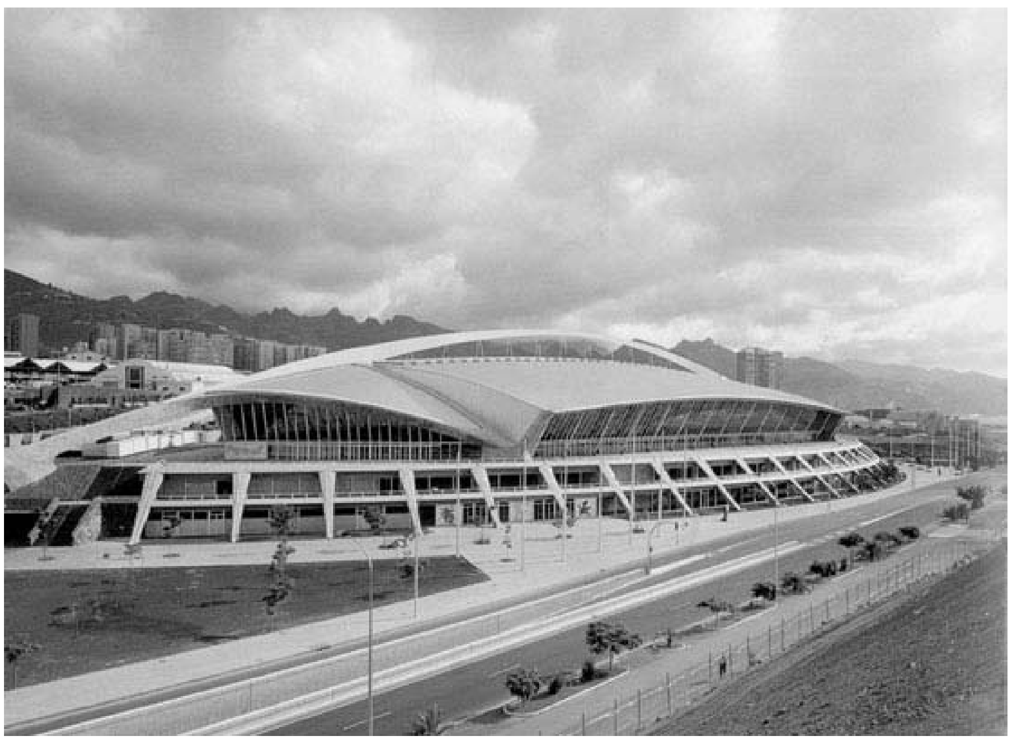


Figure 15: Tenerife Exhibition Center, 1992

The main task was to design a multipurpose space that would accommodate fairs as well as carnival parties. For this purpose, Calatrava designed a hall which did not have any structural obstacles within it. A steel arch was used to span the 142-meter hall between two concrete, splayed buttresses at each end of the curved plaza slab (Figure 18). This 39-meter high arch suspends a shallower arch, whose apex is 30 meters high above the floor slab.

This arch is intended to hold the roof in its center together with the outside slanted columns. The transference of vertical loads, whether from the roof weight or from wind loads, is solved with the arch and slanted columns (Figure 19, Figure 20).

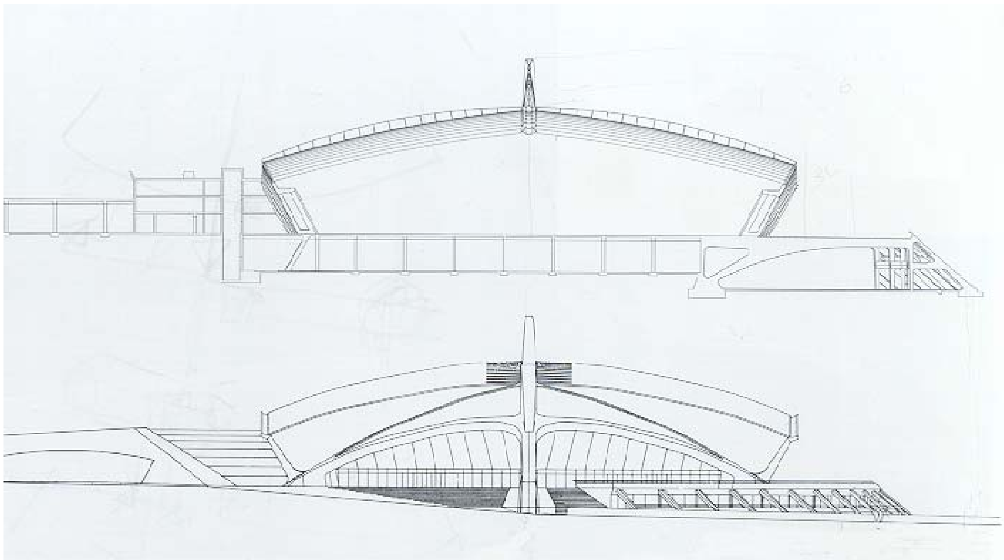


Figure 16: Latitudinal façade and cross-section,Tenerife Exhibition Center, 1992

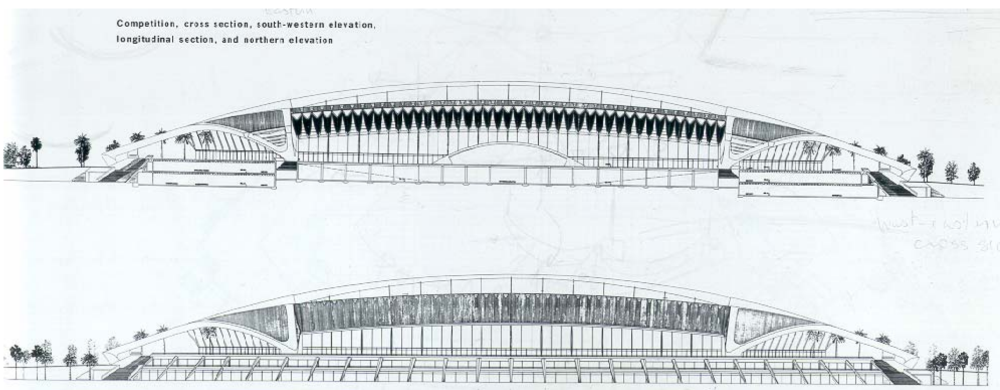


Figure 17: Longitudinal façade and cross-section,Tenerife Exhibition Center, 1992

The shallower arch is linked to 18-meter long curved and triangulated latticework trusses that hold the roof weight. Through their form – slightly curved toward the middle – the trusses resist the moment created by loading this beam. These lattice trusses are held together in such a way as to resist the horizontal component of wind loads in two important ways: first, each two lattice trusses form a triangle that provides stiffening for the roof structure; and second, the binding of these beams creates shear forces between themselves which together produces a force equal and in an opposite direction to the horizontal component of wind loads (Figure 22).

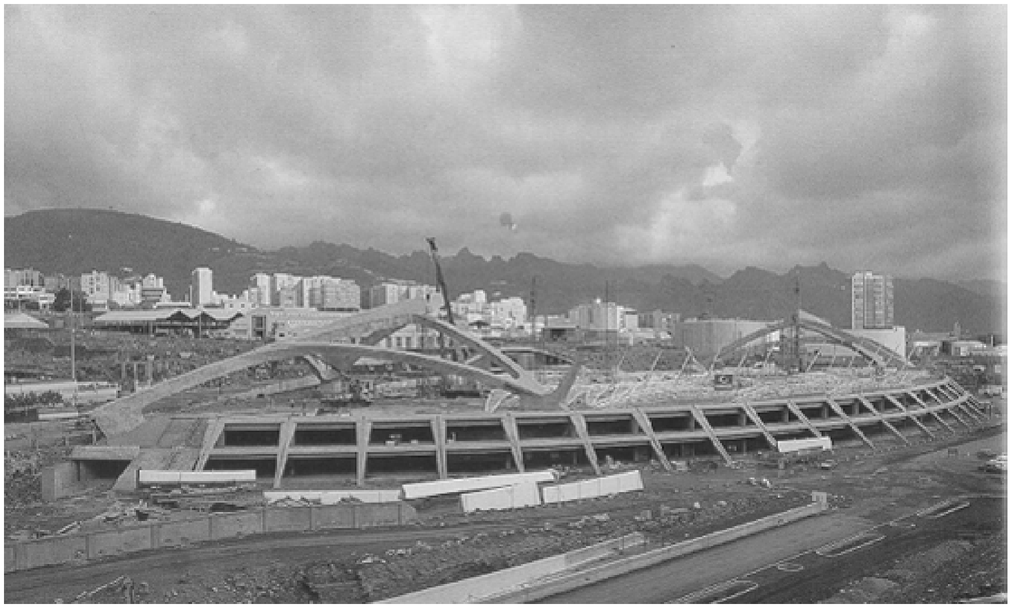


Figure 18: roof construction, Tenerife Exhibition Center, 1992

Similar lattice trusses were already used in Calatrava's earlier Jakem building, although the corrugated sheet cladding of the Jakem building is not structural. This precedent shows that adaptations were necessary to solve problems of the structure as a whole particular to the case in hand.

A second precedent is the arch itself. The arch suspending the roof was used earlier in the asymmetric roof structure of the Jahn Sports complex, a project that was developed for Berlin earlier in the same year (Calatrava, Tischhauser et al. 1998). One could also say that the structural arch d-gene used in designing bridges was used to produce the design of a roof.

In the case of Le Corbusier, we stated that we could represent the transference of the piloti from the savage hut to his designs with the concept of the d-genes. If we compare bridges to roofs, we could also use this d-gene representation and describe the transference from one kind to the other.

However, in this case, it is the structural d-gene that is being transferred rather than the regulatory d-gene. Bridges as well as roofs are beams, and proceeding from this fact, we can provide several similarities and differences, making it possible to exchange the explicitly similar data from one design to the other. The regulatory d-genes of these artifacts show dissimilarities. A bridge refers to the crossing of people, goods and vehicles from one point to another, surmounting an obstacle. These live loads are extremely changeable (e.g. the traffic of trucks and other vehicles exerting asymmetric loads on the carriageway) and are reflected in the structural solution. The roof is a means of protection against climate or environmental circumstances. Except for special cases such as the Central Library of TU Delft, there will be no people traffic on the roof; and in general, there will be no vehicle traffic over the top of it except in the case of specific buildings. The structure of a roof is thus more straightforward than that of a bridge.

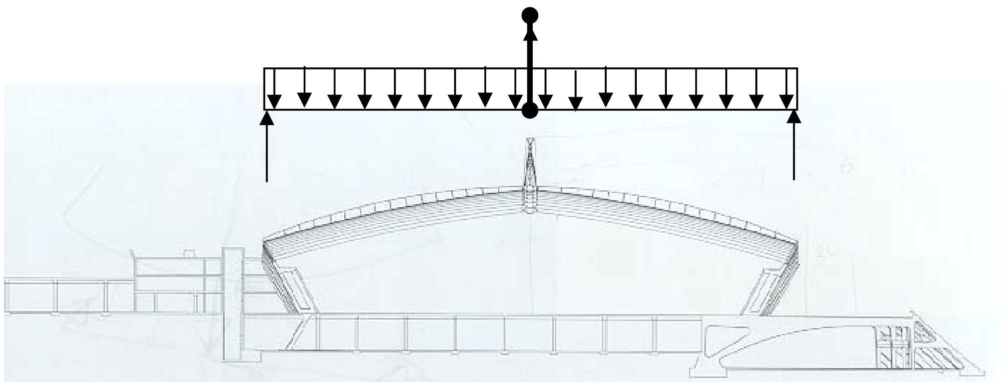


Figure 19: Cross Section, Symetric Loads (dead loads), Tenerife Exhibition Center, 1992

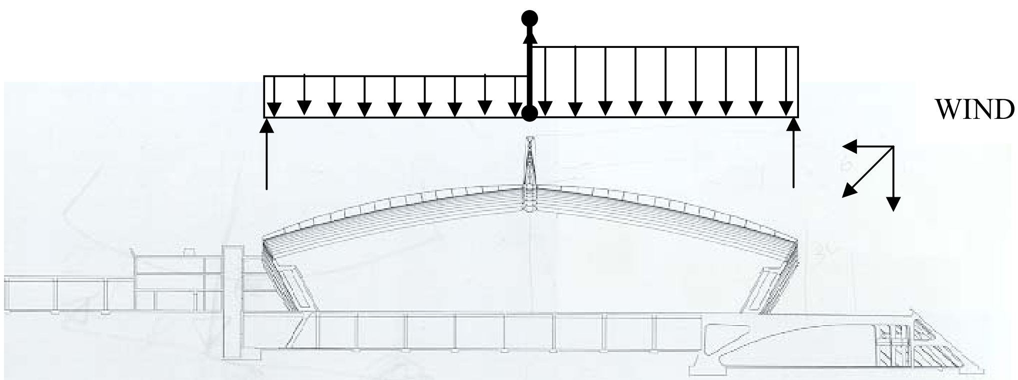


Figure 20: Cross Section, Asymetric loads (vertical component of wind loads), Tenerife Exhibition Center, 1992

With this last case, examples were provided of the transference of a structural d-gene. This structural d-gene seems to carry instructions of its regulatory d-genes, in particular the geometric configuration, while it left the intentional function (topology) of its regulatory d-gene behind.

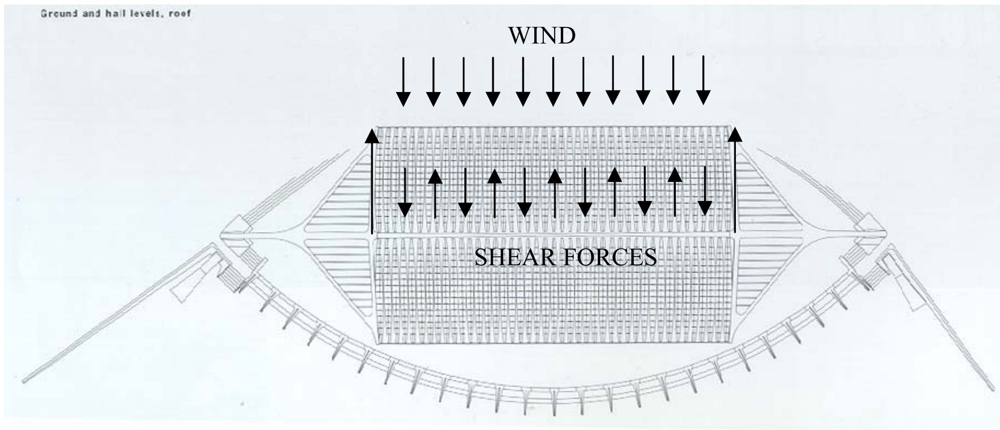


Figure 21: Roof Plan, Asymetric Loads (horizontal component of wind loads) Tenerife Exhibition Center, 1992

8.5. Fitness and the Expression of the Arch D-gene

In this research we have not discussed fitness much; however, it is of extreme importance for the selection and re-use of design precedents. The selection of design precedents is done based on their internal fitness (organization and stability of the structure), their external fitness (regarding the site conditions), and certainly according to their esthetic expression. After selection, there is the transference of features from one design to another independent of the species. After the transference of these precedents, the growth and morphogenesis of these designs are still highly dependent on how the forces are distributed through the structure in order to attain equilibrium and stability.

Fitness refers to performance; the more an artifact “matches” the desired performance, the higher is its fitness. As in nature, fitness in design refers primarily to the expression of d-genes; in other words, it is the phenotype/design that is tested, not the instructions. Fitness is related to the regulatory and structural d-genes.

However, the bridge is not a mere assembly of elements; it refers to internal organization and its relation to the environment. The structure must be stable and in equilibrium, and it must also be serviceable for the intended function of the bridge (the topology) and should satisfy esthetically. Consequently, fitness does not refer to one d-gene alone but to the interaction of various genes and the performance of the whole. As Thompson asserted (Thompson 1992, p. 1019), “The biologist, as well as the philosopher, learns to recognize that the whole is not merely the sum of its parts. It is this, and much more than this. For it is not a bundle of parts but an organization of parts, of parts in their mutual arrangement, fitting one with another, in what Aristotle calls ‘a single and indivisible principle of unity'." It is not enough to test the outcome of the d-genes individually, but what all the d-genes generate together.

For example, since the arch d-gene is composed of arch(es) and cables, these elements should be positioned in such a way so as not to interfere with the plan layout of the bridge (topology), which must facilitate the transit of people and vehicles. In other words, hangers should be positioned in a way so as not to disturb the efficient flow of traffic and the safety of pedestrians and drivers. The height of the arch must relate to the span it must cross[9] as well as to the kind of vehicles that will move along the carriageway. The way hangers are attached must also contribute to the stability of the whole.

Fitness: fitness depends on the interaction of the parts		
Interaction among the parts should result in the safety, efficiency and effectiveness of the artifact.	The plan layout of the bridge must facilitate the transit of people and vehicles in safety.	Arches and cables must be placed in such a way so as not to disturb the transit of people and vehicles.

In summary, and above all, there must be a stable structure that facilitates the crossing of people, goods and vehicles. Through changes such as rotating the asymmetric arches, as in the case of Gentil Bridge, Calatrava placed the structure in an innovative way in a state of equilibrium and stability. It goes without saying that a stable structure that facilitates the production of topologies as made explicit by the d-genes has a high performance that increases its chance of being selected as a future possible solution, in particular when contextual conditions are similar.

A fitness test in nature is carried out by selection mechanisms such as natural and sexual selection. Natural selection is not affected if the selected organisms look "distasteful"[10]. Natural selection seems to work only on the performance of the structure, the function of the organs, and the interaction with the environment. A computational tool should at least be able to express whether the structure is able to carry the live and dead loads safely. As Daniel L. Schodek asserted in his *Structures*, "The structure must be able to carry the design load safely – without excessive material distress and with deformations within acceptable range. The ability of a structure to carry loads safely and without material distress is achieved by using safety factors in the design of the element. By altering the size, shape, and choice of materials, stress levels in a structure can be maintained at a level considered acceptable for life safety and such that material distress (e.g., cracking)

[9] There is a rule of thumb that assumes a 1:6 relation; i.e. for every six meters of span, the arch should be at least one meter high.
[10] What would be distasteful to whom?

does not occur. This is basically a strength criterion and is of fundamental importance" (Schodek 1980, p. 80).

However, like "sexual selection" (imposed by the organisms themselves), in design, fitness also refers to the esthetic expression of the artifacts; in other words, it refers to the morphological expression of regulatory d-genes and their respective geometric configuration. Designers have preferences that vary through the years and from culture to culture; their contribution was highlighted in this research with the development of the Unité d'Habitation. The greatest challenge in the development of a computational design tool for the re-use of design precedents is to provide access to regulatory and structural d-genes and a mechanism for selection.

8.6. Test Result

This chapter has presented descriptions of two arched-bridges of Calatrava: the symmetric Lusitania Bridge, and the asymmetric Puerto Bridge with its vertical arch, blades and cables. Afterwards, the description of a general arch bridge was re-structured in the proposed model. In a further step, the chapter formulated an example of what a d-gene could be in this context of Calatrava's designs: an "arch d-gene" that was composed of arch(es) and hangers. The examples of variation of the theme was given, as well as transference and recombination to other orders of designs.

This section is subdivided into two parts. The first refers to fitness; the second refers to the adequacy criteria of the model. Before we start the description of them, it is important to recall once more that this qualitative model pictures the process of the re-use of design precedents; it does not explain of how architects think in reality. Moreover, as Schön asserts, architects reflect while acting, and therefore their "direction" may change according to their intermediate discoveries and the "local" constraints imposed.

8.6.1. The Proposed Model: the Question of Generalization

Does the proposed model have the potential to be applied to diverse oeuvres (generalization)? The four most important representations of the model refer to: firstly, transference of parts of designs; secondly, modification (mutation or recombination); thirdly, adaptation; and fourthly, variation. This qualitative model pictured how certain features (d-genes) were introduced, modified and integrated to a series of designs of Le Corbusier and Santiago Calatrava who are very distinct from each other. However, it should be tested many times with the work of other designers to improve its structure and enrich it.

8.6.2. The Proposed Model: Criteria for Evaluation

In this sub-section, we shall respond to general adequacy criteria such as the validity and reliability of the proposed model with regard to its purpose, and we shall return to the adequacy criteria that we provided in Chapter 3.

General Adequacy Criteria

Validity. Does the proposed model structure the process of re-use of design precedents in a fruitful way? We assert that it does.

1. The proposed model seems to have the potential to picture the process of re-use of design precedents of numerous architects.
2. The resultant model presents a methodological ordering that enables comparison of the process of re-use of precedents among designers.
3. Its concepts have the didactic potential to be communicated among designers in training.
4. The phenomenon of change fits better in this analogical model than in other existing design theories.

Effectiveness. Does the proposed model provide the user with new insights into the use of design precedents? This model as it is developed until now seems already to have a certain amount of effectiveness because it has provided us with new insights into the process of re-use of design precedents. Based on the second and third cases, one can say that this model enables the architect (architectural student) to see the phenomenon in its totality. In other words, it is possible to see the design precedent individually and/or integrated in the lineage of designs, showing the phenomenon of change that resulted in innovations due to the re-use of precedents over time.

Efficiency. Does the use of the proposed model provide a representation that is serviceable with regard to time? One needs to consider the purpose of the model. In education, we can say that it presents a concise method to point to different kinds of re-use of design precedents. Once the model is understood, the transferences of certain features become easier to be communicated among architectural students and teachers, in particular because of its phylogeny-ontogeny structure as well as its d-genes structure (regulatory d-genes, structural d-genes and linkages). Therefore we believe that the use of this qualitative model in education works as an efficient device. If the purpose of the model is to move towards a computational tool to be used in architectural practice, then we cannot answer this question concerning efficiency before developing the model further and producing an algorithm that may represent its concepts.

Reliability. Does the proposed model resist conditions that would cause failure? This model was applied to the work of very different architects and still made evident its descriptive power. But, a satisfactory reliability test could only be carried out by applying this model to numerous case studies. It is not in the scope of this research to provide a real reliability test for this model.

Robustness. Can this proposed model lead to new developments? This model has already led to a development different to its original intention, i.e. it is not only a device for researchers studying the process of re-use of design precedents in architecture, but it may be used as an analytical device in education, which can instruct students on the role of precedents and compare the design processes of designers. We believe that it may lead to new developments in fields such as industrial design or in any field where constraints play a pressing role in the creation process.

Specific Adequacy Criteria

Chapter 3 presented nine heuristic adequacy criteria that a computational tool for the re-use of design precedents should meet if it is meant to be used by architects in architectural practice. These criteria seem to be relevant to the other two cases as well. Recalling:

1. Given that the architect often uses a part of a design precedent and not the whole of it, the model ought to have mechanisms to explore, select and recall parts of a project. The second and third cases in this research show that indeed Le Corbusier and Santiago Calatrava often use one or more features (precedent components) of a project. A typical example of this in Calatrava's oeuvre is the arch and hangers studied in this chapter.
2. Given that features of a design are often recruited from diverse design precedents, the model ought to provide mechanisms to search per element. Le Corbusier's Unité d'Habitation is a good example of this. Calatrava's oeuvre has evolved out of a limited number of what Tzonis called Calatrava's five "seminal projects". Beyond this dissertation, one can find descriptions of this recruitment in numerous publications on Calatrava's projects.
3. Given that features (characteristics) of a project are only good or bad in relation to a certain environment and specific constraints, the system ought to provide as a search result not only the most fitting but also several precedents. It seems to be good sense to not constrain the possibilities of the designers presenting only one solution which may not be suitable for the current project due to its particular constraints or that may lead them to a local optimum rather than to one of the most successful options for the situation.

4. Given that architects go back and forth in the search for solutions to their designs, reflecting while acting (see Schön 1983), the system ought to provide mechanisms to save the desired stages of the project. This behavior was observed in the second and the third case as well. An example of this is to be seen in the process of designing Calatrava's structures, where the integration of the parts is essential for the stability of the construction, one action resulting in several changes, which therefore modify the expression of the whole artifact.
5. Given that design precedents are not simply used, but most of the time are adapted to the new situation, the model ought to have mechanisms to support adaptation. A typical example of this in Le Corbusier's use of precedents is to be seen in the way he resolved the position of the garden in his Immeubles Villas, which was positioned in the roof of earlier projects. In Calatrava's Tenerife Exhibition Center the use of the arch and hangers also had to satisfy other constraints.
6. Given the use of principles in projects, the system ought to be able to recall design precedents based on the use of specific principles. In the second case we have seen how Le Corbusier's five points for a modern architecture evolved from design precedents and that they became principles in a later stadium of his career. Another example, in Calatrava's oeuvre the use of implicit structural principles originated from his analytical reasoning on foldable structures.
7. Given that some features often appear combined with others, the model ought to provide a mechanism to apply features combined with others by a series of principles or by geometrical configuration. An example of this in Le Corbusier is once more to be seen in his five points for a modern architecture, where in a previous chapter we have shown the interdependency of these features. In Calatrava's oeuvre, some structural solutions are directly dependent on certain elements working intrinsically together such as arches and hangers.
8. Given that architects are active agents in the design process, the model ought to have mechanisms that enable them to add, subtract, mutate, substitute and combine elements of design precedents. This behavior was widely shown in the description of the second and the third case.
9. Subsequently, given architects' traditional way of working, modifying a solution or redrawing it on top of initial designs, the model ought to provide design precedents in manageable formats. It seems to be good sense to fit a program to the behavior of creative designers rather than to constrain their natural behavior with a superimposed design method.

Therefore being relevant in depicting the process of re-use of design precedents in the three case studies carried out in this research, these criteria should be taken as suggestions in developing a computational tool to be used in architectural practice. The notion of d-genes seems to enable the application of these adequacy criteria. Even when focusing on one feature, like in the last case, we have seen how many variations and constraints are attached to its adaptation to new situations and its recombination with other features. The challenge of programmers in producing a future design tool to be used in architectural practice is, then, to solve each of these criteria and seemingly many others not revealed by these initial cases, so that the risk of misrepresenting the design process itself can be controlled.

The next chapter will provide the conclusion of this research. It will show the implications of such a rough theoretical model related to its two possible uses. Proceeding from the findings of this research, it will also speculate on the requirements of future research if the development of a computational tool is desired.

CHAPTER 9

CONCLUSIONS

The motivation to carry out this research was to facilitate the creative re-use of design precedents in architectural practice by introducing a new computational tool that could deal with the phenomenon of change through the adaptation and recombination of precedents accumulated over the years. This research contributes to this ultimate goal by developing a model of the phenomenon. In other words, by drawing an analogy between the process of re-use of design precedents and the model of natural evolution, the research develops a model to explain the phenomenon of change that occurs through the re-use of design precedents in architecture. The research product is a qualitative model; it is a preparatory step that may be developed into a computational model.

This proposed model can be more directly used as an educational analytical device to explain to designers in training the phenomenon of change through the re-use of precedents in designing.

This chapter presents a review of the process and evaluates the model according to what was promised and fulfilled, as well as its reservations and limitations. It also presents constraints and possibilities for further research.

9.1. Review of the Process: Research Summary

In developing a model to picture the phenomenon of change through the re-use of design precedents in architecture, we followed two main strategies:

1. The use of an analogy with the evolutionary model: heuristics
2. The use of cases: heuristics, adequacy criteria, illustration and testing the evolutionary design model under development.

Essential in the development of this model is the use of Darwinian evolutionary theory in combination with recent theories of genetics and embryology. The research uses an analogy[1] with evolutionary biology in order to identify a conceptual structure to represent the process of re-use of design precedents in architecture. In this research, the analogy between this process and biological evolutionary models was taken as heuristics for three main reasons: firstly, there is no theory that systematically explains the phenomenon of change in design. Secondly, the biological model ties the facts of the phenomenon of change to some basic ideas about design; thirdly and subsequently, the analogical model is used to reduce the data of the real world to some assumptions, reducing the complexity of reality. We believe that the analogy between the process of re-use of design precedents can be heuristically and pragmatically used, when well controlled and constrained, to model the phenomenon of change in architecture to the extent that it is based on the re-use of design precedents.

Cartwright, drawing on a model based on a van der Pol oscillator[2] asserts: "The success of the model depends on how much and how precisely it can replicate what goes on."

To develop and evaluate our model, the research employs three case studies from the architectural domain. The first case is employed to identify adequacy criteria. The analogy between the process of re-use of design precedents and the biological evolutionary models seems to be endorsed by the adequacy criteria generated by this case study. The case is drawn from a series of housing projects of the Dutch architect J.J.P. Oud. The second case depicts the conception of the Unité d'Habitation of Marseilles by Le Corbusier, and it is used to illustrate the components and behavior of the model under development. The third case, drawn from Santiago Calatrava's structures, is used to enrich and test the proposed model.

In order to develop a design model picturing depicting the process of re-use of design precedents in an analogy with the evolutionary model, we went to the sources: to biology. The analogy was used pragmatically to picture the architectural phenomenon, and thus, through a series of questions on the architectural process of the use of design precedents, similarities and differences between design and natural evolution were identified. The evolutionary analogy was fruitful in modeling the process and subsequently the elements of design precedents, their adaptations and recombinations over the years.

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[1] Analogies such the one pursued in this research have been in use in developing scientific models from the beginning and they are used to cope with the human inadequacy in dealing with infinity.

[2] "Is a helium-neon laser really a van der Pol oscillator?" Cartwright asserted that a helium-neon laser "is really a mix of helium and neon atoms, in about the ratio nine to one, enclosed in a cavity with smooth walls and reflecting mirrors at both ends, and hooked up to a device to pump the neon atoms into their excited state. It is not literally a triode oscillator in a d.c. circuit. If we treat van der Pol's equation for a triode oscillator, we will be able to replicate a good deal of the behaviour above threshold, and that is our aim."

The main ideas from biology applied in the design model are the use of two levels of evolution: phylogeny and ontogeny; and from developmental genetics, the processes carried out by "d-genes" and their linkages. There are two main aspects concerning this second idea.

First, each design precedent used in this qualitative model can be sub-divided into two interlinked sets of instructions: a) we have the "regulatory d-gene" that deals with the conceptual or configurational instructions; and b) we have the "structural d-gene" that deals with the technique and materials used to produce a structure that is stable and in equilibrium which facilitates the configurational instructions.

Secondly, we could say that in design, as well as in "genetic engineering", "genes" can be transferred from one "organism"/project to another, even if they belong to another "species". However, for the expression of these genes (phenotypes/features) to succeed, the notion of fitness is fundamental. On the one hand, fitness relates to internal constraints; i.e. how the parts function individually and how they are integrated to the whole project. On the other hand, fitness relates to external constraints; it relates to a multi-dimensional ecological environment. In other words, in design, this fitness refers to how the project (as a whole) functions at the given location in interaction with its direct environment, and its value is tied to the satisfaction of its users.

In its analysis and synthesis of architectural precedents, our model pictures the phenomenon of change in a series of designs of a single designer through modification, recombination and accumulation of design precedents over the years. The proposed design model does not represent the mind processes carried out by the designer,[3] but it does, however, provide insights into how creative minds got their "material" in the creation of innovative designs.

9.2. Promises and Accomplishments: What was Promised and Fulfilled?

As explained in the chapter on the research method, and according to Cartwright, theory entry occurs in two stages. She asserts: "We start with an unprepared description which gives as accurate a report as possible of the situation. The first stage converts this into a prepared description. At the second stage, the prepared description is matched to a mathematical representation from theory" (Cartwright 1983, p. 15).

[3] In other words, we can use for example a calculator or our brains to calculate the result of a certain equation. We can obtain the same result both ways; however, the calculator does not solve the equation by mimicking our brain processes, and neither does this provisional model.

This research provides an "unprepared" or rough description of the process of re-use of design precedents and it provides some insights at the first stage of theory entry. The qualitative model has descriptive power, and therefore it can be successfully used as an Educational Analytical Device.

9.3. Possible Uses: is the Model Successful?

The success of a model depends on it serving its purposes and subsequently it depends on whether it satisfies its users.

Who would use the model? How would they use the model? This model, in its actual state, is an educational analytical device that could be used by teachers in describing and explaining the phenomenon of change to designers-in-training. Teachers, and also students and design researchers, may also use it to compare and analyze the design processes carried out by different architects. In the case of students, they would have a device to structure (part of) their study and potentially assist them in developing their own way of designing.

Programmers who are interested in developing a computational tool to assist creative architects in using design precedents could use the proposed model to learn from its insights into the process and the adequacy criteria that the model must fulfill if the model is meant to assist designers in architectural practice. We believe that these insights can help them in developing a meaningful tool for architects in practice.

The representation of design precedents, as features that are taken apart, modified and recombined, is more fruitful in explaining the phenomenon of change than the use of the abstract and often fuzzy concept of "type". As mentioned earlier in this dissertation (Chapter 8), we had a 'messy' phenomenon, and the model helps in structuring it. It allows us to see a systematic process in the work of the designers studied, which permits us to compare the process of re-use among them. Moreover, the phenomenon fits better in the model than in existing design theories. In this sense, and not in a mathematical sense, the model is successful.

9.4. Strengths of the Qualitative Model: Findings

Our model consists of a framework which, after the identification of features that are re-used as design precedents over the years by an architect, allows us to decompose these features into their conceptual and structural parts, and to describe their "instructions" with the help of the POM reasoning system.[4] It allows us to see what is indeed being transferred, and how it is adapted and/or recombined over the years, which often contributes to the creation of innovative designs.

In what concerns the use of design precedents, the application of the model on our three cases made more explicit that:

1. The phylogenic design process[5] that leads to new inventions is not linear. Features are brought to the design from several sources. However, they are not consistently used in all subsequent projects.
2. Innovative designers often transfer precedent-components (features) to their new designs instead of the whole precedent-scheme (project or type). They are then modified and recombined with other features.
3. It is not only the introduction of new technology that can generate innovation in design. Innovative designs can be originated from the recombination of a particular feature in a new design.
4. Often only the configuration or the tectonics of a feature is transferred to new designs.
5. Precedent-component (features) can become part of the architect's set of principals or concepts and from there on can be used without reference to the design precedent.
6. Due to successful recombinations, features can form linkages and be transferred together to new designs.
7. Design precedents are not innovations in themselves; however, when transferred, modified and recombined in a new situation, they may contribute to the generation of unparalleled designs[6].

9.5. Reservations and Limitations:

The reservations and limitations of this research first refer to the use of the case studies. The heuristic use of cases in research always carries the risk that in a general sense, they are not representative of the facts of the phenomenon under study. Only by carrying several other cases we can test whether the findings of this research are applicable to the use of design precedents by other architects.

Second, there are also limitations that refer to the development of a computational tool for the re-use of design precedents in architectural practice. They refer to the coupling from the first stage of theory entry to the second; to the risk that our descriptions may not fit into equations and boundary conditions leading to a computational tool; or, in other words, that the prepared description

[4] See Chapter 6
[5] In contrast with a design process carried out to develop one design, a phylogenic design process is one that is carried out by one designer in producing a series of projects.

cannot be matched to a mathematical representation of the theory. In the sense of developing a computational tool, if there can be no algorithm that links the descriptions to their mathematical representation, then the model will not suit its purposes, and therefore, according to the simulacrum account, the model would not be successful. This limitation does not apply to this model when used as an Educational Analytical Device.

Third, there is the impossibility of modeling “instinct” or why architects choose a particular direction over others, or why they move towards other alternatives during the design process; and the impracticality of representing recognition or how architects recognize the potential of a determined precedent in supporting their design moves.

Fourth, there are some reservations on the use of the biological terminology that can be misunderstood and therefore misused. Most probably, misunderstandings would arise from the tendency to justify everything in design as an adaptation derived from a precedent.

9.6.Future Extensions

As an educational analytical device to explain the phenomenon of change, the proposed model could be improved by:

1. Developing a computer based tool using precedents to aid design.
2. Developing organizational tools for managing information in an architectural practice.
3. Enhancing education in architecture using precedents.
4. Providing more understanding in creative design as a psychological process.

9.7. Concluding Remarks

The use of precedents in creative design is a fact in architectural practice. Whether highly creative designers such as those referred to in our cases here or more ordinary mainstream architects, they usually employ and re-use previous design solutions. The present research tries to develop a model that would facilitate the re-use of these precedents as they are accumulated in design practice. It seems that such a tool is needed because the re-use of design precedent is here to stay.

[6] As Lefaivre and Tzonis asserted, “Calatrava appears to confirm Freud’s claim that ‘the *creative* imagination… is quite incapable of inventing anything; it can only combine components that are strange to one another.” (Lefaivre and Tzonis 2001, p. 10)

Without it, the architect is not left free but rather becomes overwhelmed by the combinatorial explosion of design possibilities.

As we have established, the proposed model here is not an Ars Inventio: it will not provide architects with a future tool that will recognize potential concepts and translate them into architectural elements. Architects should be able to conceive designs with their d-genes and to change and recombine them as they wish, because the continuous act of recognition of new features as well as the modification of existing ones in the minds of architects seem to be the true force behind innovation. Though we cannot automate this very personal process of recognition, we can look at a way to automate the recognized findings and allow these findings to evolve through time. Without trying to interfere in the creative act of recognizing new features, our approach aims to support the transference and adaptation of architectural features/genes from one design to another, which seems to be a very interesting source of creativity as well. Evidently, by re-using d-genes, architects will not become creative designers. The act of recognition, recombination and adaptation will probably always need the architect’s creativity.

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SAMENVATTING

Eeuwenlang hebben architecten ontwerpprecedenten gebruikt bij het bedenken van nieuwe ontwerpoplossingen. Sommige architecten maakten daarvan expliciet gebruik – men denkt aan Le Corbusier, James Stirling en Jo Coenen; anderen deden het minder nadrukkelijk – bijvoorbeeld J.J.P. Oud, Aldo van Eyck en Santiago Calatrava. Deze praktijk voerde tot zeer voordelige, efficiënte, effectieve en innovatieve resultaten. Het doel van dit onderzoeksproject is het vergemakkelijken van deze praktijk door middel van de constructie van een model dat greep heeft op de belangrijke kenmerken van een ontwerpproces dat gebruik maakt van precedenten. Dit model wordt geconstrueerd door een analogie te maken met de natuurlijke evolutie. Het is niet de bedoeling om processen die zich in het hoofd van de architect voltrekken te representeren, maar veeleer hun gedrag zoals dit tot uitdrukking komt in de ontwerpproducten.

Het project maakt gebruik van de multidisciplinaire methodologie van de ontwikkeling van ontwerpinstrumenten zoals ontwikkeld door het Design Knowledge Systems Research Center. Het bedient zich van een analogie met de Darwinistische evolutietheorie, in combinatie met recent ontwikkelde theorieën in genetica en embryologie. Nuttigheidscriteria voor wat betreft het afbeelden van een fenomeen in de architectuur bepalen de aandacht voor bepaalde aspecten van deze analogie. Het onderzoek gebruikt drie case studies uit het domein van de architectuur: J.J.P. Oud, teneinde criteria van adequaatheid voor het model te bepalen; Le Corbusier, om de componenten en het gedrag van het model in ontwikkeling te illustreren; en Santiago Calatrava, om het model te testen. Dit onderzoek ontwikkelt een voorlopig, aan de computerisering ervan voorafgaand kwalitatief model, dat inzicht verschaft in het proces van hergebruik en in de criteria waaraan een model moet voldoen opdat de architectonische praktijk succesvol is.

Gegeven de notoire geschiedenis van vervormingen van het Darwinistisch model en van het misbruik ervan als legitimatiemiddel, is grote zorg besteed aan het afbakenen van de grenzen van deze analogie. Er zijn fundamentele verschillen tussen ontwerpmodellen en modellen van evolutie. Het belangrijkste verschil is het selectieproces - natuurlijke versus kunstmatige selectie. Als “fokkers” roepen ontwerpers uit hun geheugen en/of uit hun archieven zaken op doormiddel van “kunstmatige selectie”. Dit komt niet voor tijdens natuurlijke selectie. Bij natuurlijk evolutie zijn mutaties ”toevallig”, terwijl natuurlijke selectie de richting ervan verzorgt. Bij het menselijke ontwerpproces zijn mutaties en selecties veelal intentioneel. Veel analogieën lijden aan een verwarring tussen een natuurwetenschappelijk begrip van evolutie en de culturele notie van vooruitgang; ze reduceren in hoge mate de voorstelling van het cognitieve ontwerpproces en geven er een verkeerd beeld van.

De evolutionaire en genetische analogie dient als heuristisch middel om een voorstelling te geven van de mechanismen van het proces van gebruik en aanpassing van ontwerpprecedenten, en van elementen van dergelijke precedenten die over jaren zijn geaccumuleerd en weer worden aangepast en hergebruikt tijdens een ontwerpproces dat vaak voert tot ontwerpinnovaties. Het model hanteert de notie van "ontwerpkenmerk", dat wil zeggen een component van een precedent, als meest belangrijke eenheid van selectie. Er wordt geput uit de ontwikkelingsgenetica met gebruikmaking van het idee van regulatieve genen. Zo wordt elk kenmerk afgeleid uit twee onderling verbonden soorten instructies. Enerzijds het "regulatieve d-gen" dat zich met de configuratieve instructies bezighoudt; anderzijds het "structurele d-gen" dat zich met de gebruikte techniek en de materialen bemoeit. In het ontwerpmodel is, net als in de evolutie, de notie van geschikte omgevingsbeperkingen bij het generen van vorm essentieel. Geschiktheid hangt samen met zowel interne als externe beperkingen; het is multi-dimentioneel in een ecologische omgeving met meer criteria.

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Karina Moraes Zarzar was born on May 9, 1961, in Recife, Brazil. In April 1985 she obtained her Bachelor’s degree in Architecture at the Faculdade de Arquitetura, Universidade Federal de Pernambuco, Recife, Brazil. After a two-year post-graduate OPB course (Design education: design, planning and management) taken between 1989 and 1991, she obtained a Master’s degree in Technological Design from the Eindhoven University of Technology, Eindhoven, The Netherlands.

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