CARDIFF UNIVERSITY

DESIGN PROBLEM-SOLVING:

A THEME FOR CRITICALLY DEBATING THE INTEGRATION OF BUILDING THERMAL PHYSICS AND ARCHITECTURE DESIGN

A THESIS SUBMITTED TO WELSH SCHOOL OF ARCHITECTURE CARDIFF UNIVERSITY IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

BY

CLARICE BLEIL DE SOUZA

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APPENDIX 1:
Specimen Layout for Thesis Summary and Declaration/Statements page to be included in a Thesis

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Para Carlos, Susana, Paulo e Maritza.

Nada teria sido possível sem vocês.

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ABSTRACT

This thesis proposes to theoretically and critically examine how building thermal simulation tools might be integrated throughout the whole building design process considering the knowledge and thinking involved in building thermal physics as well as the knowledge and thinking involved in architecture. It focuses in understanding both worlds to discuss how they can potentially interface with each other.

In order to fully acknowledge the interdisciplinary character of this type of research, a critical and theoretical discussion is undertaken in opposition to the dominance of empirical studies and practical propositions that have been currently used to deal with the issue of integration. The proposed critical and theoretical reflection is based on a critically constructed structured methodology centred on the theme of design problem-solving.

Design problem-solving is initially discussed in a domain independent basis setting up the premises for commonalities and differences between the two professions to be debated. Individual discussions in design problem-solving are presented for building thermal physics as well as building design, analysing the different paradigms they subscribe to when designing. Paradigms are contextualised within specific worldviews and related to representation systems, practices and computer tools used by each group of practitioner in their everyday activities. Contrasts between these two debates are outlined and potential scenarios to critically reflect on integration are proposed.

The outcomes of the research suggest that there is no single solution for building thermal simulation tools to be better integrated throughout the whole design process. The best solution needs to be critically constructed every time a new problem arises. In order for that to happen, building physicists and architects education needs to be improved for the two professionals to be able to properly communicate and effectively construct a joint practice. Additionally, simulation tools need to be designed with configurable interfaces that can address the idiosyncrasies of each practice together with the peculiarities involved in dealing with each specific problem at hand.

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1. INTRODUCTION

"Our society distinguishes itself by conquering the centrifugal social forces with Technology rather than Terror, on the dual basis of an overwhelming efficiency and an increasing standard of living" (Marcuse 1991)

When the amount of control developed nations had over natural resources was challenged in the 1970s with the oil crisis, a sudden preoccupation with alternative sources of energy and environmental preservation arose from industrial, financial and governmental institutions in the developed world determining new aims for a so-called 'post industrial society'.

Efficiency and increasing standards of living, two of the most important aims of the contemporary industrial society, suddenly became an issue for legislation once the actual models of organising and utilising the available resources reached a point in which 'optimal development' was compromised. The paradox of diminishing the rate of resources depletion without compromising the increasing standards of living was 'accommodated' within the flag of 'efficient use of resources' which justified the control and regulation for instance in energy use.

As part of control and regulation in energy use, building energy performance targets are being set and explicitly measured. Legislation, initially prescriptive with regards to energy efficient parameters, evolved to what is called 'performance based'. In 'performance based' legislation targets are clearly defined in order for objects being designed to be compliant with. Targets are consonant with the industrial and technological development, they not only force professionals to be compliant with regulations but also direct designers to use 'environmentally friendly' building components as well as available technologies in order to meet them.

Putting aside why technologies and components are created as well as the reasons for their ultimate use, the building design community as a whole is left with an everyday reality in which guidelines, rules of thumb and qualitative judgements about energy performance are not accepted anymore. There is a requirement to predict energy uses and demands on a quantitative basis to be compliant with building regulations as well as to 'please' the industrial and financial systems by efficiently selecting the most 'appropriate' and 'environmental' components, estimating costs and investments, quantifying marketing value, etc.

Predicting building energy performance using computer simulation tools

It is important to understand that design guidelines and rules of thumb do not show how a building really performs (Soebarto 2005) because they do not take into account the interactions between the parts of the specific building being designed (Donn 2004). They simply indicate trends. They suggest what can be done but not what will effectively happen (Soebarto 2005). As intuition is not a reliable source in energy matters (SERI 1985), "the ability to predict performance is only possible through simulation" (Papamichael in Donn 2004).

Although predicting energy uses and demands on a quantitative basis has been possible for quite a long time, the creation and evolution of computer simulation tools enabled the complexities involved in modelling and quantifying building energy related phenomena to be almost fully addressed. These tools are computer versions of complex thermodynamic mathematical models that take into account the case-by-case interactions between the weather and the building surroundings, usage, client preferences, among others. They are incredibly powerful allowing decisions to be made based on actual or accurately predicted building behaviour.

Mainly supported by governmental institutions, computer simulation tools have been developed since the 1970s to be used in HVAC system design, energy efficient building design and environmental friendly building design, providing for the first time the construction industry with "the means to address the underlying thermodynamic complexities and undertake integral performance appraisal of options at reasonable costs" (Clarke 2001). Users now have the ability to quantify the performance of individual building designs, undertake many types of assessments and examine an enormous amount of design possibilities (Donn 2004).

As a result, the requirement to predict energy uses and demands on quantitative basis can be translated in practical terms into a widespread need to use computer simulation tools to predict and evaluate the energy performance of buildings being designed.

The challenges involved in the use of building thermal simulation tools

However, empirical studies show that the use of building thermal simulation tools have been having limited application in architecture design practice (Morbitzer 2003). In general, they tend to be used by experts in later design stages when only few parameters can be changed, providing no insight into characteristics of a proposed building (Morbitzer 2003). Besides that, "the continuous increase of capabilities and complexity ... seems to increase the barriers to integration of building design and building simulation even further" (de Wilde and van der Voorden 2003).

A review of the research literature about building thermal simulation tools will suggest that the main reasons for these tools not being integrated throughout the whole building design process are the following:

(i) There is a lack of knowledge from the building designer side about fundamentals of physics (mainly about heat transfer and dynamic phenomena) to understand simulation results (Soebarto 2005) as well as to make design decisions based on these results (Donn 2004);

(ii) There is a lack of knowledge from the building designer side about simulation in general, which can be perceived by observations such as:

a. a lack of trust in prediction,

b. a lack of confidence in the modelling process,

c. a lack of ability to relate results to personal experiences,

d. a lack of knowledge about priorities to be modelled, as well as

e. a lack of quality control mechanisms related to modelling (Donn 2004 and Donn 1999);

(iii) "Designers have to work within the model of design offered by the authors of the tool (as) the nature of interaction between designer/user and the program is not addressed" (Donn 2004). Due to this there are no tools that function with data entry simplifications (Soebarto 2005), nor tools that function when the building description is vague (Donn 2004 and Clarke 2001). There are also no tools to summarise and detect patterns in outputs, i.e. tools that "aid understanding the relationships between design factors and building performance" (Donn 2004) and as a whole software provide no user support mechanisms to investigate reasons behind performance (Morbitzer 2003, Radford and Gero 1980 and Hand 1998);

(iv) There is a lack of performance guidelines or performance assessment methods to understand the implications of performance recommendations (Donn 2004, Clarke 2001, MacDonalds et al 2005);

(v) There are difficulties in coordinating architects and consultants due to a dissociation between those who design and those who analyse (Donn 2004) with an addition that experts tend to be ineffective in relating environmental issues to the interests and concerns of architects (Morbitzer 2003);

(vi) There is an excessive amount of time needed to construct and analyse computer models (Donn 2004, Morbitzer 2003 and Hand 1998).

From the foregoing review of the literature, it is possible to conclude that a discussion about how building thermal simulation tools might be integrated throughout the whole design process is necessary.

1.1. The research aims

The 6 points outlined in the previous section illustrated that building thermal simulation tools have not been used throughout the whole building design process for the following three main reasons:

(i) Lack of knowledge from building designers about the fundamentals of thermal building physics as well as about issues related to modelling;

(ii) Lack of knowledge from building physicists about the building designers way of working and thinking, and

(iii) The consequent problems of communication between the two professions resultant from these lack of knowledge.

From the main reasons outlined above, it is clear that the issue of integrating building thermal simulation tools throughout the whole building design process is a matter of interdisciplinary research. As a matter of interdisciplinary research it cannot be handled simply by a distinct group of specialists (building physicists) as it involves more than simply using specialised knowledge to solve design problems. Fundamentals of building physics as well as issues related to modelling cannot be understood from a reductionist point of view and the way of thinking and working of building designers cannot be treated as something simply empirical.

In order to fully acknowledge the interdisciplinary character of this type of research, empirical studies and practical propositions alone will not suffice. Critical thinking and reflections on theoretical aspects involved in the two professions are also necessary to undertake a research with enough rigour to study the knowledge involved in building thermal physics as well as the knowledge involved in building design.

In this context, this thesis proposes to theoretically and critically examine how building thermal simulation tools might be integrated throughout the whole design process considering the knowledge involved in building thermal physics as well as the knowledge involved in building design. It focuses in understanding both worldviews in order to discuss how they can potentially interface with each other.

1.2. Thesis outline

In order to meet the aims of the thesis, a discussion about the state of the art in integrating building thermal simulation tools throughout the whole design process is presented in the next chapter, criticising the effectiveness and comprehensiveness in addressing the issue considering its interdisciplinary nature.

In chapter 3, the methodology to be used in the thesis is proposed with its basis in a theoretical debate in design problem-solving.

Chapter 4 proposes a theoretical discussion in design problem-solving independently of any design domain, setting up the premises for commonalities and differences between the two professions to be debated in the two following chapters.

Chapter 5 concentrates on discussing design problem-solving in building thermal physics whereas chapter 6 concentrates on discussing design problem-solving in architecture.

Chapter 7 uses design problem-solving as a new basis to discuss integration, contrasting the debates between the two different professions and discussing the construction of potential scenarios to critically reflect about the issue.

Finally, chapter 8 presents the outcomes of the critical theoretical reflection in design problem-solving used to discuss the issue of integration undertaken along this thesis together with suggestions for future work.

1.3. Significance and limitations of the research

The present work focuses on knowledge and paradigms involved in building physics problem-solving and building design problem-solving by the two professions. It is about the way of thinking of the two different professions; about each culture's pre-requisites for perception while undertaking design problem-solving activities. It questions propositions of integration based on specialisation and reliant on translation metaphors and discusses integration based on general knowledge and critical thinking.

In this frame of mind the work is limited to a theoretical philosophical discussion. Examples to illustrate the discussion are interpretations of empirical work and interpretations of more practical considerations about design problem-solving in the light of the different paradigms debated. More specific examples and other means of illustrating the discussion are not used as it was considered that these would potentially distract and confuse the reader, rather than enlighten them, as there are numerous ways of interpreting the interactions and to use only one example might be to unduly emphasize a particular issue.

The contributions of the present work to the current body of knowledge are:

(i) Debating integration using a philosophical and thinking approach rather than an empirical one;

(ii) Using critical constructivism as an underlying philosophy to discuss integration;

(iii) Demystifying the idea that there is *a* best solution to integrate tools into the design process;

(iv) Analysing the two professions in terms of the common denominator of design problem-solving;

(v) Reflecting on knowledge and thinking involved in the two different fields of study on a side-by-side basis;

(vi) Calling attention to the fact that not only the paradigms of each field of study should be analysed individually but also the paradigms of putting the two fields of study together should be debated.

To the best of the author's knowledge, no-one with detailed experience of both worlds has published research on the interface between these two professions which therefore makes this work the first attempt towards it. Although this research is presented as mainly a theoretical piece of work, the reasoning behind it would not have been possible without the author's experience with building thermal physics, which was developed further in this thesis, on top of her architectural design background.

The result is a detailed discussion which develops as a sequence of interconnected arguments that are built on interpretations of paradigms and structured sequences of thinking. The conclusions 'wrap-up' the discussion and set up the proposed foundations for a different point of view in analysing integration between the two design professions.

2. HOW BUILDING THERMAL SIMULATION TOOLS HAVE BEEN CURRENTLY INTEGRATED THROUGHOUT THE BUILDING DESIGN PROCESS

"If numbers are boring, then you've got the wrong numbers" (Tufte 1991a)

This chapter critically examines the main trends in attempting to integrate building thermal simulation tools throughout the whole building design process.

To meet these aims a review of the research literature on the issue is presented (following a similar approach to the one proposed in Bleil de Souza and Knight 2007), which shows that so far attempts have been concentrated in propositions to improve thermal simulation tools data interpretation as well as propositions to improve the role of tools in building design practice. This review focuses on studies related to building design, not addressing studies related to HVAC and servicing engineering design.

Examples of the literature related to the two topics (improving data interpretation and improving the role of tools in practice) are presented and critically examined by considering their effectiveness in addressing the interdisciplinary problem of integration. This critical examination leads to the conclusion that there is a need to re-evaluate the problem of integration by starting with a theoretical appreciation of the matter.

2.1. Propositions to improve thermal simulation tools data interpretations

As the output results of thermal simulation tools are mainly alpha-numeric files generally composed of enormous quantities of data which are difficult to be used and interpreted, then post-processing is crucial. Using this approach many attempts from tool developers as well as researchers have been undertaken in order to transform rough simulation results into something more useful for designers.

A review of the literature about thermal simulation tools shows that the two main approaches that have been used in order for rough simulation results to make sense for designers are:

(i) Improving output interface data display systems and

(ii) Setting up design advice systems in output interfaces.

A description of each of these two approaches is provided in the next two sub-sections together with examples from the literature that refer to them. These examples are far from being exhaustive and are used simply to illustrate the main ideas behind each of the two approaches.

2.1.1. Output interface data display systems

Improvements in output interface data display systems generally consist of transforming alpha-numeric results into tables and graphs. Tables and graphs either display rough data directly or interpreted information.

Tables are useful to provide quantitative summaries or quantitative detailed information about specific aspects of the simulation, for instance what happens in a specific part of a day, year and so on. Graphs, on the other hand, are powerful visual display systems to reveal the substance of the data, showing many numbers in a small space, making large data sets coherent, comparing different pieces of data and revealing different levels of detail (Tufte 1991b).

Graphs reveal patterns and trends and for that reason they tend to be the preferred type of information display to be explored by software developers and researchers when attempting to improve output interface data display systems (examples can be found in Square One Research 2008, Design Builder Software 2008, Energy System Research Unit 2008 through IPV interface, Prazeres and Clarke 2003, Prazeres and Clarke 2005, Morbizer 2003, MacDonalds et al 2005, to cite a few).

When displaying rough data directly, graphs tend to be:

(i) Time-series of loads and temperatures (for the whole building, specific zones, specific building elements, etc);
(ii) Frequency distribution of loads and temperatures and
(iii) Grids that display loads in time or temperatures in space.

When displaying interpreted information, graphs tend to be:

(i) Frequency distribution of indexes that have some meaning for designers (discomfort degree days, monthly degree days, fuel type, CO2, energy breakdowns, costs, etc.);
(ii) Linear graphs of comparative data (indoor vs. outdoor temperatures, gains and losses vs. outdoor temperatures, space loads vs. degree days, etc.);
(iii) Grids that display indexes that have some meaning for designers in space (spatial comfort, percentages of insolation levels, etc).

Graphs that have time as one or two of the displayed variables provide shapes to quantities of phenomena that develop in time, but do not provide an explanation for the causal relationships that are happening (Tufte 1991b).

Frequency distributions are useful to display behavioral trends either of the building (through loads and temperatures) or of the impact of the building on its users (through comfort indexes, etc). They provide quantities for qualitative analysis to be undertaken but without again providing an explanation for the causal relationships that are happening.

Graphs that have two resultant variables and/or two indices displayed are useful to show how one variable affects the other (Tufte 1991b). There is an account for causal relationships that are happening but these relationships are disconnected from time or space.

Graphs that have space as two of the display variables provide information about a specific behaviour, either of the building (through loads and temperatures) or of the impact of the building on its users (through comfort indexes, etc), at a specific instant in time. Quantities for a qualitative analysis to be undertaken are provided for a specific instant in time illustrating some causal relationships between spatial configuration and resultant behaviour, but only for this specific instant.

As a whole, even when made visual, the information displayed tends to be more useful for analytical purposes rather than for design advice. This is because of the following reasons:

(i) It is difficult to provide an illustration for causal relationships that are happening;

(ii) When causal relationships are illustrated, they are represented in disconnected with their development in time.

It is difficult for designers to make sense out of the data that is presented, because it is difficult for designers to understand the consequences of their design actions. As a result, in aiming to provide useful information for designers, most of the research in improving thermal simulation tool data interpretation concentrates in output interface design advice systems rather than simply on improving output interface data display systems.

2.1.2. Output interface design advice systems

Output interface design advice systems generally consist of environments in which designers can compare the results of different design alternatives. Comparisons either happening in absolute or relative terms, basically provide designers with feedback about the overall result of their design actions.

Performance indicators and notional building

The first step to make information useful for designers is to provide somehow an artifice for numbers to make sense, i.e. to provide an artifice for numbers to somehow qualitatively express building behaviour or the impact of the building in its users. The most common strategy proposed in these cases is the creation of performance indicators, indices which quantify how far the simulated building performance is from a specific performance benchmark. Specific performance benchmarks, artifices to compare design alternatives against with, can be either performance targets or notional buildings. Targets are generally provided by legislation (Approved Document L2 2002) whereas notional buildings can be found in different sources (SERI 1985, BRE 2008, ASHRAE 2004, to cite a few).

Different ways of communicating performance indicators are sometimes mentioned in the literature suggesting software output interfaces could provide traffic lights (Prazeres and Clarke 2005) or more elaborate comparisons (ASHRAE 2004) rather than simple numeric displays and pass/fail systems (as in BRE 2008 for example).

Decision support systems

Comparing alternatives is seen as an important resource in performance assessment and more elaborate propositions that allow different design options to be displayed and compared comprise decision support systems, systems that transform simulation tools results into a knowledge base display that supports decision making activities. This method is one of the most common ways of combining and processing results from simulation tools and has been developed since the late 90s. It might provide a simple efficient display system in which designers could easily compare and evaluate alternatives or it can be equipped with specific resources to explore the impacts of design changes in more detail.

Display systems in which designers could easily compare and evaluate alternatives are proposed in Papamichael, La Porta and Chauvet 1997, Papamichael 1999a and Papamichael 1999b. In this case, outcomes from different design alternatives are simply displayed side-by-side for designers to visually compare results. More elaborate display systems, with the addition of multi-criteria evaluation strategies to explore changes, are proposed in Soebarto and Williamson 1999 as well as in Prazeres and Clarke 2005.

Multi-criteria evaluation strategies to explore design changes are proposed in Soebarto and Williamson 1999 by introducing incremental design improvements, properly standardized once compared to a reference building. Each improvement is measured according to one single criterion such as energy consumption or thermal comfort for example, and costs and benefits of the final decision result from a weight linear combination of each individual cost/benefit solution proposed. This weight linear combination depends on the decisions previously taken by the designer and is function of specific design targets.

A similar proposition is explored in Prazeres and Clarke 2005 who developed a weighting system to calculate the overall benefits of the different design options explored, ranking these options according to their performance outcomes. Radford and Gero 1980 also explore the idea of analysis multi-criteria. They set up a strategy to work with different objectives simultaneously, through the use of Pareto optimisation techniques, in order for decision makers to be able to make trade-offs with knowledge of their impacts.

Databases

In order to increase the number of design alternatives to be compared as well as to enhance capabilities to explore the impacts of design changes, database output display systems started being proposed in the 2000s. These systems enable designers to formulate performance queries on results, based on organized multiple-simulation runs.

A framework to develop an information matrix of performance indicators considering magnitude, spatial and temporal extensions of these indicators is proposed in Mahdavi et al 2005. The use of scripts to generate and store large amounts of output data in an online database that can be easily accessed is proposed in Stravoravdis and Marsh 2005. These authors presented a case study with 280 models in which all the data analysis can be undertaken within a MySQL database and results of the analysis can be exported to an Excel spreadsheet to generate reports. In Knight et al 2007, users can perform interactive queries to understand the nature of the cooling demands to be met, as well as to assess potential ways of reducing these demands, in a database of more than 11000 simulations, the Customer Advising Tool (Knight, Marsh and Bleil de Souza 2006).

Investigations using statistics

Although databases are a powerful artifice to manage large amounts of data, they are difficult systems in terms of retrieving useful pieces of information. A common approach to overcome this difficulty is to investigate cause/effect relationships using statistics which not only can be applied in database results but also directly in simulation result analysis.

A simple example of applying statistics to investigate output thermal simulation results is proposed by Ghiaus and Allard 2003, who assess building adaptability through regression considering the free-run internal building temperature and the outside air temperature. A more elaborate example of statistics application to analyse thermal simulation results is provided by Morbitzer et al 2003, who considered the analysis of more than one parameter affecting performance through the use of datamining.

Datamining is a combination of visual investigation, regression techniques and uncertainty analysis which basically consists of combining data sources, selecting the task relevant data and extracting patterns from this data through a user defined technique. It can be seen in a way as a mixture of performance query and decision support system, but it is a constant refining process of including and removing variables combined with filtering.

Output interface design advice systems

Output interface design advice systems are useful for designers to compare the results of different design alternatives. Comparisons can be simple; they can depict results of different design alternatives side-by-side and/or be based on single comparisons between each alternative and a benchmark. Comparisons can be complex; they can involve a large amount of design alternatives and/or compare these alternatives with each other as well as with benchmarks.

In most cases, causal relationships that are happening within each design alternative are not addressed. Decision support systems provide methods to judge alternatives according to how acceptable their resultant behaviour is, whereas databases either follow this same proposition or simply indicate trends in behaviour based on an automatic generation of multiple design alternatives. Investigations using statistics are the only ones which explore comparisons between different design alternatives as well as causal relationships within each design alternative. However, as has already been noted in section 2.1.1, it is difficult to illustrate causal relationships that are happening and whenever this is the case, they end up being represented disconnected with their development in time.

On the whole, propositions that address output design advice systems also tend to be more useful for analytical purposes rather than for design advice. This is the case because of the following reasons:

(i) They do not address directly the issues of output interface data display systems with regards to illustrating causal relationships;

(ii) They basically provide designers with environments which enable them to compare the overall result of their design actions assuming causal relationships are going to be evaluated by trial-and-error.

As a result, aiming to provide useful information for designers, further research that proposes and prescribes how feedback from the tools can effectively inform the design process can also be found in the literature. This research is examined in detail in the next sub-section which deals with propositions to improve the role of thermal simulation tools in building design practice.

2.2. Propositions to improve the role of thermal simulation tools in building design practice

The fact that output interfaces are more suitable to be used for analysis rather than for informing the design process together with the fact that tools tend to be used mainly in later design stages, has led many researchers to focus on the development of methodologies to address how feedback from the tools can effectively inform the design process since its beginning. These methodologies are intended to widen the use of tools throughout the design process, a use which so far, according to de Wilde et al 1999, de Wilde et al 2002, Soebarto and Williamson 1999, to cite a few, have been mainly addressed the following issues:

(i) Checking compliance with regulations;

(ii) Meeting marketing targets in which the objective is to get an "environmentally friendly" label or

(iii) Optimizing a few parameters and to support some small decisions still to be considered.

A review of the literature on the subject shows that two different approaches have been undertaken so far in order to integrate thermal simulation tools throughout the design process. These two approaches can be basically summarised as:

(i) Propositions that address the building design process as a whole;

(ii) Propositions that explore the use of tools as design advisors in generating new design ideas;

A description of each of these two approaches is provided in the next two sub-sections together with examples from the literature that refer to them. Again, the examples are far from being exhaustive and are used simply to illustrate the main ideas behind each of the two approaches.

2.2.1. Propositions that address the building design process as a whole

There is a trend in propositions that address the building design process as a whole to assume that building design consists of a procedural sequence of stages with incremental levels of complexity (Morbitzer 2003, de Wilde et al 2001, de Wilde et al 1999, de Wilde et al 2002, Hand 1998, Hand, Clarke et al 1995, Soebarto and Degelman 1995, to cite a few).

Under this frame of mind, researchers believe building design is basically a sequence of decisive actions which might be specified according to different levels of detail depending on which design plan of work source was considered. Although some examples (de Wilde et al 2001) provide quite detailed sequences of actions (including: feasibility study, conceptual design, preliminary design, final design, construction drawings and building specifications), others (Morbitzer 2003) will use simplified versions of it (outline stage, scheme stage, detailed stage). A commonality among the different propositions seems to be that independently of the design work plan used, the sequence of decisive actions would increase in terms of levels of complexity and therefore "simulation tools should adapt to the design process and not vice-versa" (Morbitzer 2003).

Another commonality among researchers is the belief that architects should be running tools in the early design stages and engineers/building physicists should be running the tools in later design stages. That means architects should be running the tools while conceiving, creating and developing a design idea whereas engineers/building physicists should be running tools while refining this design idea. This proposition seems to be a common sense in the simulation community which believes in the early design stages changes are non-incremental and as a consequence they have a large design impact and a large performance impact, whereas in the late design stages changes are incremental and as a consequence they have a limited design impact and a limited performance impact (SERI 1985). With this being the case, propositions that address the building design process as a whole will tend to concentrate on:

(i) Developing simplified tools, to be used by architects in the early design stages, that connect with more advanced simulation tools, to be used later on by engineers/building physicists;

(ii) Developing different interfaces (input and output) to address the particularities of each design stage on its own but guarantee that all simulations are undertaken in the same tool;

(iii) Coordinating different designers as well as the different applications they use.

Simplified tools for architects

Examples of simplified tools to be used by architects in the early design stages, that connect with more advanced simulation tools to be used later on by engineers/building physicists, can be found in Square One Research 2008.

The intention behind Ecotect (Square One Research 2008 and Marsh 1996a and Marsh 1996b) is that designers are allowed to freely 'play around' with ideas and, at the same time, to evaluate their performance using an interactive interface which provide results to be used as feedback and encourage new experiments until a mature solution can be found. The most important quality of Ecotect is its user friendly input interface that intends to encourage basic ideas to be quickly modelled and evaluated by building designers while designing.

However, issues with regards to output data display systems also appear in Ecotect. Although designers are allowed to freely 'play around' with the idea, they still have to use output interface data display systems that do not easily communicate causal relationships that are happening within the design alternatives being evaluated. Besides that, Ecotect is quite limited with regards to its calculation engine and the use of more advanced tools is necessary if deeper analysis is to be undertaken. Under this frame of mind, it is not uncommon to find propositions that simply propose more user friendly interfaces to communicate directly with advanced simulation tools (Design Builder Software 2008) or propositions that deal with different interfaces to address different design stages guaranteeing all simulations are undertaken in a single powerful and advanced tool.

Different interfaces for different design stages

Examples of propositions that deal with different interfaces (input and output) to address the particularities of each design stage on its own, guaranteeing that all simulations are undertaken in the same tool can be found in Morbitzer 2003, Hand 1998, and Clarke et al

1995, to cite a few. In the most recent example (Morbitzer 2003), constrained ESP-r (Energy System Research Unit 2008) user interfaces are proposed, in terms of inputs and outputs, and users are expected to conceive and manipulate the object being designed through the use of wizards together with support databases with default values, after importing geometry data from CAD software.

Although in these propositions the simulation engines are quite powerful, the idea of having different interfaces to different design stages ends up restricting not only design possibilities but also simulation possibilities due to the number of a priori assumptions that need to be undertaken in order for them to be conceived. As a result, single intelligent design environments to coordinate different professionals through software interoperability seem to be a logical step further to overcome these problems.

Coordinating different designers as well as the different applications they use

Examples of propositions that focus on coordinating different designers as well as the different applications they use can be found in Clarke et al 1995, de Wilde and Van der Voorden 2003, Augenbore et al 2003, de Wilde et al 1999, de Wilde et al 2002, to cite a few. All propositions in this approach consider that "integration of building simulation and building design process take place in the category of tools for design teams with experts" (de Wilde 2004).

Propositions that include experts and their tools directly in a design team have been explored by the Scottish Energy System Research Group (MacDonalds et al 2005) and basically consist of in-house performance based assessments to provide design advice to generate better design solutions. These propositions tend to be quite successful as they are flexible enough to account for the idiosyncrasies of each different practice. Although consultants when taking part in the design team since the conceptual design stages can, in theory, deal with many questions that arise in dealing with the problem at hand, the tools they use are still not appropriate to cope with the particularities of all design stages mainly because of the way they relate to architecture drawings.

This probably explains why some studies concentrate on expanding tool capabilities with regards to information exchange (COMBINE project in de Wilde 2004 and Clarke et al

1995). These propositions generally contain a central product model connected to several building performance evaluation tools managed by tool-specific interfaces. Although these propositions are, to an extent, important to set up a practical basis for collaboration to happen, they make it difficult to handle major design changes. Interoperability separates models from analysis, making it even more difficult to assess cause/effect relationships.

Propositions that attempt to better handle the problem of separation between models and analysis can be found in Mahdavi (1999) in which, through a shared model linked to various simulation tools, building design and building performance are interconnected. The effect of changing a design variable on the resulting building performance as well as an indication of which design variable need to be changed in order to achieve a specified change in performance can be displayed (de Wilde 2004). However, the interfaces are not easy to manipulate and can become quite restrictive in order for bi-directional feedback to happen.

In order to simplify the manipulation of tools as well as the communication between participants, minimalistic interfaces related to suitable simulation tools to be used in each specific analysis task are proposed in Augenbroe et al 2003, de Wilde and van der Voorden 2003 as well as de Wilde 2004 through the Design Analysis Interface initiative. In this initiative, a tool kit is provided for a design team enabling the team to customise their analysis scenarios from design questions by automatizing many of the steps to perform simulations and analyse results. In this type of environment data transfer happens automatically and is minimised, consultants take care of integration and tools are re-defined to cope with interoperability. Although many things can be customised in this proposition, components and options as well as relevant criteria for analysis and performance indicators all need to be a priori specified. In order for that to happen de Wilde (2004) prescribes a clear and well-staged procedure for designers to adopt when designing so that consultants, with their simulation tools, can be 'plugged in' along the way and performance requirements can play a role in the decision making process. It is a rigorous top-down approach which relies on a highly stratified team work composed of a 'collage' of specialists.

Propositions that address the building design process as a whole
Overall, although many methodologies to integrate tools throughout the whole design process have been discussed, a need to better investigate the cause/effect relationships between performance and design changes, particularly in the conceptual design stages, still exists even when input interfaces are user friendly and when consultants are part of design teams.

When strategies move towards extreme specialisation, the problem of understanding the causal relationships that are happening seems to be even stronger as interoperability tends to separate model from analysis. Attempts to overcome that through shared models that enable bi-directional feedback make design possibilities quite restricted. Efforts to resolve this problem through a tool-kit with minimalistic interfaces require the process to be clear and well-staged for consultants (and their tools) to be placed within it, and the acceptance of this approach from building designers as well as the quality of solutions that result from it are highly debatable.

As a result, propositions that address the design process as a whole either do not deal with the main problem of relating cause/effect between resultant building performance and design changes, or take it into consideration to the detriment of the designer's freedom to approach problem-solving. Attempts that are less prescriptive with regards to the building design process and at the same time intend to make the use of tools more effective in building design practice, concentrate on exploring the use of simulation tools as design advisors in generating new design ideas. These approaches are discussed in detail in the next section 2.2.2.

2.2.2. Propositions that explore the use of simulation tools as design advisors in generating new design ideas

A review of the literature shows that there is a trend for addressing cause/effect relationships between design changes and resultant performance in the early design stages mainly by using the tools as design advisors to generate new design ideas. This trend is quite recent as it uses techniques that require intensive computer processing and the two most common approaches that deal with it are:

(i) Simple generative forms and
(ii) Genetic algorithms.

Simple generative forms
Simple generative forms consist of scripts that generate rough shapes contained in grids, which respond to certain performance criteria (Marsh and Haghparast 2004). The shapes generated are actually optimised forms and provide insights to the designers about possible ideas to be developed.

In simple generative forms, optimisation methods, generally used in the late design stages are brought to the beginning of the process. It is the intention that through generative forms, designers start with an optimum set of compromises from a predetermined range of possible options to develop design ideas further. Result analysis is translated directly into geometric decisions through a computer generated rough building form that meets a set of specified performance criteria. A script is used to generate the geometry (inside a predefined grid), calculate its performance and iteratively modify it until the criteria are met.

Simple generative forms are already incorporated into Ecotect (Square One Research 2008) as software features in the 'Shading design calculation wizard' such as 'extrude objects from solar envelope', 'generate optimised shading devices' and 'project solar shading potential' for instance. Further examples of this strategy can be found in Marsh and Haghparast 2004 when investigating the right-to-light as well as maximization of solar radiation falling on a stadium pitch.

Genetic Algorithms
More elaborate generative procedures can be found in Caldas and Norford 2002 and Caldas et al 2003 who explored the use of genetic algorithms in search procedures to look for optimized design solutions in sustainable design. These procedures, based in algorithms rather than simple scripts, undertake searches randomly sampling within a solution space.

Genetic operators control the evolution of the generations of a problem solution and the probabilities of a solution to be chosen will be proportional to the fitness of that solution in terms of the performance target. When genetic algorithms are used, the amount of possibilities in terms of solutions tends to be much wider and a higher level of complexity in terms of solutions can be achieved.

Caldas and Norford 2002 show the use of genetic algorithms to optimize window sizes for lighting and heating whereas Caldas et al 2003 show the use of genetic algorithms to optimize facades taking into account architecture compositional rules by minimizing the overall building energy consumption.

Propositions that explore the use of simulation tools as design advisors in generating new design ideas

On the whole, propositions that explore the use of simulation tools as design advisors in generating new design ideas are actually automatic systems of comparing and evaluating design alternatives. Instead of asking the designer to undertake comparisons and equipping them with methods, as in design advice systems (2.1.2), these automatic systems require the designer to define the evaluation criteria for an automatic process of generating – evaluating – generating to happen.

In both cases, there is no need to evaluate causal relationships as the computer can generate a myriad of design alternatives in a short period of time. The designer's task consists in defining design criteria together with one of the following activities:

(i) Defining the proper evaluation criteria for a given solution that will be used to set up a framework to generate design possibilities, in the case of generative forms or

(ii) Defining the proper evaluation criteria for a given solution to be used to analyze the performance of a group of design alternatives to advise future design actions to be undertaken, in the case of genetic algorithms.

Genetic algorithms and generative forms clearly shift the whole problem of investigating cause/effect relationships between design changes and resultant performance to a problem of defining design and evaluation criteria for automatic design alternatives and its resultant behaviours to be generated and evaluated.

2.3. Discussion and criticism

From the foregoing review of the literature it is possible to conclude that, in addition to most of what has noted in chapter 1, the integration of building thermal simulation tools throughout the whole building design process seems not to be happening also due to the following reasons:

(i) Output interface data display systems are not succeeding in illustrating the causal relationships that are happening, especially when these relationships develop in time, making it difficult for designers to understand the consequences of their actions.

(ii) Results are always presented disconnected from the models, i.e. designers have to model in 'input interfaces' and assess the resultant building behaviour in 'output interfaces'.

(iii) Design advice systems when equipping and enabling designers to compare different design alternatives, assume causal relationships are going to be evaluated based on trial-and-error. Design advice systems having the capabilities to automatically generate and evaluate design alternatives, assume designers work with clearly defined criteria to propose and evaluate design alternatives.

(iv) Most propositions tend to be based on the generation of a large number of design alternatives which consequently slow down the whole design practice.

(v) Most propositions tend to be restrictive with regards to investigating multiple parameters, mainly parameters related to geometry and topology, either because strategies do not handle them well or because results are difficult to be assessed.

(vi) Most studies that propose and prescribe how feedback from the tools can effectively inform the design process tend to be highly focused in reinforcing professional specialisation. They either prescribe which agent uses what type of interface, or prescribe clear and well-staged processes for consultants to be placed within.

(vii) In all cases, assumptions about the way building designers design are made, from the way they make decisions up to the variables they manipulate, and design practices are viewed as mainly procedural.

In addition to the above, from the foregoing review of the literature, it is possible to infer that most of the tools are developed by building physicists and as a result:

(i) Different ways of presenting results to building designers are explored without considering the meaning the information presented has for these professionals;

(ii) Design advice systems as well as data manipulation capabilities provided are based on a series of unverified assumptions about the building design process;

(iii) Design methods to improve the use of tools along the process, as well as to determine clearly the role of specialists, are prescribed based on a small number of observations from designers in action and/or on design work plans from chartered professional institutions.

It appears that one of the main obstacles is a lack of understanding of the design process from the building simulation community side. This becomes evident from the fact that "tools are being developed following a false paradigm about how designers work" (Donn 2004). As a result, it is possible to conclude that propositions to improve thermal simulation tool data interpretations as well as propositions to improve the role of thermal simulation tools in building design practice are far from being comprehensive enough to solve the problem of how building thermal simulation tools might be integrated throughout the whole building design process.

3. PROPOSING A THEORETICAL DEBATE IN DESIGN PROBLEM-SOLVING

A critical appreciation of the state of the art about how building thermal simulation tools might be integrated throughout the whole design process suggests the need for a re-evaluation of procedures to deal with the problem of integration. Attempts that focus on improving and disseminating the use of these tools are not comprehensive enough and have not been successful in achieving their aims, as discussed in chapters 1 and 2.

The majority of responses to the problem of integration are heavily based on a direct manipulation of aspects related to data interpretation and practice. They do not acknowledge major underlying assumptions behind these aspects such as worldviews and paradigms which architects and building physicists subscribe to when undertaking their everyday activities.

The first hypothesis of this thesis is that once data interpretation and practices are understood within the worldviews and paradigms that building physicists and architects subscribe to when practicing their profession, then critical theoretical reflections on the matter of integration can be undertaken setting a more solid basis for integration in practice to occur.

The second hypothesis of this thesis is that the problem of how building thermal simulation tools might be integrated throughout the whole design process could well be viewed as a problem of design. *Integration is to be created, designed* not discovered and therefore would be dependant on debates constructed based on critical reflections on design problem-solving in thermal building physics and in architecture.

The two hypothesis converge to a structured methodology that runs throughout this thesis to analyse the research problem on a theoretical basis. The starting point is a central theme, constructed from a critical appreciation of the two professions involved in the topic of integration. This theme is used as a reference to develop a critical debate to fulfil the aims of this research.

3.1. Defining design problem-solving as a research theme

The central theme of this research is design problem-solving. Design problem solving is chosen as the theme as it is the ultimate aim of the two professions in their everyday activities. Design problem-solving is then a point of convergence between the two professions and it can be used as a starting point to organise and trigger the discussion that will follow.

The proposed theme is initially discussed independently of any specific design domain. The discussion starts by characterising design problem-solving as a distinct type of activity in order to outline basic commonalities between the two design professions. It evolves into a domain independent classification of generic types of design problems and it finishes by outlining generic paradigms of design problem-solving. The idea is to reinforce design problem-solving as the central theme of this research, providing the author's own interpretation and reasoning to be used as a background in the dèbate that examines the major differences between the two design professions, as well as their commonalities.

Having set the theme for discussion, together with the backgrounds to debate major convergences and divergences between the two design professions, it is possible to examine design problem-solving in building physics separately from design problem-solving in architecture. Design problem-solving in building physics is debated first as it has a clear and rational proposition which can be used as a basis to construct the subsequent debate about design problem-solving in architecture.

3.2. Debating design problem-solving paradigms in building physics and in architecture

The debate focuses on examining the different paradigms of design problem-solving that building physicists and building designers subscribe to when designing. Paradigms are a body of theoretical and methodological beliefs used to interpret things (Kuhn 1996). Paradigms determine how to solve a problem as well as how to identify the problem to be solved (Kuhn 1996). They govern a group of practitioners and many times are used to define professions (Kuhn 1996). Paradigms are seen as a pre-requisite for perception. They set up the basis to define the fundamental entities that compose the universe practitioners work within (Kuhn 1996). They define how these entities interact with each other as well as what questions may be legitimately asked about such entities together with the techniques employed in seeking solutions (Kuhn 1996). The paradigms presented in this thesis articulate representation systems and practices together with the current technologies available, i.e. the use of computer tools.

Major differences between the two design profession's paradigms would suggest major differences in design problem-solving. A debate on paradigms involved in each of the two design professions is seen as paramount to understand why thermal simulation tools are not used throughout the whole design process as well as to set up the basis to discuss possibilities for this to happen in future. Studies focusing on integration when examining the problem simply at the level of data interpretation and practices are actually taking paradigms of design problem-solving for granted. As a result, potential ways forward to integrate the two professions tend to be always biased by the paradigms of the people setting up these propositions, i.e. building physicists and building designers will propose integration on the basis of their paradigms of design problem-solving.

To avoid this bias, the two fields of study are separately discussed in detail. This discussion involves assessing where the paradigms come from, i.e. what are the worldviews behind them, as well as how these paradigms are used to articulate representation systems and practices. It also involves assessing how paradigms, representation systems and practices are related to computer tools used in the everyday activities of the practitioners (Figure 3.1).

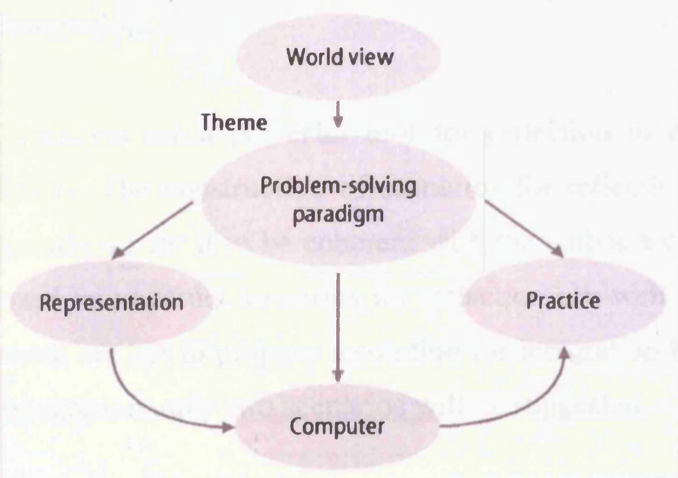


Figure 3.1 – Structure used to debate design problem-solving paradigms

The author believes the understanding of the paradigms should be critically constructed with the boundaries for such construction defined as wide as possible. Recourse to philosophy is therefore necessary in this thesis to situate paradigms within the worldviews that guide them, together with experimenting and developing skills necessary to perform building physics design tasks as well as architecture design tasks.

Although this research is presented as mainly a theoretical piece of work, the reasoning behind it would not have been possible without the author's experience with building thermal physics on top of her architecture design background (Adnot et al 2007, Bleil de Souza and Knight 2007, Bleil de Souza et al 2006, Knight et al 2007, Knight, Marsh and Bleil de Souza 2006, Knight et al 2006). This experience has been gained during this thesis and the results of experimenting and developing skills to deal with both types of design problem-solving underlie all the critical reflections undertaken in this research as well as supports the construction of a methodology to meet the research aims.

3.3. Using design problem-solving to construct the critical basis for a discussion about integration

Having established the paradigms underpinning architecture design and building thermal physics design the next section of the thesis is a critical debate about design problem-solving undertaken for each of the two professions. Through this it is possible to contrast the different paradigms in order to understand why thermal simulation tools are not fully integrated throughout the whole building design process. The same debate can also be used as a resource to discuss the construction of potential scenarios to reflect on the problem of integration.

Scenarios are a powerful tool for reflection to create and interpret narratives (Carroll 2001). The construction of scenarios for reflection would again involve a discussion of paradigms for it to be coherent with the author's critical position. A review on paradigms used to construct scenarios for reflection can well be a study in itself. As the aims of this work are not to propose a solution for integration but to critically examine the problem of integration, only two scenarios will be suggested.

The first scenario will be based on a critical analysis on the current propositions of sociology of scientific knowledge to discuss interdisciplinary work. The second scenario will be constructed as an opposite to the first one, based on a critical appreciation of the discussions about interdisciplinary work together with the critical debate in design problem-solving undertaken in this research.

Once worldviews underlying the critical discussion about scenarios are set, discussions at the level of problem-solving paradigms, representation systems, practice and the role of computers in each of the two design professions can be undertaken. The discussion then becomes recursive recalling debates in design problem-solving undertaken in this research (Figure 3.1).

The idea of using scenarios for reflection illustrates that the problem of how building thermal simulation tools might be integrated throughout the whole design process can well be seen as a problem of design.

3.4. Summary of the research methodology

The aims of this research are to theoretically and critically examine how building thermal simulation tools might be integrated throughout the whole design process. A critical and theoretical reflection on the matter is proposed in opposition to the dominance of empirical and practical studies referring to integration.

The critical and theoretical reflection is centred on a critically constructed structured methodology based on the theme of design problem-solving in which:

(i) Design problem-solving is characterised independently of any specific design domain and generic types of design problems are classified outlining generic paradigms of design problem-solving. Commonalities and differences among these generic approaches are used as a basis to debates undertaken for building thermal physics and architecture reinforcing the theme the author wants to use as the background for the reflections that will follow.

(ii) Debates in design problem-solving are undertaken considering building physics and architecture, analysing the different paradigms they subscribe to when designing. Paradigms are contextualised within specific worldviews and related to representation systems, practices and computer tools used by each group of practitioner in their everyday activities.

(iii) Contrasts between the two debates in design problem-solving are outlined and used together with samples of discussions about interdisciplinary work to construct potential scenarios to critically reflect about integration. The discussion follows the same structure used to debate design problem-solving paradigms.

Outcomes of debates in design problem-solving as well as critical appreciations about proposed scenarios for reflecting on integration of different design problem-solving paradigms, representation systems and practices are outlined in the final conclusions of this thesis and used to suggest themes for future work.

4. DESIGN PROBLEM-SOLVING AS A RESEARCH THEME

"Designers first design things with their imagination and then erect things in reality"

(Lawson 1997)

The aim of this chapter is to discuss design problem-solving, which is the central theme of this research.

To meet this aim, design problem-solving is characterised initially independently of any specific design domain and generic types of design problems are outlined. Commonalities and differences among generic approaches used in design problem-solving are outlined, setting up the basis for reflections about design problem-solving in building physics and design problem-solving in architecture.

Design problem-solving is considered the central theme of this research because it is the ultimate task building physicists and building designers undertake in their everyday practice: the one of designing a building with value. Design problem-solving is a point of convergence between the two design professions as in both cases "designers first design things with their imagination and then erect things in reality" (Lawson 1997).

A short description with examples from the literature about the relatively new science of design is provided, emphasising formal attempts to define the design activity together with comparisons and contrasts of design activities with science and puzzle-solving tasks. This description is followed by the definition of three different types of design problems, finishing with a discussion about how these different types of design problems are related to generic paradigms of design problem-solving. Commonalities and differences among generic approaches used in design problem-solving are used to set up the design domain dependent individual debates that will follow.

4.1. Characteristics of design problem-solving activities

From the literature, the most common efforts to characterise design problems either attempt to formally define design or prefer to work out a soft definition for it by comparing and contrasting the design activity with science and puzzles. Both approaches concentrate on timing, aims and process involved on the design activity.

It is common sense that science works backwards whereas design works forwards. Once the product of analysis already exists it is up to science to identify recurrent phenomena and regularities to provide models to represent or reproduce them. Once the aims of the activity are to produce something new, it is up to design to translate a list of abstract requirements into a new form or content.

Jones 1981 and Alexander 1971 provide formal examples of definitions for design that clearly address these issues:

- "The imaginative jump from present facts to future possibilities" (Page 1966 in Jones 1981);
- "A creative activity – it involves bringing into being something new and useful that has not existed previously" (Reswick 1965 in Jones 1981);
- Design is about inventing physical things which display new physical order, organisation and form in response to function (Alexander 1971).

All these definitions carry within them aspects referring to timing whether we agree with them or not.

Jones 1981 and Simon 1996 discuss this topic further providing comparisons of design activities with other types of activities.

Jones 1981 believes design is about changing a specific situation from one state to another in form and content, foreseeing this future situation visually. "Designers must be able to predict the ultimate effects of their proposed design as well as specifying actions that are needed to bring these effects about" (Jones 1981). He emphasizes the idea of timing, i.e. the fact that designers operate in the future. In comparing design with other types of activities he suggests that scientists describe and explain phenomena that exist whereas designers "have to specify ways in which the foreseen thing can be made to exist" (Jones 1981).

For Simon 1996, design is concerned with how things might be. Natural sciences are about objects and phenomena, characteristics and properties they have, how they behave and interact with each other. Artificial sciences, or knowledge about the artificial object and phenomena, are concerned with how things ought to attain goals and to function. "Science is concerned with how things are. Design is concerned with how things ought to be, with devising artefacts to attain goals" (Simon 1996).

It is also a consensus that the focus in science problem solving is in finding 'the' solution or 'a' solution for a specific problem whereas in design the focus is in the creation of a solution with value: "Relating product to situation to give satisfaction" (Gregory 1966 in Jones 1981) or providing "the optimum solution to the sum of the true needs of a particular set of circumstances" (Matchett 1968 in Jones 1981). To put this clearly, what matters in design are the values and/or the quality of a solution and there is not only a single solution for a design problem but, according to Eastman 2001, a space of possible solutions for the best compromising solution.

For Bachman 2003, design can be good or bad but not right or wrong. For Simon 1996, aims in design are: purpose and character of artefact together with the environment in which it performs. What matters in design is the value of the solution; therefore design is a specific type of problem solving (Kuhn 1996). "There is not only one correct outcome several outcomes are welcomed as long as they have values or interests of some kind" (Simon 1996). The ultimate aims of design activities are then very clear: to create a solution with value and the discussion can be shifted not to questioning values for whom (the sponsor, the user?) but to questioning to what extent the values that are created affect the process.

It is not up to this part of the work to answer that question but to carry on examining the fact that the process of solving design problems differs from the process of solving scientific problems, although both have similarities with regards to initial states, go through transformations from one state to another, many times using explicit knowledge and search strategies to reach solutions whilst reducing the amount of information being manipulated (Akin 1986).

Design is not only about the process of problem solving but also about the process of materialising a solution. "Designers must not only decide what effects they wish to achieve, they must also know how to achieve them" (Lawson 1997). "Design is then a sophisticated mental process capable of manipulating many kinds of information, blending them all into a coherent set of ideas and finally generating some realization of these ideas" (Lawson 1997). "Design will simply be considered any problem solving activity that results in the creation of an artefact or a plan for generating an artefact" (Craig 2001). The designer is not only concerned with the product but also with the "long chain of interrelated predictions and specifications" (Jones 1981) to materialise the product acknowledging that the designer control ceases before the production process starts.

In design "process and product are the complementary aspect of a single result" (Eastman 1999), i.e. it is difficult to separate process from product. "Final goals are actually criteria for choosing the initial conditions" (Simon 1996). "We pose a problem by solving the state description of the solution. The task is to discover the sequence of processes that will produce the goals state from an initial state" (Simon 1996). "Design takes place through individual decisions that reinforce and build upon each other to achieve a total comprehensive design-proposal" (Akin 1986). "Design product is a direct consequence of the preceding cognitive activity and not some arbitrary process that is independent of such activity" (Akin 1986).

In design "you find a solution path by making assumptions about the search strategy" (Simon 1996). "Since the consequences of design lie in the future, it would seem that forecasting is an unavoidable part of every design process" (Simon 1996). "The heart of the data problem for design is not forecasting but constructing alternative scenarios for the future and analysing their sensitivity to errors in the theory and data" (Simon 1996). For Simon design as problem-solving consists in discovering a process description of the path that leads to a desired goal.

Jones 1981 provides examples of formal definitions of design that clearly address these issues:

- "Decision making, in the face of uncertainty, with high penalties for error" (Asimow 1962 in Jones 1981);
- "A goal-directed problem solving activity" (Archer 1965 in Jones 1981);

- "Simulating what we want to make (or do) before we make (or do) it as many times as may be necessary to feel confident in the final result" (Booker 1964 in Jones 1981);

Generally the evaluation of the solution is more important than the analysis of the problem (Cross 2001), "Instead of generating abstract relationships and attributes, then deriving the appropriate object to be considered, the subjects ... generate a design element and then determine its qualities" (Cross 2001). In other words, designers try to find solutions for the problem before fully trying to formulate it. Because the evaluation of the solution is what matters not the analysis of the problem, designers can generate a design element and then determine its qualities.

On the other hand, in science, questions about the problem and also problem analysis are the drivers for the process of finding a solution. Problems are about determining significant facts, matching facts with theory and articulating theory using experiments to corroborate it, in this environment the ones who succeed are the one goods at solving puzzles (Kuhn 1996). "Normal science is related to puzzle solving because of the strong network of commitment between: conceptual, theoretical, instrumental and methodological aspects" (Kuhn 1996). Learning science is very much like learning to solve puzzles as text books teach facts through examples and ask puzzle like questions to be solved developing applied knowledge skills in the student. Students are exposed to different technologies and procedures not to different ways of deriving a solution. Scientific training is to solve problems not to ask questions and the approach is vertical, it happens in depth not in breath (Kuhn 1996). "Scientists solve puzzles by modelling them on previous puzzle-solutions with minimal recourse to symbolic generalisations" (Kuhn 1996). The whole of scientific education has puzzle solving as a goal. When you have a problem with only one single correct answer you can systematically solve it by trying to find its contradictory and inconsistencies and therefore eliminate alternatives to make the search quicker (Simon 1996).

However, it can be very simplistic to state that scientists are problem focused, i.e. they try to discover the structure of a problem, whereas designers (or architects in this case), are solution focused i.e. they generate solutions for problems until one of them prove to be acceptable as claimed by Cross 2001 and Lawson 1997. It is even simplistic to suggest that design is about synthesis rather than analysis, i.e. that it is an abductive process in which an idea is instantiated and tested against facts rather then a deductive process in which chains of logic are used to analytically reduce what is known to a final conclusion (Bachman 2003).

"Design reasoning does not follow inductive or deductive procedures in a simple way" (Zimring and Craig 2001). Deductive procedures are reversed, they are not deterministic but they do happen (Zimring and Craig 2001). The logic of moving "from general and abstract to the specific and concrete, from analysis to synthesis" (Zimring and Craig 2001) applies to organising the contexts of a design problem and to the evaluation of the resulting design. Between these two stages designers reason and rely on intuition, they use guesswork and analogical reasoning. This combination results in dynamic changes in the problem space through interactions with the physical situation designers create (Zimring and Craig 2001) and that is why to talk about design is always very controversial.

4.2. Generic types of design problems

Differences in knowledge, procedural skills, cognitive processes, general problem structure and social practices occur among different design domains. There are also differences in practices, the sorts of tasks designers' face, the kinds of artefacts produced by designers, the kinds of knowledge and the cognitive processes carried out among different design activities. However, despite all these differences the types of design problems encountered have been able to be generalised into well-defined problems, ill-defined problems and wicked problems.

A non-exhaustive discussion about the overall nature of well-defined problems as opposed to ill-defined problems as well as a discussion about wicked problems is presented in this next section, considering the definitions and characteristics behind each type of problem-solving.

Simon 1973 was one of the first to introduce the concepts of well-defined and ill-defined problems. He provided a list of characteristics to well-defined problems and as opposed to this list he conceptualised ill-defined problems.

The main characteristics of well-defined problems outlined by Simon 1973 can be summarised in the following four main points:

- Problems with clear solution criteria and ways of applying these criteria;
- Problems with initial states, desired states, final aims and moves to achieve these aims, as well as the knowledge acquired by the problem solver, possible to be represented once searching for a solution;
- Problems in which the application of procedures used to solve them "reflect the laws of nature that govern the external world" (Simon 1973);
- Problems in which information to solve them is available "with the help of only practicable amounts of search" (Simon 1973).

The two first points outlined by Simon 1973 imply that well-defined problems are problems with a definite problem spectrum and a definite problem-solving technique available to be used. A definite technique involves fixed solution criteria, transformation rules and fixed boundaries for restructuring (Zimring and Craig 2001). Problem states are unambiguous and do not change with context, constraints and structure. As a consequence, commitments to general ideas deepen the problem space and "movement is from one idea to a more detailed version of the same idea" (Goel 2001).

The focus of well-defined problems is on decisions regarding the solution points and the general form of the solution is fixed (Eastman 2001). That means that, in general, well-defined problems are problems in which work is necessary only in the solution space (Craig 2001) and a wide range of solution concepts can be explored (Cross 2001) as the focus is mainly in the solution (Eastman 2001). The exploration of a wide range of solutions is possible because there is less scope for problem setting (Cross 2001), the problems "are only restructured discretely" (Zimring and Craig 2001), there is no room for a continuous redefinition of what the problem is (Simon 1973) and only incremental improvements or marginal variations are allowed to happen (Akin 1986).

The two latter points defined by Simon 1973 imply that in well-defined problems the work in problem space is restricted to mapping the problem into well-known frames of reference so that a procedure based on conceptual models to work on the solution can be applied directly. Relationships between description and solutions are deterministic as the problems have an a priori defined representation, transformation states, goals and evaluation criteria

(Akin 2001). The problems then seem to be logical, linear with processes applied to solve them as believed to be true and not open to contestation in terms of solutions they produce (Akin 2001). Many of these procedures can be transformed into algorithms and optimization techniques do apply.

The impression is that "well-formed design problems can be solved straightforwardly from the presentation of the problem as encountered" (Gao and Kvan 2004). However, well-defined problems only exist after being defined as so once acted upon by problem solvers, i.e. they only exist once they have been formalised for problem solvers (Simon 1973). Before that, all problems are considered to be ill-defined (Simon 1973), which would imply that increasing amounts of well-defined problems would be constructed as a normal and natural consequence of solving currently ill-defined problems.

To check if this is actually true, a definition of ill-defined problems needs to be examined before establishing this debate.

Ill-defined problems tend to be defined as opposed to well-defined problems and according to Simon 1973 have the following characteristics:

- Problems with no definite criteria to test proposed solution nor ways of applying these criteria;
- Problems with no meaningful definition of the problem space, i.e. no clear desired states, aims and moves to achieve these aims once working in the problem-solving state, as these would need to encompass all kinds of possibilities in terms of problem structure, design processes and organisation of design processes to be considered;
- Problems have loose boundaries allowing new alternatives to arise in the problem space, which means the problem space is opened to constant redefinition;
- Problem space can only be defined in a later stage after a large amount of information and knowledge has been put together.

The first two points are reinforced and complemented by many authors. Ill-defined problems are "problems with start states (information and resources), operators used to transform states (changing parts, materials, etc) and goals (criteria to judge the states in problem space) open to redefinition" (Newel and Simon in Zimring and Craig 2001). In ill-defined problems there are no explicit evaluation functions to be used to identify the achievement of a solution, designers apply their own judgement in evaluating solutions and earlier solutions regenerated tend not to be used (Akin 1986). "Criteria for acceptability of solutions are themselves similarly ill-defined and flexible ... significant aspects of acceptability criteria change and develop in response to parallel changes and developments in aspects of emerging problem" (Harfield 2007).

The absence of clear definitions of initial conditions (Cross 2001) make the discovery of new rules desirable, "even though a large set of conventions is available as part of the culture of design" (Akin 1986). The states are ambiguous and contextual, allowing for creativity with low degrees of commitment (Goel 2001). Widening the problem space is encouraged through "movements from one idea to a slightly different idea rather than a more refined one" (Goel 2001).

The focus is on defining the solution space not on searching the specific solution points within it as the general form of the solution is open (Eastman 2001) and problems have more than one possible solution (Goldschmidt 2001). An ill-defined problem is a problem in which, the definition of the problem space as well as the criteria applied to the candidate solution are part of the design task (Eastman 2001). These result in more scope for problem framing and therefore the generation of fewer solutions (Cross 2001).

More scope for problem framing implies that the problem is constantly being restructured and reformulated. "Parameters that established the problem as given may change during the course of the process, positioning the problem in a state of potentially continual revision" (Harfield 2007). The problem cannot be understood in isolation from consideration of the solution, so solution conjectures are used to explore and understand the problem formulation (Cross 2001). Besides that the problem space depends on more than what is given in a problem statement and changes continuously throughout the solving episode as new information comes in (Craig 2001).

As these problems have large space for potential restructuring and restructuring is allowed at any level of abstraction, there are no procedures to be transformed into algorithms and optimization strategies do not apply. In this context, how is it possible to go from an ill-structured problem to a well-structured one?

For Simon 1973, designers go from ill-structured problems to well-structured ones by acting directly upon an ill-defined problem structure decomposing it into self-contained parts to be transformed into well-structured sub-tasks "with a retrieval system which continually modifies the problem space by evoking new constraints and sub-goals" (Simon 1973). "When a problem is gradually decomposed the problem space is under continuous change, detailing certain parts will be deferred until other parts have been completed" (Zimring and Craig 2001). That makes one believes that "any problem with a large base of potentially relevant knowledge may appear to be an ill-structured problem" (Simon 1973) and subsumes the main difference between ill-defined and well-defined problems to the amount of knowledge that needs to be manipulated. It also makes implicit that an ill-defined problem can only be solved by setting up well-defined parts within an ill-structured whole. It was believed that this decomposition could be treated scientifically and procedures for doing it were somehow embedded in many of the "scientific" design methods brought up during the 1970s in which the aims were to set up deterministic relationships between problem description and problem solution.

Unhappy with this deterministic approach to problem solving, planning professionals (Rittel and Webber 1974) proposed the concept of wicked problems. Slightly different from ill-defined problems, wicked problems clearly acknowledge the social and political forces embedded in the problem-solving process (Zimring and Craig 2001). The word "wicked" is used to clearly illustrate the fact that the problems "rely upon elusive political judgement for resolution" (Rittel and Webber 1974) and therefore can be easily manipulated in a devious or tricky way. Wicked problems cannot be modelled into clear distinct phases as the constraints for the solution space as well as the constructed measures to evaluate it are all wicked and contextual.

Wicked problems have no definitive formulation because problem and solution are concomitant to each other. "The process of formulating a problem and conceiving the solution are identical" (Rittel and Webber 1974) because "the problem cannot be defined until a solution has been found" (Rittel and Webber 1974). This means that it is not possible to first understand and then solve because information cannot be searched "without the orientation of a solution concept" (Rittel and Webber 1974).

There are no stopping rules for wicked problems and the problem ends when the solution is either good enough, the best within the limitations or the one the designer likes. There is no "the" or "a" solution, neither a true or false solution but a good or bad solution with the criteria to judge it made objective through convention. That is to say many parts will assess the solution according to their interests, values, ideologies, beliefs, etc. As a result any solution hypothesis cannot be put to crucial test. "The analyst 'worldview' is the strongest determining factor in explaining a discrepancy and, therefore, in resolving a wicked problem" (Rittel and Webber 1974). Besides that the set of potential solutions is quite small and there is not a "well-described set of permissible operations that may be incorporated into the plan" (Rittel and Webber 1974).

"Every wicked problem is essentially unique" (Rittel and Webber 1974). The problems cannot be put into classes for principles of solutions to be developed as there are no "families" of problems to apply a set of techniques to solve them. Solution transfers are dangerous due to the contextual, contingent, uniqueness of the problem (Rittel and Webber 1974).

In wicked problems the emphasis is in the subjective nature of the result as something heavily dependant on the viewpoint of the problem solver (Buchanan 1995, Zimring and Craig 2001, Coyne 2005) as well as in the problem framing strategy to cope with the symbiotic relationship between problem statement, criteria and solution (Harfield 2007, Zimring and Craig 2001).

Wicked problems did not refute ill-defined problems but expanded them acknowledging the social forces involved in shaping any kind of problem structure. This does not deny the idea that any wicked problem would develop into a well-structured one so that it can be solved (Gao and Kvan 2004). However, this act is now interpreted as an evolution of the problem solving activity over time. It cannot be based on a deterministic decomposition of an ill-defined whole into well-defined parts because the word wicked implies no neutral possibilities to allow the setting up of a problem structure. This means wicked problems could only become well-defined ones by considering that the criteria and rules applicable to frame the problem space and the solution space would evolve towards refinement. "Decisions invariably propagate constraints, gradually narrowing the search space as the design proceeds (Zimring and Craig 2001). As any transformation from a wicked problem into a well-defined one "would depend on the abilities and priorities of a problem solver not necessarily by a problem given" (Zimring and Craig 2001) the deterministic relationships between problem description and problem solution can be denied. Wicked problems would not necessarily become well-defined ones due to a direct and "scientific" act upon the problem structure but due to a designer decision about shifting the whole problem framing from constant problem restructuring to only discrete restructuring.

4.3. Generic paradigms of design problem-solving: Relating domain independent types of design problems to design problem-solving processes

From the domain independent characterisation of design problem-solving activities it was possible to see that conceiving the new is a strong point underlying any design activity. "Scientists are concerned with understanding the universal properties of what is, while designers are concerned with conceiving and planning a particular that does not yet exist" (Buchanan 1995). Conceiving the new involves conceiving and planning the artificial and "professional designers should be recognised for their ability to conceive products as well as plan them" (Buchanan 1995).

Conceiving the new also implies that the qualities and values of this new are the ultimate aims of its conception which means that there is more involved in problem-solving than simply conceiving an object to solve "a" or "the" specific problem. The ultimate aims of it are always directed towards producing a solution with value.

Problem-solving becomes a complex activity once design is understood not only as a process of solving a problem but also as a process of materialising its solution. It is difficult to separate process from product when they are a complementary aspect of a single result and the activity itself involves a combination of inductive, deductive and abductive processes which are interchangeable and interrelated.

When, on top of that, generic types of design problems are introduced, different paradigms of design problem-solving can be outlined. If the problem statement is rewritten consciously into known structures, it is likely that it will have specific constraints and will follow predefined rules which therefore will make it well-defined. If the problem statement is rewritten unconsciously into 'loose' structures, it is likely to have less constraints and more flexibility in its rules which will make it ill-defined.

In the first case, the interpretation of the problem consists in mapping it into a familiar structure, previously defined by the design community, and the problem solving activity is subsumed to a search through a solution space with clearly defined boundaries. The problem structure tends not to be questioned and the whole design activity becomes mainly a matter of optimisation. In the second case, the interpretation of the problem is up to the designer to handle which implies the discovery of a strategy to invent an appropriate problem structure to be used when formulating a design hypothesis.

In either case, the design problem will start from "a synthetic activity related to indeterminacy, not an activity of making what is undetermined in natural laws more determinate in artefacts" (Buchanan 1995). Even if for some design thinkers (Simon 1996 among others), the design activity would consist in decomposing an ill-defined whole into well-defined parts to apply search procedures and use natural laws as deterministic criteria to shape the artefact, it would still start with indeterminacy and therefore would be opened to wickedness.

In this context, it can be said that all design problems occur "in the context of the indeterminacy of wicked problems" (Buchanan 1995). That "all problems have a character of wicked problems" (Coyne 2005) in which well-defined problems are diminished versions of this wickedness either determined by a single designer or by a whole community. "What we normally regard as an objective position is nothing more than a position prescribed within a particular horizon" (Coyne and Snodgrass 1991) that will depend on the rigidity of the paradigm imposed by the community to deal with design problem-solving (Figure 4.1).

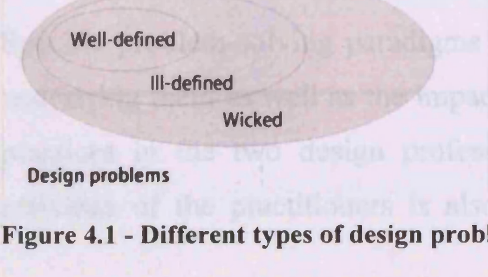


Figure 4.1 - Different types of design problems as diminished versions of wicked problems.

The paradigm imposed by each community, that actually reflects how each community is structured to deal with problem-solving, is what effectively resides between the design product and the design process. Problem-solving paradigms put together "views of subject matter held by designers and the concrete objects conceived, planned and produced as expressions of those views" (Buchanan 1995), and are the main elements that differentiate one design domain from the other.

Generic paradigms of design problem-solving are made specific in the next two chapters. Chapter 5 will explore in detail thermal building physics design problem-solving, and chapter 6 will explore in detail architecture design problem-solving. The author's hypothesis is that the paradigm used by building physicists in design problem-solving can be directly related to well-defined problems whereas the paradigms used by architects in design problem-solving can be directly related to wicked problems (Figure 4.2).

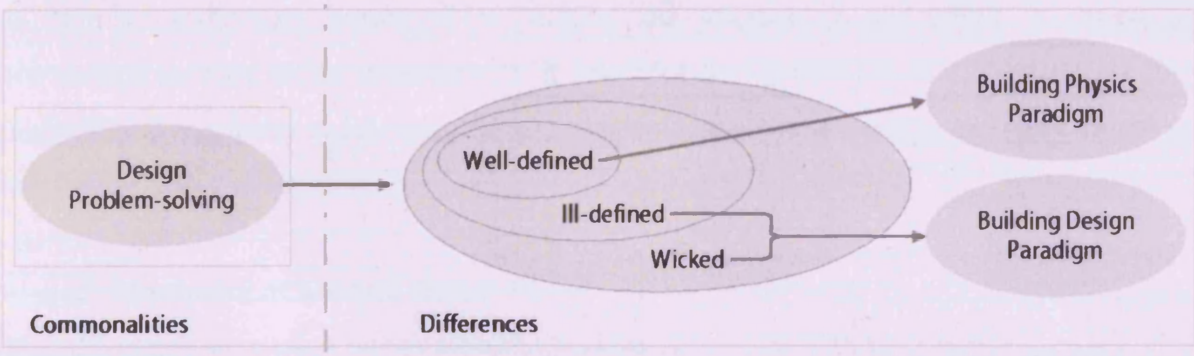


Figure 4.2 – Constructing the theme for debate

Problem-solving therefore effectively becomes the central theme of this research, as it is used to outline commonalities between the two design professions with regards to the ultimate aims to be achieved. At the same time generic types of design problems, together with the implications of these types of problems in the different paradigms used in problem-solving activities, can be used as a basis to outline major differences between the two design professions (Figure 4.2).

Specific problem-solving paradigms can then be analysed with regards to the worldviews underlying them as well as the impact they have in articulating representation systems and practices in the two design professions. The role of computer tools in the everyday activities of the practitioners is also examined considering problem-solving paradigms, representation systems and practices. The author critically constructs a debate based in design problem-solving, starting with an analysis of the paradigm involved in building physics which is used as a basis to construct the subsequent debate about design problem-solving in architecture.

5. DESIGN PROBLEM-SOLVING IN THERMAL BUILDING PHYSICS

The aims of this chapter are to understand how the modelling community is structured to deal with design problem-solving in thermal building physics and why this community sees design as something clearly procedural.

In order to meet the aims of the chapter, an analysis of problem-solving paradigms, representation systems, computer tools and practices building physicists use in their everyday activities is proposed. This analysis, far form being neutral or impartial, has its basis in general system theory, the philosophy used by the simulation community to develop the tools and deal with design problem-solving.

General system theory has a basis in structuralism as it studies the entities, how they interact with each other and what questions may be legitimately asked about these entities as well as techniques employed in seeking the solution (Kuhn 1996). Recourse to philosophy is seen to be necessary as it provides the specific body of theoretical and methodological beliefs to interpret the community viewpoint, as well as a context to set up debates about the fundamentals.

A short description of general system theory is provided followed by a description of how this philosophy is applied to the relevant domain of physics: thermodynamic systems. The way thermodynamic phenomena are represented using mathematical models and how those models are transformed into simulation tools are then introduced, finishing with a discussion about the predictive capabilities of these tools and the impact of these predictions in building design. An overview of the design problem-solving approach in building physics is finally provided relating this specific design activity with the design domain independent discussion from the previous chapter.

5.1. Overall philosophy behind thermodynamic systems

The philosophy behind thermodynamic systems comes from classical general system theory. General system theory sets up a paradigm of scientific thinking with its knowledge residing in the investigation of organised wholes or structures and its beliefs residing in the fact that these wholes or structures behave or function like organisms.

The paradigm comes formally from the biological sciences but is based on structuralism and functionalism philosophies. It emerged from the needs to understand and deal with complexity proposing an interdisciplinary approach to nature. It started in the 1920's as a reaction to the positivistic, reductionist and mechanistic viewpoints that proposed that the whole was a sum of parts; that the phenomena could be reduced to its elementary units which could be investigated independently of each other. Science was seen as a set of conceptual boxes with their own rules and procedures in which different views of nature were competing with each other (Kuhn 1996). Analysis was used as a mean to draw general conclusions from experimentation and observation and synthesis was about "making logical deductions form premises and axioms" (Coyne 1995).

The idea of studying the whole not only the parts arose in several different scientific fields at the same time as scientists discovered that the dynamic interaction of parts make them behave differently than when studied in isolation. There was a concern about how the parts were organised and how they behaved when in a higher configuration or when belonging to the whole. This was a paradigm shift in science from reductionism to structuralism. This new paradigm can be understood as a structure as it tells the scientists about "what entities that nature does and does not contain and about the way in which those entities behave" (Kuhn 1996). Entities are now understood within the context of a structure, which opens the debate for new systems of relations and new frameworks for sets of data (Kuhn 1996).

This idea set up the basis for a new scientific paradigm with reality understood as a "hierarchy of organised wholes" (Von Bertalanffy 1969) in which entities are not treated in isolation or only with regards to their position in the structure but also as performing specific functions within this whole or structure. This whole or structure acts as an organism allowing general cognitive principles to be identified from it. The principles come from understanding the relationships (interactions and transactions) between the elements as well as from understanding the way these elements are organised and perform in the overall structure.

The systematisers believed that the understanding of the principles would allow them to build up relationships between different knowledge domains and therefore integrate sciences. So in the 1950s lots of efforts were spent in order to build up a "unified science" which would investigate general isomorphic concepts, look for identities or similarities in structure that would allow transfers of knowledge from one field to another, and from these concepts develop adequate theoretical models in each field avoiding duplication of theories and providing better communication among specialists.

The whole scientific method is redefined once the whole is seen as more than simply a sum of parts (Von Bertalanffy 1969). Analysis is about "breaking the phenomena down into its constituent parts to better understands it" (Coyne 1995) through investigating the purpose and position of each part in the whole (Von Bertalanffy 1969).

There is a clear method to analyse phenomena and identify the type of structures underlying them. The method states that if the nature of interactions between the parts is identified as weak enough to be neglected or non-existent, the parts can be worked independently and logically and put back together mathematically. If the relations describing the behaviour of the parts are linear, the whole will be the result of the sum of the parts. However, if neither the independence of the parts can be clearly identified nor the relationship between them described as linear, the whole is clearly a system and requires a different and specific approach to be understood and acted upon.

Synthesis is about building up the whole by assembling the parts into something complex (Coyne 1995). Theory is a hypothetical proposition that needs to be proven or transformed into a set of mathematical rules and models so that it becomes something useful and essentially predictive, i.e. it can be used to predict general principles (Coyne 1995). Once general principles are established, generalised systems can be derived "irrespective of their particular kind, the nature of their component elements and the relations of forces between them" (Von Bertalanffy 1969) because many times, although the causal mechanisms and the entities involved are different, the law that put things together is the same. General theories of organisation can then be developed, either qualitatively or quantitatively, and represented as models that can be used and transferred to different fields of knowledge through analogies.

Models either transformed into mathematical expressions or not, are essential in system theory (von Bertalanffy 1969). They work as the main guiding idea of the theory as they describe not only the interactions between the parts but also the overall functioning of the structure. They define the hierarchical order of the parts, i.e. the system structure, as well as the hierarchical order of the processes, i.e. the system functions. Many times they can be represented mathematically, when the interactions between the different parts of a system can be prototyped into a set of simultaneous non-linear differential equations.

The most important point about systemic thinking is the comprehensive understanding, the thinking in terms of composed parts that can be organised hierarchically into a structure in which the behaviour of the whole cannot be predicted by separating the parts from each other (Buckminster Fuller 1976). Clearly defined structures can be easily represented as models.

The second most important point in systemic thinking is exactly this representation system with mathematical models composed of differential equations that account for the simultaneous phenomena going on, in the centre of it. And because modelling allows prediction, the third most important point in systemic thinking is the ability of the models to predict system behaviour which opens possibilities for control and decisions theories to be developed.

General system theory becomes then a very powerful theory to deal with the physical world because once a structure is established and modelled, the "known behaviour of the whole and the known behaviour of a minimum of known parts often makes possible the discovery of the values of the remaining parts" (Buckminster Fuller 1976).

5.2. Thermal building physics problem-solving paradigm

The understanding of building thermodynamic phenomena becomes quite straight forward when seen within a system theory paradigm especially if presented using a top-down approach. A top-down approach allows a clear understanding about the overall structure of a building thermodynamic problem as it starts by showing all the component parts, developing towards showing how the parts are interconnected, how these interconnections can be mathematically represented and how an overall solution can be achieved so that the system behaviour is synergistic, i.e. cannot be predicted "by the separately observed behaviours of any of the system's separate parts or any subassembly of the system parts" (Buckminster Fuller 1976).

Thermodynamic systems are, as the name suggests, dynamic systems, with a behaviour "usually changing with time so that there is no status quo or lasting steady state" (Shearer et al 1971), systems in which the phenomena will be occurring in the time/frequency domain. It is very important to understand that the phenomena being analysed are behavioural, non-tangible and that they develop in time not in space.

As the "currency" of physics is energy (Von Bertalanffy 1969), building thermodynamic systems are systems in which energy exchange happens either through heat transfer processes and/or mass exchanges across the system/building envelope. Energy is expressed in terms of heat flow and temperature differences, the two main variables of interest, and the problems are structured and articulated to express the heat flow in terms of variations in temperature differences over periods of time.

Buildings once interpreted by thermal or service engineers as thermodynamic systems have a clear framework for decomposition. The inside building environment is the system under study, many times the one which will be acted upon, and the building envelope is the interface between this inside environment and the outside weather. Temperatures can either be controlled to a fixed range or set point by adding or removing energy to the inside building environment (controlled behaviour) or they can be allowed to fluctuate inside the building by taking advantage of favourable weather conditions, without being artificially controlled (adaptive behaviour).

It is important to define which of the two situations will happen at each specific time interval. Adaptive behaviour has heat and mass exchange happening freely, in an uncontrolled manner and the designer's attention is focused mainly on the building envelope. Controlled behaviour has heat and mass exchanges affected by energy delivered or removed from them in order to control their internal temperature to a fixed range or set point. The designer's attention in this case is focused not only on the building envelope but also on the machines that will remove or deliver energy to control the internal temperatures. Figure 5.1 provides a simplified illustration for each of the two types of behaviour.

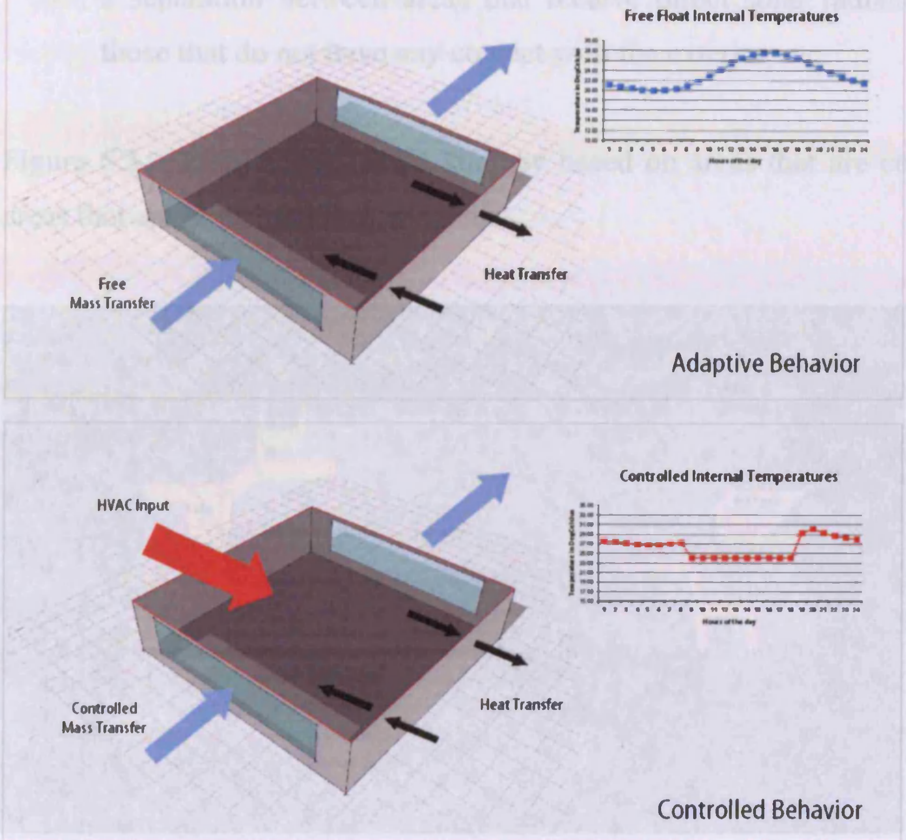


Figure 5.1 - Examples of adaptive and controlled behavior

Following the logic of systemic thinking, the inside building environment can also be decomposed into nested subsystems to which the same thermodynamic principles are applicable. Subsystem boundaries are conventionally called 'zones' by thermal/service engineers.

Zones do not necessarily coincide with the internal space distribution. They are generally defined differently depending on whether behaviour is considered as adaptive or controlled. When adaptive behaviour is considered the zoning generally coincides with the internal space distribution or internal layout (Figure 5.2) but when controlled behaviour is considered zoning can have boundaries defined based on, for example:

- HVAC types,
- HVAC supply and return points,
- areas with the same set point temperatures,
- areas with the same type of usage,
- areas that are completely internal and areas that are in the building perimeter,

- a separation between areas that receive direct solar radiation and sunlight from those that do not have any contact with the exterior, etc.

Figure 5.3 exemplifies a zoning strategy based on areas that are completely internal and areas that are in the building perimeter.

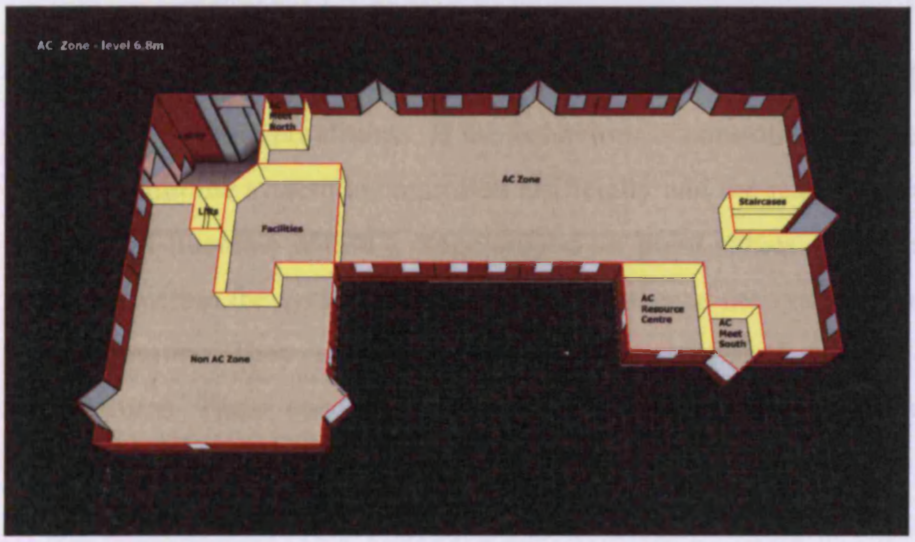


Figure 5.2 - Example of zoning according to adaptive criteria (Bleil de Souza et al 2006)

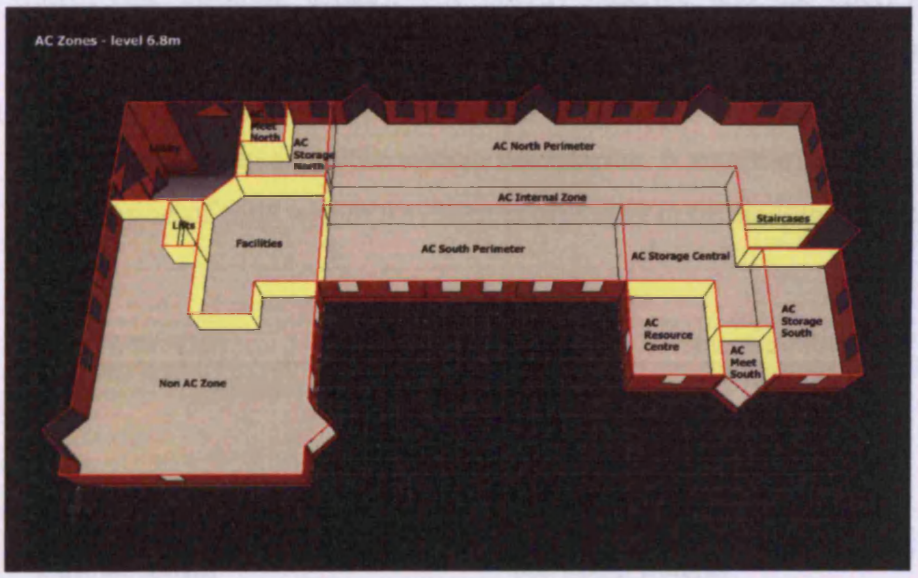


Figure 5.3 - Example of zoning according to controlled criteria (Bleil de Souza et al 2006)

Identification of subsystems or zones within a building is critical step in evaluating the energy processes. Boundaries need to be established to make it possible to mathematically model those energy processes in order to calculate energy flows and temperature differences at different moments in time. These energy flows and temperature differences depend on:

(i) The energy generated within the system;

(ii) The energy entering the system;

(iii) The energy leaving the system.

If the behaviour is adaptive the change in the amount of energy within the system is uncontrolled and the resultant temperatures within the system will fluctuate depending on the outside weather conditions. If the behaviour is controlled the change in the amount of energy within the system is controlled artificially and the resultant temperatures within the system will fluctuate within a range around set point values. These changes in the amount of energy within the system, or the energy balances of the system, over a period of time are called outputs. They are either expressed in terms of energy demands or internal temperatures. These outputs are used in the evaluation of the system against its design aims, respectively controlled aims and adaptive aims.

The energy generated within the system depends exclusively on what happens inside the system (the building usage). The energy entering and the energy leaving the system, although being affected by the energy generated within the system, depend on surface phenomena which comprise the heat transfer processes across the envelope surfaces as well as the mass crossing the system boundaries. A summary of the overall energy balance over a period of time within a system is provided in the annotated equation in Figure 5.4.

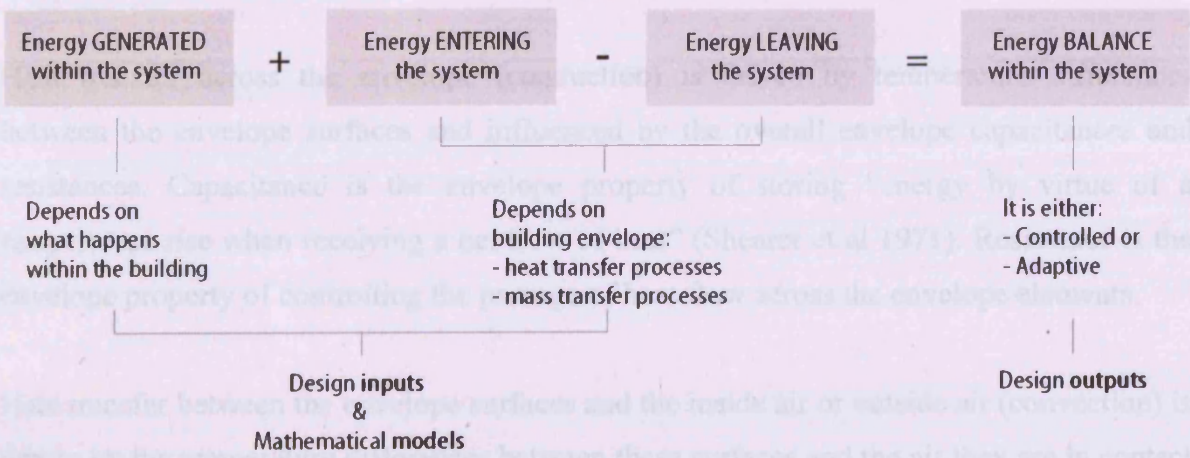


Figure 5.4 - Annotated equation of overall energy balance

The energy generated within the system is calculated based on parameters that come from each zone occupancy and usage. The first term of the equation refers to the heat generated by the people occupying the spaces while performing a specific activity whereas the second term of the equation refers to the heat generated by all artificial lighting and equipment used within these spaces.

The surface phenomena comprise interdependent mathematical models that represent the four heat transfer processes across the envelope as well as the two types of mass transfer across the system boundaries. They are also affected by the energy generated within the system.

"Heat transfer is thermal energy in transit due to spatial temperature difference" (Incropera et al. 2006) and in buildings it is conventionally divided into the following four different modes:

(i) Conduction heat transfer: Comprises heat transfer across the envelope;

(ii) Convection heat transfer: Comprises heat transfer between the surfaces and the inside and outside air;

(iii) Long wave radiation heat transfer: Comprises the heat transfer between envelope surfaces, internal surfaces and other surrounding surfaces at different temperatures without the direct interference of the air;

(iv) Solar heat transfer: Includes the direct solar radiation falling on the building envelope which is absorbed, reflected and transmitted through its surfaces to the inside environment surfaces.

Heat transfer across the envelope (conduction) is driven by temperature differences between the envelope surfaces and influenced by the overall envelope capacitances and resistances. Capacitance is the envelope property of storing "energy by virtue of a temperature rise when receiving a net flow of heat" (Shearer et al 1971). Resistance is the envelope property of controlling the passage of heat flow across the envelope elements.

Heat transfer between the envelope surfaces and the inside air or outside air (convection) is driven by the temperature differences between these surfaces and the air they are in contact with.

Heat transfer between envelope surfaces, internal surfaces and other surrounding surfaces at different temperatures without the direct interference of the air is driven by temperature differences between the surfaces.

Direct solar radiation falling on the building envelope which is absorbed, reflected and transmitted through its surfaces to the inside environment surfaces (solar heat transfer) depends on the amount of solar radiation available in the outside, the context the building is in and the surfaces properties, area, position and topology.

Mass transfer across the building envelope contributes to the overall thermodynamic behaviour of the system once the mass entering or leaving the envelope, driven by pressure differences, carries amounts of energy within it. If the mass exchange is voluntary or controlled it is called ventilation whereas if the mass exchange is involuntary or uncontrolled it is called infiltration.

The surface phenomena and mass phenomena depend on a range of variables most of them defined by the building designer once the surfaces, composed of their respective materials, are put together to shape the building internal spaces. The usage of the internal spaces and the information which characterises the context in which the building is situated (weather and building surroundings data) complement the data necessary to fully understand the building behaviour, collectively known as the input data.

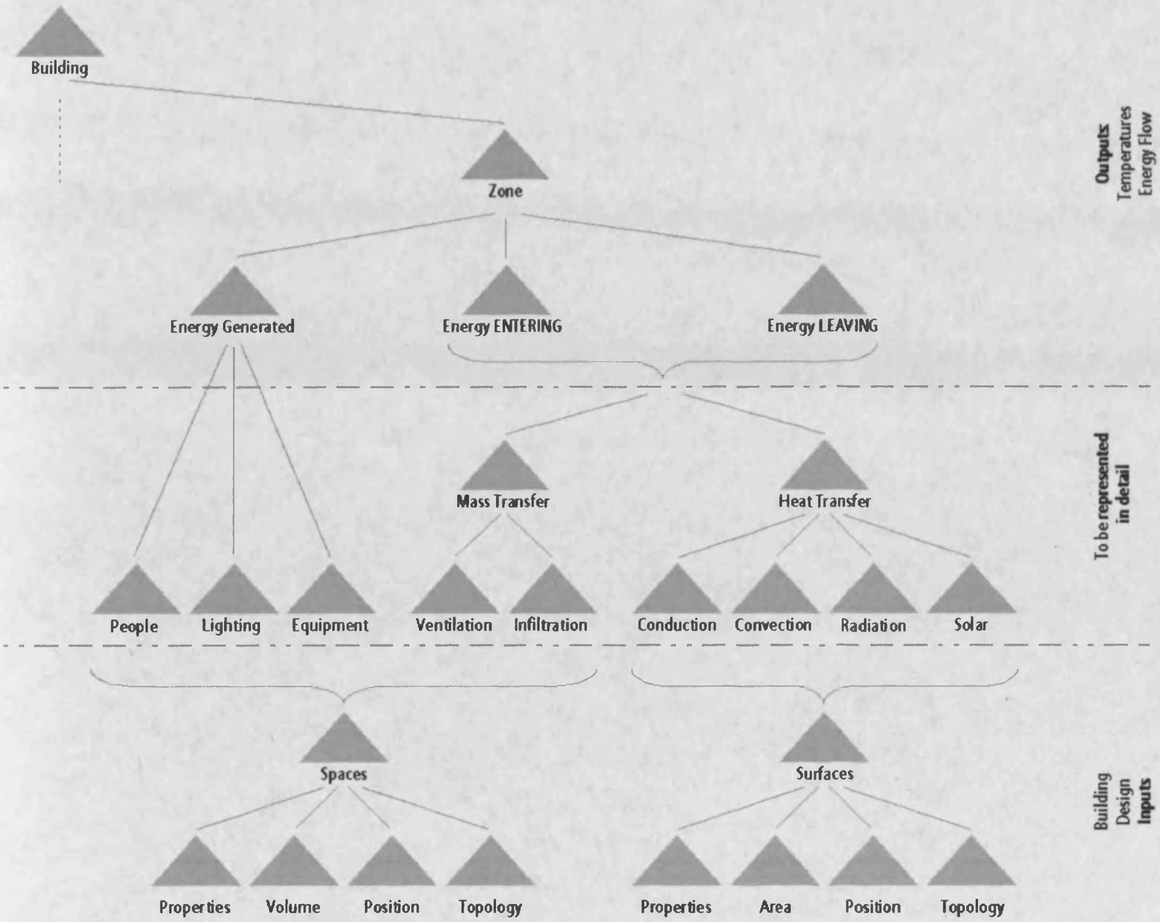


Figure 5.5 - Structural diagram of a building thermodynamic system

The top-down approach presented allows the setting up of a clear structure to represent the component parts of a building thermodynamic problem. From Figure 5.5 it can be seen that the building is considered as a whole comprised of several minor systems, the zones. Each zone has an energy balance over a period of time that depends on the heat generated inside them as well as on the heat entering and leaving the system due to surface phenomena. Heat generated inside has nested in it different origins for its generation, mass transfer phenomena have nested in them two different energy transfer processes and heat transfer phenomena have nested in them four different energy transfer processes. The bottom of the diagram displays the input data controlled by the building designer which will influence all the described phenomena.

5.3. Mathematical models as the main representation system

The tree diagram of Figure 5.5 illustrates how the whole is decomposed into parts in a thermodynamic system but it does not display how the several parts are interconnected with each other to define this whole. A continuation of the tree diagram used before is proposed to explain these interconnections.

It is again a top-down approach used to explain how each heat transfer, mass transfer and energy generation process further subdivides into elemental parts to be mathematically modelled. These parts are called elemental system equations and once mathematically represented allow the commonalities between the parts to be seen suggesting points of interconnection. A topological description of these interconnections enables the elemental models to be mathematically assembled into a full quantitative model that predicts the thermodynamic behaviour of the overall system.

Elemental equations for heat transfer processes are mathematical models that set up heat flow in terms of variations in temperature differences over time considering areas and thermophysical properties of building surfaces (internal and external).

Conduction elemental equations are represented by two diagrams illustrated in Figure 5.6:

(i) The capacitance equation establishes relationships between heat flow and temperature differences with the energy stored in the mass of a building element. It depends on the mass, area and the specific heat of the envelope elements;

(ii) The resistance equation establishes relationships between heat flow and temperature differences with the energy that passes through a building element. It depends on the conductivity, area and thickness of the envelope elements.

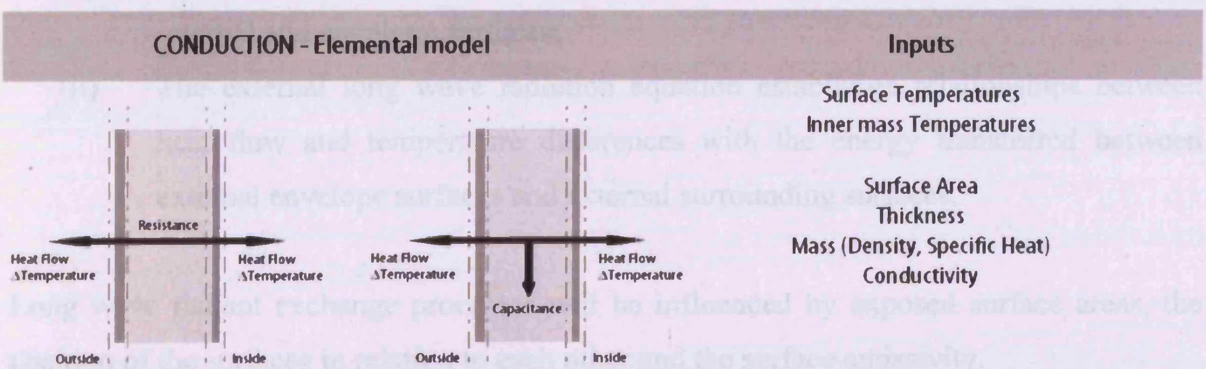


Figure 5.6 - Conduction heat transfer process

Convection elemental equations are represented by two diagrams illustrated in Figure 5.7:

(i) The internal convection equation establishes relationships between heat flow and temperature differences with the energy transferred to/from the internal air to/from the internal surface of the building element;

(ii) The external convection equation establishes relationships between heat flow and temperature differences with the energy transferred to/from the external air to/from the external surface of the building element.

They are both influenced by the exposed surface roughness, exposed surface areas and tilt angle of each surface, together with the nature of the air motion and other thermodynamic and transport properties of this same air that is in contact with the surfaces.

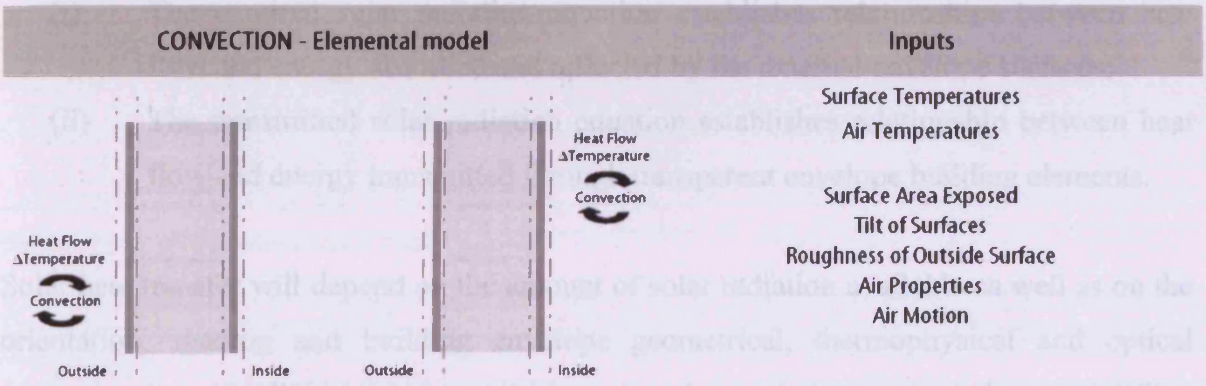


Figure 5.7 - Convection heat transfer process

Long wave radiant elemental equations are represented by two diagrams illustrated in Figure 5.8:

(i) The internal long wave radiation equation establishes relationships between heat flow and temperature differences with the energy transferred between internal and envelope surfaces;

(ii) The external long wave radiation equation establishes relationships between heat flow and temperature differences with the energy transferred between external envelope surfaces and external surrounding surfaces.

Long wave radiant exchange processes will be influenced by exposed surface areas, the position of the surfaces in relation to each other and the surface emissivity.

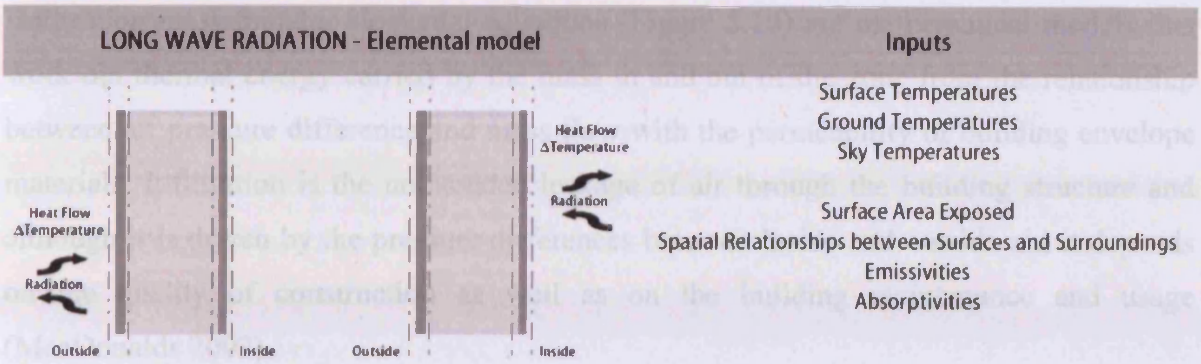


Figure 5.8 - Long wave radiation heat transfer process

Solar heat transfer elemental equations are represented by two diagrams illustrated in Figure 5.9:

(i) The external solar radiation equation establishes relationships between heat flow and energy absorbed and reflected by the external envelope surfaces;

(ii) The transmitted solar radiation equation establishes relationship between heat flow and energy transmitted through transparent envelope building elements.

Solar heat transfer will depend on the amount of solar radiation available as well as on the orientation, shading and building envelope geometrical, thermophysical and optical properties (specifically area, size, position, proportion and shape of windows as well as absorptivity, transmissivity, and reflectivity of the glazing system).

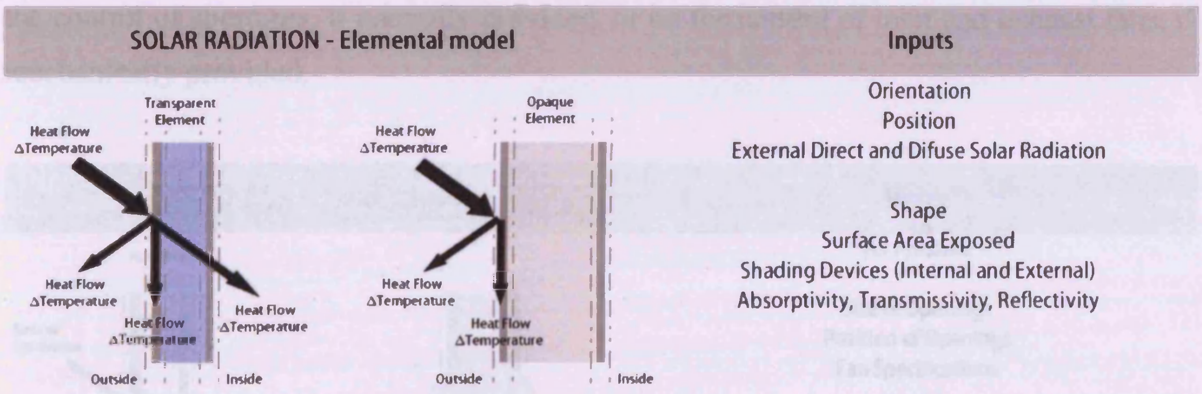


Figure 5.9 - Solar radiation heat transfer process

Elemental equations for mass transfer processes are mathematical models that set up relationships between pressure differences and mass flow with energy entering or leaving the environment due to mass exchanges.

Infiltration mass transfer elemental equations (Figure 5.10) are mathematical models that work out thermal energy carried by the mass in and out of the zone from the relationship between air pressure difference and mass flow with the permeability of building envelope materials. Infiltration is the unintended leakage of air through the building structure and although it is driven by the pressure differences between inside and outside air, it depends on the quality of construction as well as on the building maintenance and usage (MacDonalds 2002).

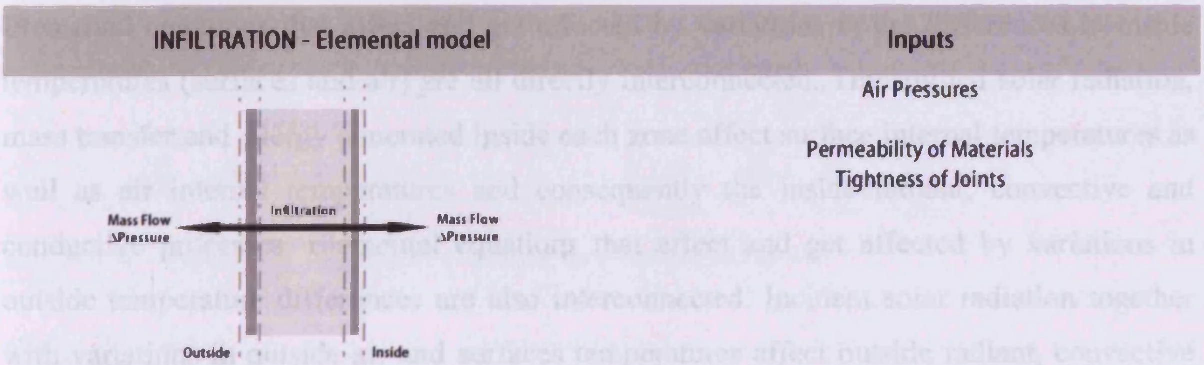


Figure 5.10 - Infiltration mass transfer process

Ventilation mass transfer elemental equations (Figure 5.11) are mathematical models that work out thermal energy carried by the mass in and out of the zone from the relationship between air pressure difference and mass flow with the air allowed to go inside the building either naturally or through controlled mechanical means. Ventilation depends on the control of apertures, if naturally provided, or on the control of inlet and exhaust fans, if mechanically provided.

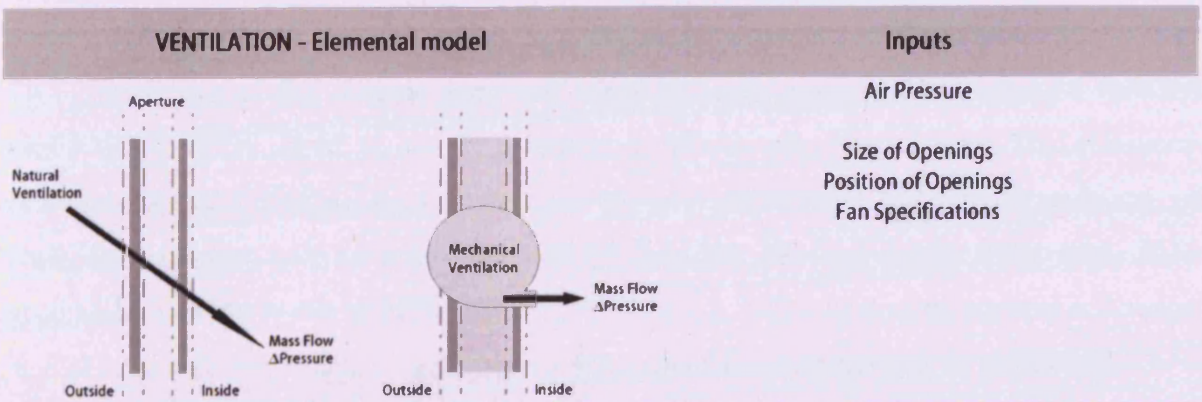


Figure 5.11 - Ventilation mass transfer process

There are no elemental equations for energy generated within the zones. Schedules containing occupancy and usage of artificial lighting and equipment together with direct outputs from the several energy sources within the zone are generally the most common information used. Heat flows from sources are then combined with information from schedule and direct source energy outputs.

From the previous discussion about elemental equations for all heat and mass transfer phenomena it is possible to see the interdependences among these elemental models. Elemental equations that affect and get affected by variations in the differences in inside temperatures (surfaces and air) are all directly interconnected. Transmitted solar radiation, mass transfer and energy generated inside each zone affect surface internal temperatures as well as air internal temperatures and consequently the inside radiant, convective and conductive processes. Elemental equations that affect and get affected by variations in outside temperature differences are also interconnected. Incident solar radiation together with variations in outside air and surfaces temperatures affect outside radiant, convective and conductive processes. The inside and outside environments are made interdependent once connected through the heat flow function of temperature difference across the building envelope, the conduction heat transfer process. The diagram in Figure 5.12 illustrates the topology of these connections developing further the thermodynamic structure diagram used in Figure 5.5.

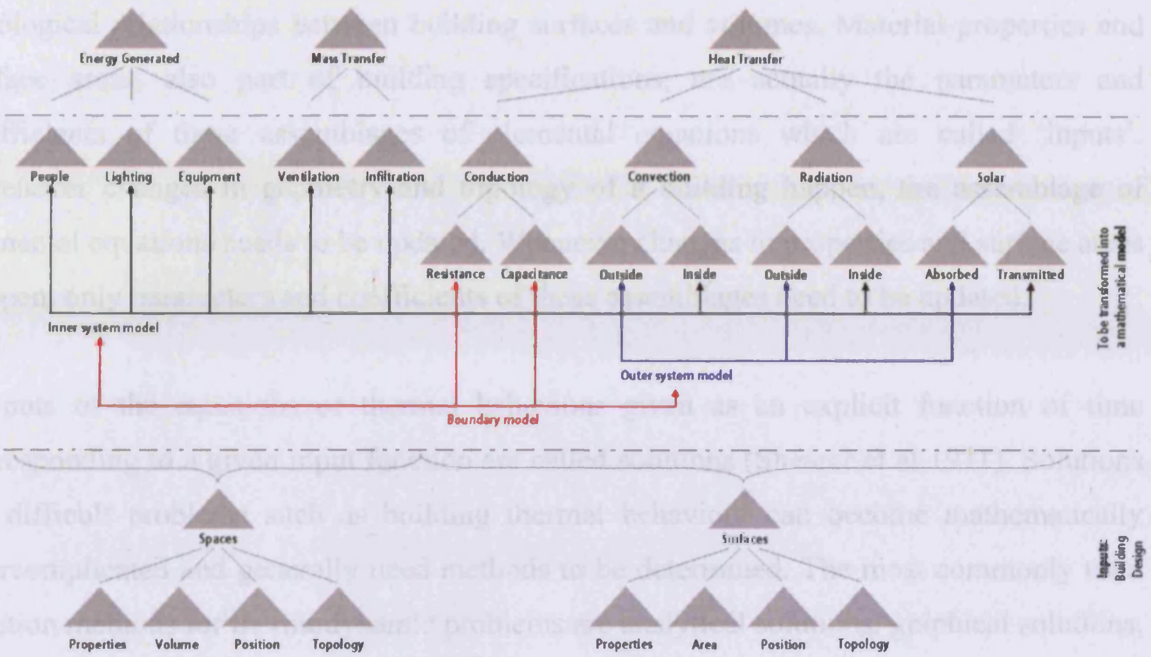


Figure 5.12 - Topological diagram of a building thermodynamic model

Once the points of connection are established it is possible to clearly see all the simultaneous phenomena going on. However, because thermodynamic behaviour expresses heat flow in terms of temperature differences over time, it is important not only to consider the simultaneousness of the phenomena but also the response of the system to the past and the present situations. There is a need to establish a starting point in time from which a specific system response in terms of heat flow is calculated so that when temperature differences start varying further system responses can be computed. As dynamic systems have no "status quo or lasting steady state" (Shearer et al 1971) it is not possible to calculate these conditions but to make assumptions about them.

Theoretically, once a set of initial conditions is defined and the articulations and interconnections of the system parts are mathematically represented a straight forward analytical solution could be derived. However, this is not always true. The elemental equations and the mathematical models for the interconnections and interdependences of elements represent generic scientific rules to calculate thermodynamic behaviour. They need to be applied to the specific set of input data, i.e. building design, context and usage so that a specific behaviour over time, as a function of these inputs can be calculated.

Whenever a building is modelled, a set of elemental equations representing different heat transfer and mass transfer phenomena are assembled, depending on geometrical and topological relationships between building surfaces and volumes. Material properties and surface areas, also part of building specifications, are actually the parameters and coefficients of these assemblages of elemental equations which are called 'inputs'. Whenever changes in geometry and topology of a building happen, the assemblage of elemental equations needs to be updated. Whenever changes in properties and surface areas happen, only parameters and coefficients of these assemblages need to be updated.

Outputs of the equations or thermal behaviour given as an explicit function of time corresponding to a given input function are called solutions (Shearer et al 1971). Solutions for difficult problems such as building thermal behaviour can become mathematically overcomplicated and generally need methods to be determined. The most commonly used solution methods for thermodynamic problems are analytical solutions, graphical solutions, numerical methods and analogue computers/operational block diagrams (Shearer et al 1971). The analytical and numerical methods are the most common ones used as they both lead to the development of the simulation tools that are currently in use.

Analytical methods developed into time-domain response function and frequency-domain response function methods. Both are simplifications of the analytical solutions (mathematical models) and are suitable to handle simpler problems in which the parts of a thermodynamic system are not heavily interdependent and the parameters are time-invariant. Simplified elemental models are assumed with coefficients and properties kept constant over time.

Response function methods work at a time step level, i.e. the phenomena is broken into small predefined increments of time (time steps) and simplified functions are used to calculate the response of each particular element at each time increment. These responses are then superimposed and the overall response is achieved (Clarke 2001). Frequency response function methods are composed of weather time series of periodic cycles (steady state condition) plus a number of harmonics with increased frequency and reduced amplitude. The system response is then evaluated for the periodic cycle and its harmonics and the result is again superimposed (Clarke 2001).

Numerical methods also break the analytical models into small predefined increments of time (time steps) but instead of dealing with the parts individually they deal with the whole system. The system is decomposed into a "nodal equation-set, which is then solved simultaneously" (Clarke 2001). The basic computation is repeated several times (Shearer et al 1971), i.e. the method is iterative. Initial conditions are assumed for the temperature differences and the heat flow which will originate a residue, to be worked upon until convergence is achieved (Clarke 2001). Numerical methods are very suitable to handle problems in which the parts are highly interdependent and parameters are time variant. They can handle more comprehensive elemental models, as well as coefficients and properties varying over time.

5.4. Building energy performance computer simulation tools

Simulation tools as discussed in this thesis are programming routines developed to solve thermodynamic problems that either use methods that evolved from analytical solutions methods and/or numerical ones. Defining which solution method is better to be used depends largely on the thermodynamic problem being examined.

Frequency-domain response function methods, evolved into the admittance method, are aimed at demonstrating the role of internal mass in modifying the room temperature and are suitable to calculate maximum temperatures in naturally and mechanically ventilated buildings. They were developed for calculating heating loads with radiant systems and provide good estimates of combined radiant and air temperatures (Rees et al. 2000). An example of a computer simulation tool that uses the admittance method is the Ecotect software (Square One Research 2008).

Time-domain response function methods as well as numerical methods, evolved into the heat balance method. The heat balance method is suitable for the evaluation of cooling needs to be met by air based systems. It was developed aiming at the control of the internal temperatures using HVAC systems (Rees et al 2000) and nowadays is basically composed of different numerical method algorithms to solve the different parts of the problem. The older tools tended to uncouple the building from the HVAC system and solve things sequentially with no feedback from the building to the system and vice-versa (DOE 2007). An example of a computer simulation tool that uses these former heat balance methods is the DOE-2 software (Lawrence Berkeley National Laboratory 2008a).

New simulation tools are more integrated and solve the building and the HVAC equations simultaneously (DOE 2007). An example of a computer simulation tool that uses the integrated heat balance method is the EnergyPlus software (US Department of Energy 2007).

The heat balance calculation method is considered the most fundamental and comprehensive method but it is heavily computer dependent because of the large amount of iterations. It deals with the problem by having a group of algorithms to handle the outside condition and another group of algorithms to handle the inside condition. The outside condition is dealt by evaluating heat transfer through fabric and glazing (including solar radiation) and the inside condition is dealt by evaluating convection and radiation heat transfer models. Analogies with electrical networks are the starting point to develop the algorithms (Rees et al 2000).

Figure 5.13 provides an illustration of the overall structure of the heat balance method as well as the nodes of interest at which the heat balances are calculated. From Figure 5.13 it can be seen that the basic elements of the heat balance methods are: the outside surface heat balance, the inside surface heat balance, the air heat balance and the conduction processes that connect the outside surface heat balance to the inside surface heat balance (ASHRAE 2005).

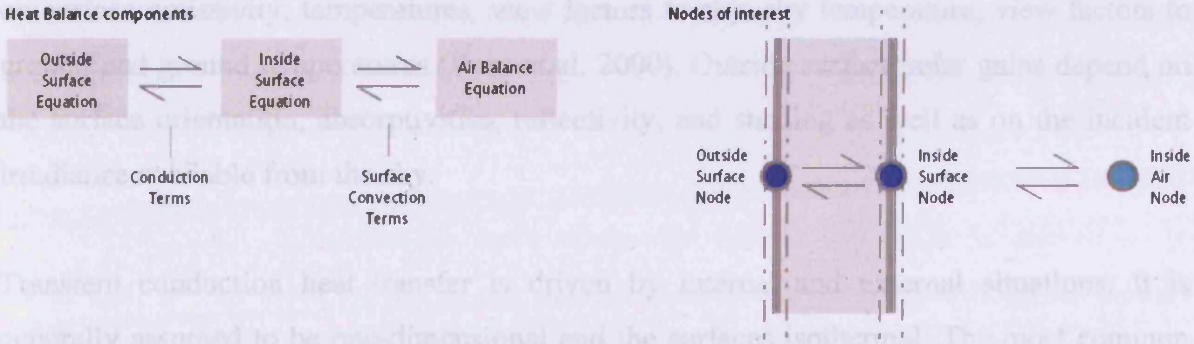


Figure 5.13 - Diagram of heat balance components and nodes of interest

Figure 5.14 provides a full description of each of the three heat balance equations individually from which it can be seen that the surface heat balance equations involve convection, radiation and conduction heat transfer processes and the air heat balance equation involves convection heat transfer, mass exchanges and HVAC delivery. The two surface heat balance equations are coupled by conduction heat transfers through the building envelope. Thus the heat flux from one side of the wall to the other is not governed by the air temperatures but by the surface temperatures. Flux and temperature calculations have to be dealt in a simultaneous condition (ASHRAE 2005).

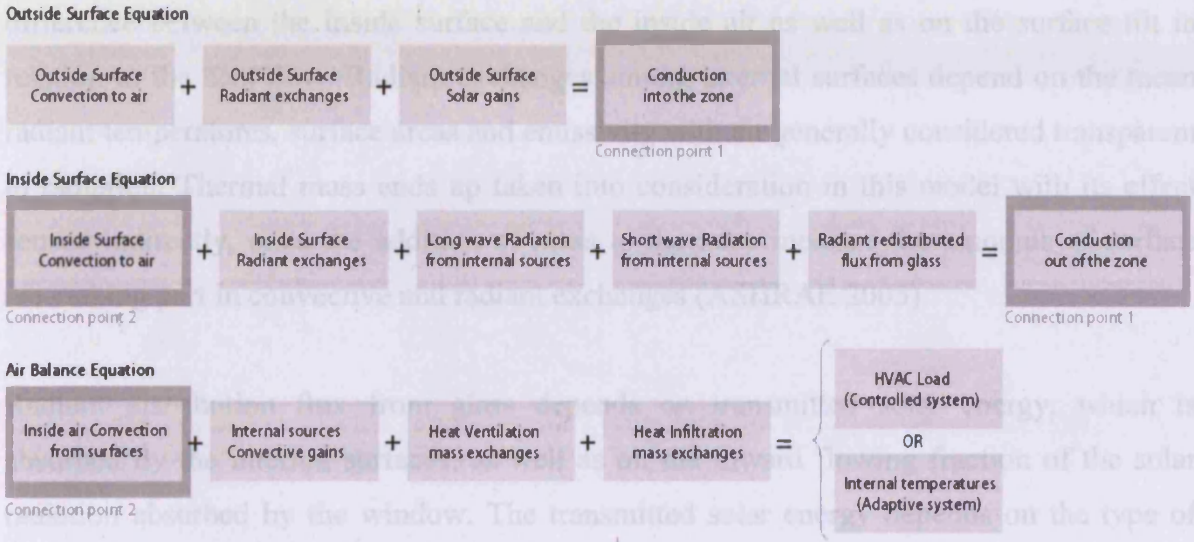


Figure 5.14 - Diagram of each heat balance equation

Outside surface heat balance equation deals mainly with convection and radiation heat transfer processes. Convection from the external surfaces to the outside air is dependent on the surface properties, wind speed and on the temperature difference between the outside air and the outside surface. Long wave radiant exchanges with the outside surfaces depend on surface emissivity, temperatures, view factors to sky, sky temperature, view factors to ground and ground temperatures (Rees et al. 2000). Outside surface solar gains depend on the surface orientation, absorptivities, reflectivity, and shading as well as on the incident irradiance available from the sky.

Transient conduction heat transfer is driven by internal and external situations. It is generally assumed to be one-dimensional and the surfaces isothermal. The most common algorithm used for the solution is the CTF (Conduction Transfer Function) which models the transient conduction considering internal and external excitations simultaneously. The algorithm also relates the actual heat flux across the surfaces to the current values of inside and outside surface temperatures, the past values of inside and outside surface temperatures and the past values of inside and outside surface fluxes. Specific coefficients are calculated for any combination of material layers without including the inside and outside surface conductance (Rees et al 2000).

Inside surface heat balance equation also deals mainly with convection and radiation heat transfer processes. Convection from surfaces to inside air depends on the temperature difference between the inside surface and the inside air as well as on the surface tilt in relation to the heat flow. Radiant exchanges among internal surfaces depend on the mean radiant temperatures, surface areas and emissivity with air generally considered transparent to radiation. Thermal mass ends up taken into consideration in this model with its effect sensed indirectly, once the addition of mass to the zone increase the amounts of surface area taking part in convective and radiant exchanges (ASHRAE 2005).

Radiant distribution flux from glass depends on transmitted solar energy, which is absorbed by the internal surfaces, as well as on the inward flowing fraction of the solar radiation absorbed by the window. The transmitted solar energy depends on the type of glass, the SHGC (Solar Heat Gain Coefficient) and on the incident irradiance.

Internal gains have a convective portion that contributes instantaneously to the air heat loads and two radiant portions (short wave and long wave portions) that, once uniformly distributed over all the interior surfaces of the zone, are both transformed into surface heat fluxes that are part of the inside surface heat balance equation. Heat transfer through mass exchanges such as ventilation and infiltration are assumed to be instantaneously mixed with the zone air and unless specific air flow models are provided within the tool, tend to be input directly by the designer in terms of volume flow in a specific time interval.

The HVAC loads calculated, in cases where the system behaviour is chosen to be controlled, are the result of the energy needed at each time interval to keep the internal temperatures within a specific predefined range of set points. If the system behaviour is not controlled, the resultant of the air heat balance equation is null as the inner environment temperature is allowed to vary at each time interval adaptively, responding to temperature variations in the outside environment.

The heat balance programming routine is used to describe all the elemental models and all the connections between these elemental models from the information contained in the design of a building. An overview of the whole structure of a building interpreted as a thermodynamic system is presented in Figure 5.15 with the building design information relevant to evaluate the building behaviour (inputs), the topology of the mathematical model of this thermodynamic behaviour and the resultant behaviour of the system (outputs). This behaviour is expressed in terms of heat fluxes and temperatures at specific time intervals for the building internal environment and the temperature differences as well as the heat flows across the system are topologically represented by the connections displayed in red.

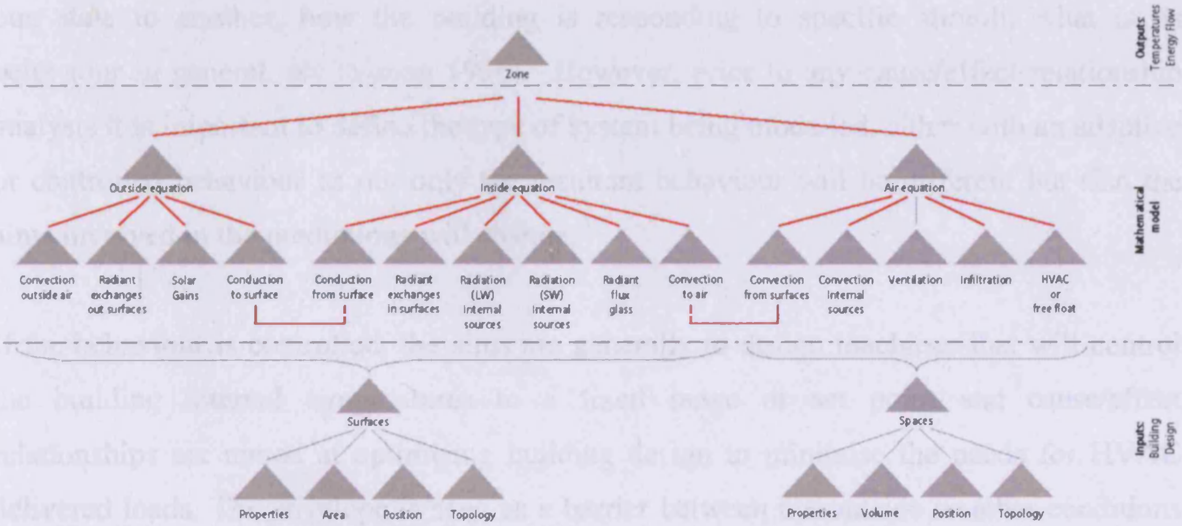


Figure 5.15 – Diagram of the whole structure of a building thermodynamic system

As can be seen from Figure 5.15, a building thermodynamic system is an extremely complex system in which the parts are heavily interconnected and cannot be studied in isolation. The response depends not only on the relationships among the parts but also on the intensity and history of variations in temperature differences over time. The behaviour thus cannot be evaluated intuitively. As the input information to these models varies in every building design, because it depends on surfaces and internal spaces properties, area, volume, position and topology, the resultant building behaviour is always something completely unique.

5.5. Building physics practice: prediction/evaluation cycles and design tools

The relationships between building design, context and usage information (inputs) and the resultant building behaviour from this specific design (outputs) are extremely complex, and almost impossible to evaluate without the help of sophisticated mathematical models. The models allow the mapping of thermal building physics design problems onto known problem-solving structures in which techniques to identify cause/effect relationships or design tools that deal with prediction/evaluation cycles between building design, context and usage information (inputs) and building thermodynamic behaviour (outputs) can be applied.

Many aspects can then be considered while designing a thermodynamic system such as limits of performance, maintenance conditions while performing in a given state, shift from one state to another, how the building is responding to specific stimuli, what is its behaviour in general, etc (Simon 1996). However, prior to any cause/effect relationship analysis it is important to define the type of system being modelled, either with an adaptive or controlled behaviour as not only the resultant behaviour will be different but also the aims involved in the predictions will change.

If the behaviour is controlled, the aims are generally to design machines that will control the building internal temperatures to a fixed range or set point and cause/effect relationships are aimed at optimising building design to minimise the needs for HVAC delivered loads. The envelope is seen as a barrier between the outside weather conditions and the artificially conditioned space and defensive design options will be preferred. Lots of investments in time and money are made in optimizing the machine (mainly the HVAC distribution system), controls, set points etc. and improvements in the building envelope are only worthwhile if the consequences of them impact in reducing HVAC capital costs (SERI 1985), though running costs and performance are now also becoming considerable factors as environmental issues become important.

If the behaviour is adaptive, the aims are generally to provide advice about how to achieve comfortable temperatures inside the building without it being artificially controlled and cause/effect relationships are aimed at designing for the achievement of comfortable inside conditions so that the envelope and form are seen as filters that balance the positive and negative influences of the weather and inside usage (SERI 1985). As form and envelope have to filter and distribute available energy sources in the interior according to occupants needs, reject the unwanted heat and repel detrimental climatic effects, the building needs to be studied under a range of design conditions (SERI 1985).

Although SERI 1985, is very strict about an upfront definition of the type of system involved in the analysis one has to understand that this definition does not need to be kept constant for the whole period of time being analysed. The type of system can vary at every pre-specified time interval so that an overall hybrid condition is the case. This hybrid condition generally consists in using HVAC as supplementary to an adaptive situation, implying that inside controlled conditions are only applied once comfortable conditions cannot be achieved by maximizing or minimizing weather effects through the building envelope and form.

Once the type of behaviour is defined, aims can be established and cause/effect relationships for specific states and actions evaluated. Ultimate aims tend to be clear and are generally connected with improving overall performance or behaviour. The designer needs then to establish, based on specific problem interpretations, the state of the desired situation in order to be able to set up the differences between the present situation and the desired state of affairs so that actions that remove these differences can be established. "We pose a problem by giving the state description of the solution. The task is to discover a sequence of processes that will produce the goal state for an initial state" (Simon 1996). Progress happens when the differences between desired state and initial state are reduced.

However, because differences between the desired state and the initial state can be reduced through several, most of the time, infinite ways it is not possible to establish a search through a vast maze of possibilities for a sequence of actions that would best reach the desired situation. The search needs to be selective, reduced to manageable proportions and assumptions about the search strategy to find a specific solution path need to be made (Simon 1996).

Assumptions about search strategies are totally problem specific and might rely on trial and error or guessing, experience, experiment or programming routines. In trial and error or guessing various paths are tried. Generally the search starts with an axiom of previous references and transformations are undertaken until a path that leads to the goal is discovered. When rules of thumb, heuristics methods, analogies or similar paths are used the search is seen as based on experience.

Design tools such as sensitivity analysis tools, elimination parametrics, factorial simulations and Monte Carlo simulations or optimization algorithms, genetic algorithms and cellular automata are programming routines that either act like experiments or establish iterative prediction/evaluation cycles.

Sensitivity analysis consists basically of altering building design parameters (inputs) to measure the consequent effects on the building behaviour (outputs). The aim is to mathematically relate input parameters with output parameters through the definition of sensitivity coefficients. Although sensitivity analysis can be undertaken by varying the initial conditions, varying input parameters and/or varying functions that are part of the mathematical models that describe the behaviour of the system (Tomovic 1963) the second type of sensitivity analysis is by far the most commonly used.

Parametric sensitivity analysis can be used either to look for parameters that significantly change the outputs when disturbed, even when the disturbances are small, or to understand the way input parameters propagate through the model causing a large variation in the outputs (Hamby 1994). It is generally conducted by assigning ranges of values or even functions to input parameters, "assessing the influence or relative importance of each input/output relationship" (Hamby 1994). Tomovic 1963 discusses sensitivity analysis in depth, and includes several mathematical models to derive sensitivity coefficients, Hamby 1994 provides and overview of the most common sensitivity analysis methods in Lomas and Eppel 1992 together with MacDonald 2002 discuss applications to building thermodynamic simulation problems providing examples.

Parametric runs or differential sensitivity analysis are calculations in the effect of independent individual input parameter variations (MacDonald 2002). A base model in which all input parameters receive average values is set, followed by several models in which each parameter is varied individually, generally to a minimum or maximum value, so that any difference in behaviour in each model is entirely due to the parameter varied. This model does not take into account interactions between parameters as only one parameter is varied at a time.

Elimination parametric is a method in which variations in the building behaviour are assessed by eliminating one parameter at a time. A base model in which all input parameters receive values as designed is set. After that several models are simulated eliminating one parameter at a time, checking the overall system reaction when doing it in attempts to identify which parameters are dominating the process (SERI 1985). This approach is actually very useful for design as it does not require multiple runs to provide an overall idea of which are the most important parameters affecting the building behaviour.

Factorial analysis is a type of sensitivity analysis that takes into account interactions between parameters by undertaking simulations for all possible combinations of parameter variations. This strategy is only efficient when the number of parameters is small as the number of simulations will depend on the number of parameters being varied as well as on the number of variations attributed to each parameter. The method is more suitable to identifying critical parameters rather than quantifying output effects (MacDonald 2002).

Monte Carlo methods also account for interactions between parameters but by relying on a statistical analysis of the results from generally 80 simulations in which the parameters have been varied randomly. In this method each input parameter is described by a probability distribution curve and the simulations proceed by "randomly generating perturbed models which lie within the distributions defined for the input parameters" (MacDonald 2002). The result is a probability distribution for the overall system performance. "Different designs can be compared statistically to test the significance of a design alteration" (MacDonald 2002).

In optimization algorithms "all alternatives must be measured in terms of a common utility function" (Simon 1996). This utility function is similar to a "natural" law for the problem and is created in order to allow the evaluation of alternatives to be quantified. The programming routines, such as GenOpt or ArtDot (Lawrence Berkeley National Laboratory 2008b and Mourshed, Kelliher and Keane 2003) will then find admissible values for inputs that maximise this predefined utility function. However, optimization processes are not always possible to be used as generally the routines deal with few parameters and only a couple of utility functions.

In genetic algorithms, computational models that mimic the process of evolution, or cellular automata, systems able to self-reproduce, there are algorithms to control the evolution or self-reproduction mechanisms that generate solution alternatives until the desired state of affairs is reached. The approach in this case might be axiomatic as the designer has to work directly with the criteria used to set up rules for the evolutionary or self-reproductive processes to happen.

Simulation tools provide solutions for mathematical models that imitate building behaviour, "to work out the implications of the interactions of the vast number of variables to predict how the assemblage proposed will behave" (Simon 1996). They are therefore predictive/causal tools. They allow the problem to be interpreted under the law of natural sciences and are suitable to be connected with design tools that test and evaluate cause/effect relationships. Interpretations of behaviour require specialized scientific knowledge that, although provided by specific handbooks (Waltz 2000), are based on learning the theories and techniques of applied sciences and developing the skills to solve concrete problems by learning to model unfamiliar problems on familiar ones (Schon 1991).

After mapping cause/effect relationships the problem becomes clearly defined. Schon 1991 states that cause/effect relationships are mapped as instrumental, leaving the designer to decide and test possible search strategies. However, once the input/output model is there, an objective function, which measures performance, can be defined together with a "set of possible strategies of action and a range of techniques for implementation" (Schon 1991). The challenge in problem solving resides in discovering a process description of the path that leads to the desired goal, i.e. defining means to ends by developing correlations between goals and actions to achieve the goals (Simon 1996). The solutions are most of the time deterministic as the search for them depends on the problem structure (Simon 1996).

5.6. Design problem-solving in building physics: well-defining the ill-defined

By understanding how the simulation community is structured to deal with building thermodynamic problem solving it is possible to see that the body of theoretical and methodological beliefs to use and interpret simulation results relies on general system theory which provides the conceptual level for setting up the structure, representation and actions to be undertaken.

Although general system theory is not necessarily procedural per se it does open possibilities to be applied in a procedural manner as the paradigm not only determines how to solve problems but also how to state problems.

The construction of the thermodynamic problem-solving structure is illustrated step by step through successive structural diagrams that explore the articulations of the parts and their interactions with each other and the whole. This structure can easily be taken as a map of interactions and provides the foundations to represent phenomenological laws believed to be true (Hacking 1983). The laws are represented through mathematical models, "intellectual tools that help us to understand phenomena and build bits and pieces of experimental technology" (Hacking 1983).

As "the paradigm theory is implicated directly in the design of the apparatus able to solve the problem" (Kuhn 1996), models are transformed into tools. The tools are suitable to predict how buildings will behave and hence cause/effect relationships can be explored. Further algorithms are then developed to test and explore cause/effect relationships, determining which problems are the most significant ones to be solved and/or guiding design actions.

The paradigm implies a procedural approach to problem solving once it starts with a well-defined design proposition to be evaluated with regards to how well it responds to the natural world and vice-versa in order for it to be judged according to its value. This response is quantified through the use of simulation tools. These tools are developed based on natural science principles rather than on design problems, they are therefore predictive and can only be applied on a well-defined object.

Once the response is quantified it needs to be meaningful and so it is compared with a reference, generally a desired situation to be achieved. The design aim becomes pretty much straightforward: to work on the difference between the reference situation and the proposed one through actions that involve correction, intervention or new propositions. Guidance in these actions can be achieved with the use of design tools such as optimization methods, sensitivity analysis, evolutionary processes, etc.

Both techniques to identify cause/effect relationships or design tools to set up iterative predictive/evaluation cycles are connected with simulation tools and need not only a well-defined object but also a well-defined set of criteria for actions.

The whole description of problem-solving implies a procedure to be applied on a well-defined problem. Professionals are trained to map a proposition into an existing model, predict its behaviour, and judge its value by comparing it with a predefined reference and act towards an aim that improves the proposition. Overall, general system theory is the worldview underlying building physics design problem-solving paradigms, mathematical models are the main representation systems used to build up simulation tools and highly procedural practices in which prediction/evaluation cycles direct and control design moves are the norm (Figure 5.16).

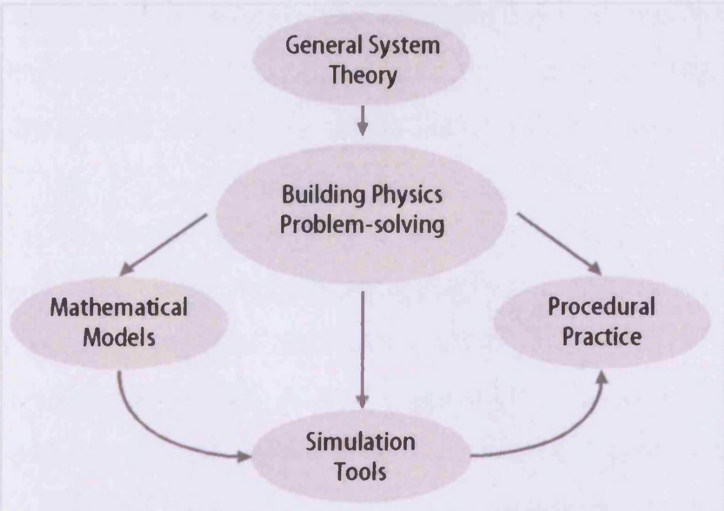


Figure 5.16 – Clear and rational proposition of design problem-solving in building physics.

Once the design as a whole becomes something procedural, the strategies for problem-solving become deterministic as there is no contestation or debate about the problem-solving structure, its models, its performance aims and the methods for providing solutions. As concepts cannot be invented independent of a context (Kuhn 1996), a false atmosphere of neutrality is created in which instrumental theories and methods are applied assuming to be universal truths.

Whether this paradigm and its implications in representation systems, computer tools and practices might be debatable or not with regards to its applicability to natural science problem-solving, it is certainly controversial with regards to its applicability to building design problem-solving. In order to start illustrating the controversies, the next chapter starts with a similar structure of analysis to debate design problem-solving in architecture. The multiple worldviews involved in building design problem-solving paradigms and the consequences of them in representation systems, computer tools and practices are discussed in detail in chapter 6 which refers to design problem-solving in architecture.

6. DESIGN PROBLEM-SOLVING IN ARCHITECTURE

"Architecture is not a given – like gravity. It is a contested site of meanings and conceptualizations. There is a struggle to define the field of knowledge. In this sense architecture is war – intellectual war, class war, cultural war over the right and the space to make decisions about the arrangements of the physical environment, about who controls the shaping of the built world" (Ward 2008)

The aims of this chapter are to understand how the building design community is structured to deal with design problem-solving, and why this community sees it as something subject to multiple interpretations.

In order to meet these aims, the focus of the chapter is not on architecture history and theory but on the reasoning underpinning building design problem-solving paradigms and how these paradigms affect and get affected by representation systems, computer tools used for designers while designing as well as design practices.

As the body of theoretical and methodological beliefs to interpret the community viewpoint is far from being a single one, the chapter will start with an overview of the main philosophical discourses underlying building design. Rationalism, the basis for design science to exist, is the focus of the philosophical discussion. Contrasting viewpoints, mainly based on pragmatism and post-modern discourses, are then introduced to either criticise or reinforce rationalist concepts. Recourse to philosophy is seen to be necessary as it will illustrate the diversity of theoretical and methodological beliefs the building design community uses as well as provide the context to set up the debate about building design problem-solving paradigms.

The short descriptions of the main philosophical discourses underlying design problem-solving paradigms in architecture is also used to discuss representation system used for designers to manipulate and work upon design problems, the role of the computer in building design problem-solving as well as the different descriptions of the design process itself., i.e. the different types of design practice.

An overview of design problem-solving paradigms in architecture is finally provided relating this specific design activity with the previous design domain-independent discussion from chapter 4.

6.1. Is there an overall philosophy behind building design?

Building design problems are 'indeterminate' and 'wicked' "because a design has no special subject matter of its own apart from what a designer conceives it to be" (Buchanan 1995). This subject matter, although potentially universal in scope needs to be discovered or invented by the designer out of the problem and its specific issues. Different solutions, different arguments and methods used to reach these solutions are explored, determined consciously or unconsciously by different philosophies.

Although, this might indicate an open mindedness with regards to problem-solving, a review of the literature about design science indicates some dominant philosophical discourses behind the different approaches to building design. As a consequence, "the history of design is not merely a history of objects. It is a history of changing views of subject matter held by designers and the concrete objects conceived, planned and produced as expressions of those views" (Buchanan 1995).

The overview of the main philosophies behind building design problem-solving starts with the main philosophical discourse underlying the science of design since its beginning in the 1970s, i.e. the Rationalism. It explores criticism of and the different reactions to, the rationalist position ending with a brief introduction of pragmatism and other post-modern theories.

6.1.1. The Rationalist viewpoint

The rationalist point of view in design science is mainly based on structuralism and general system theory. It set up the basis for design to become a discipline in itself in the 1970s with the emergence of design theories and design methods, lately evolving to the study of computing and cognition in design learning.

The main assumption underlying a rational viewpoint is the separation between what is subjective and what is objective, in which the subjective is to be dealt by the arts and individuals whereas the objective is the focus of sciences. The objective part can be further separated into theory and practice in which theory is about abstraction and practice is about what works in the context of human activity. Practice follows theory and is not a primary concern to rationalists (Coyne 1995). Therefore rationalism preaches minimal user participation, as social groups can be sources of error and prejudice; with experts having access to theories and the know-how to deliver them. Practice is a "matter of involvement in community"; it is about applying theory to a context (Coyne 1995).

Rationalism focuses on the development of objective theories applying scientific methods. The major concerns are identifying the fundamental entities in each situation, analysing how these entities interact with each other, and then examining what questions might legitimately be asked about such entities and what are the techniques employed in seeking for solutions (Kuhn 1996). Theories express regularity of phenomena of interest, which are corroborated from observations and experiments; "systematic rules can then be used to draw logical conclusions" (Winograd and Flores 1986). These rules are de-contextualised, procedural, have a small number of variables and are used mainly in predictions. Theories, methodologies and assumptions are used to "explain the operation of deterministic mechanisms whose principles can be captured in formal systems" (Winograd and Flores 1986).

Besides that, rationalism separates means from ends, "means (technologies) are subservient to ends (human needs)" (Coyne 1995). Technologies are developed to address needs, they are therefore subservient, and the way they present themselves in a work context is largely a matter of interface (Coyne 1995). Once technology systems are separated from interfaces, the way they might be used can be considered after the system is designed (Coyne 1995). As a result, the priority lies on codifying knowledge and placing rules in a technology system without paying too much attention to how people will interact with it.

Rationalism elevates the mind over the body and believes that knowledge and information are capable of being stored and can be represented and transmitted. Cognitive models, knowledge representation, formalized procedures and generalisation of behaviour in terms of variables can all be codified and represented. Language and computer theories based on rationalism are centred in symbols which are "composed information patterns that stand for things in the world" (Winograd and Flores 1986).

Rational decision making and problem solving are about "choosing among alternatives according to an evaluation of outcomes" (Winograd and Flores 1986). Decision making is procedural and includes listing alternatives, determining, comparing and evaluating consequences of these alternatives by using sophisticated methods and models containing rules that describe behaviour, and are used as the objective means to evaluate results and compare alternatives (Winograd and Flores 1986).

Rationalism in design science

The application of scientific methods to design problem solving was the starting point of a proposition of a science of design in the 1970s. "Design methods began with rigorous prescriptions of how design should proceed" (Coyne 1995). Methods were objective scientific models based on rational determinism prescribing stages of activities (Rowe 1987). The basic framework was a three stage procedure: analysis, synthesis, evaluation; that would happen at each level of design detail, from problem setting to refinement. Design should progress from problem statement to solution to be evaluated against a problematic situation.

Methods break the problem into parts, proceed through logical deductions into new facts (geometrical proof), "iterate through the process to be sure nothing was left out" (Coyne 1995). Design methodologists believed that the complexity of a problem "can defeat us unless we find a simple way of writing it down, which let us break it into smaller problems" (Alexander 1971). The whole idea behind design methods was not to be arbitrary in choosing the formal order, something that could be achieved if the problem was clearly understood. "Design methods also involve the numeric and symbolic formulation of design tasks to facilitate simulation, (modelling how a design will perform) and optimization (generating 'the best' design from a range of possible designs)" (Coyne 1995). The whole process needs to become open to inspection and critical evaluation, this process needs to be documented so that it can be criticised and replicated (Lawson 1997) therefore an extensive use of process diagrams to make the design process objective and explicit was the norm.

Most of the methods evolved as guides for practice rather than prescriptions (Coyne 1995), and are mainly used nowadays for management purposes and design teaching. Hierarchical structures and "loosely formed rules, the application of which required a sensitivity to the context" (Coyne 1995) evolved to environmental design models or models based on behaviourist psychology and operational research (Lawson 1997).

Rationalism in architecture

Rationalist ideas applied to architecture refer to "a hypothesized society or interpretation of man and his world" (Rowe 1987). Functionalism and Modernism developed a 'science of man' based on analogies with methods of natural sciences (Rowe 1987) to be applied to architecture. Orthodox ideas were "founded in an ardent and powerful conviction that there is a structure underlying all human behaviour and mental functioning" (Rowe 1987). Apart from the structure, there was a strong belief pervading the modernist doctrine stating that form should follow function which resulted in a mechanistic aesthetics accused of not taking symbolism into account.

Apart from that, further examples of applications of a rationalist discourse to architecture can be found in recent formalist theories in which a shape grammar system codifying design language with a hierarchical structure "starting with spatial descriptions of the world in terms of points, lines, planes and labels" (Coyne 1995), a discipline grid and a system of transformations. Additionally, a lot of the rationalist discourse can be seen in applications of computer tools to assist the design process or are used to understand design with regards to the cognitive aspects involved in it.

Rationalism in cognitive science

Cognitive science aims to unify theories of human thought and language (Winograd and Flores 1986). It is a mixture of linguistics, psychology, artificial intelligence and philosophy of the mind. It has its basis in rationalism because its main characteristic is the assumption about outside and inside cognitive experiences. Inside experiences are related to 'internal knowledge' and outside experiences are related to the 'world knowledge' in which you retrieve information about the outside world through memory. Additionally, cognitive sciences use most of the elements from artificial intelligence:

(i) A task environment composed of states, actions and goals;

(ii) Internal representations, a collection of symbols that represent the task environment;

(iii) Information processes, a search among alternative courses of action that lead to the desired goal and

(iv) Bounded rationality, heuristic guides to short cut the computing of alternative courses of action.

In artificial intelligence knowledge is made explicit as procedures, rules, frames or semantic networks, and the operations to be undertaken by the problem solver are searches "in a problems space determined by the task environment and internal representations" (Winograd and Flores 1986).

Cognitive processes are understood by analogy to programmed computers. They are symbol systems that can be codified, represented and transformed into a computer program that "when run in the appropriate environment will produce the observed behaviour" (Winograd and Flores 1986). Cognitive science is "the newest science of the artificial" (Winograd and Flores 1986) and it influences the new science of design learning in which the aim is to understand how designers solve design problems. The focus is on structure of knowledge, teaching and learning methodologies, not on design problem-solving structures (Eastman et al 2001). That is why examples of applications of cognitive science to design concentrate on studies about learning based on prior knowledge up to the exploration of cognitive phenomena in design, from reasoning to representation.

Learning based on prior knowledge in design means basically using personal accumulated knowledge together with external references to create a representation of the problem structure in order to understand it. Researchers in this area generally focus on the early design stages using educational constructivist theories as a basis. Some examples that emphasize design learning, stating that the most important thing in design is what the learner already knows, can be found in Atman and Turns 2001, Kokotovich 2008 and Wendy, Newstetter and McCracken 2001.

Cognitive models in design are models of human reasoning and perception which try to model what design is in an abstract way (Coyne 1995). "Designing involves building up complex networks of such generic descriptions through experience, matching new situations to schemas, navigating through these schemas by considering inheritance and component linkages, and implementing rules and problem solving strategies associated with instantiations within schemas" (Coyne 1995). The models are structuralist, do not take into account the context, and are tied to the individual and cognitive neuroscience brain-functioning mechanisms.

Descriptive models of design for research, education and practice, using this approach are developed by Akin 1986 and Oxman 2001. The first author proposes the theoretical basis for understanding design from empirical studies, calibrate the components of an information processing model (containing representation, problem-solving and knowledge), simulate the human cognitive behaviour to evaluate the proposals and discuss successful CAD interfaces and approaches to education. Whenever design problem-solving is viewed through the eyes of information processing, decisions are made towards the fulfilment of objectives. Causal relationships for goal driven systems and cognitive behaviour are dependant on knowledge acquired by the problem solver to deal with each specific problem context. The second author explores categories of cognitive phenomena in design based on representational schemes and operations with a focus on virtual reasoning with mental images and visual representations.

Creativity challenging rationalist ideas

However, whilst "the essence of thoughts can be described in terms of formulas, production rules and axioms in practice calculus, able to be processed through context-independent and unprejudiced reason" (Coyne 1995), creativity is extremely difficult to be captured. "Creativity is evident where we are not merely mapping goals and plans to situations through readily articulated knowledge" (Coyne 1995). Creativity is the type of internal knowledge that cannot be represented through cognitive models. Attempts have been made by Akin and Akin 1996 who analysed the cognitive capabilities that underlie creative insights and the conditions for it to happen in order to measure and model this behaviour. They proposed a computational model to better understand creativity, to act as a support in problem framing which help designers to identify sudden mental insight strategies through the analysis of the problem and the frame of reference that constrains it. Akin and Akin 1996 computational models use shape grammar and heuristic methods to match problem states with breakout strategies together with heuristic rules to help with recognizing creative and unusual solutions.

Another example of a study about creativity is provided by Csikszentmihalyi 1996 which undertook systematic studies of around 100 creative individuals. Although in earlier studies (Csikszentmihalyi 1992) seemed to be extremely compliant with rationalist ideas, by stating that optimal experiences depend on skills one possesses to "cope with challenges at hand, in a goal-directed, rule-bounded action system that provides clear clues as to how well one is performing" (Csikszentmihalyi 1992), he acknowledges that creativity is extremely complex.

In Csikszentmihalyi 1996, he tries to analyse the creative process, the lives of creative individuals and the different domains of creativity, concluding that creative individuals actually have complex personalities in which dialectical tensions such as: playfulness and discipline, imagination and rooted sense of reality, extroversion and introversion, aggressiveness and cooperativeness, pain and enjoyment, tradition and rebellion, passion and objectiveness, etc. occur all the time. The dialectical tensions conform to the rationalist viewpoint.

The dialectic personality, together with an interest in the domain and a sense of curiosity, make individuals become deeply involved in a subject matter in which the 99% of perspiration they devote to it is actually allied to a playful adventure in which they hold on to what is known and at the same time pursue an ill-defined truth.

Overview of rationalism applied to design problem-solving

In the rationalist approach, understanding can be articulated as formulas, process diagrams, charts, tables and lists. Statistical analysis of behaviour is used to set up and design computer systems. The main assumption is that it is valid to reduce complex human behaviour to measurements as variables are objective, means are independent from ends and experiment is detached from the situation (Coyne 1995). Architecture, cognitive psychology, artificial intelligence and learning theories under the rationalistic tradition believe in the existence of an underlying structure, centred in symbols of information patterns. This underlying structure is context independent and metaphysics.

6.1.2. The criticism of rationalism

A major criticism of rationalism concerns the dialectics of what is subjective and what is objective, what is theory and what is practice, the separation of means from ends and the consequences of decontextualisation together with the assumptions behind underlying principles and structures.

The fact that some fundamental problems cannot be described by mathematical techniques available and that it is very difficult to handle problems creatively with systemic thinking is pointed out by Von Bertalanfy 1969. However, the fact that models can be very useful even when not mathematically expressed and that systemic thinking provides explanations 'in principle' about structures and organisation (Von Bertalanfy 1969) is considered sufficient to guide research in many subject matters to a point of which Von Bertalanfy 1969 calls attention to the fact that, many times, the application of systemic thinking results in meaningless analogies and is purely an extension of the mechanistic view it tries to replace.

Critics of systemic thinking will go deeper in their analysis of the proposition of structures and principles, stating that "the fact that design does not comply with the tenets of general system theory is taken as a statement about design rather than a pointer to the inadequacies of system theory or its applications" (Coyne 1995). There are difficulties in distinguishing subjective knowledge from objective knowledge, because things are involved in a context even if 'objective'. Formulations are therefore problematic and goals are generally elusive.

Rationalism ranges from objective existence through problem-solving not taking into account the way problems are formulated and particularly not taking into account the problem context and the problem interpreter (Winograd and Flores 1986). Different interpreters will result in different problems, potentially the use of different tools, different actions and, as a consequence, different design solutions (Winograd and Flores 1986). Knowledge and understating do "not result from formal operations on mental representations of an objectively existing world... they arise from an individual's committed participation in mutually oriented patterns of behaviour that are embedded in a socially shared background of concerns, actions and beliefs" (Winograd and Flores 1986). Systemic thinking and structuralism advocate the study of structures without understanding or questioning these structures, i.e. "rationalism largely ignores the social and prejudicial nature of its own understandings" (Coyne 1995).

The majority of the work about design discussed so far in this thesis does not pay much attention to the context and the content of the problem and the emergence of the solution. Very little is found about an explanatory framework that considers why the observed patterns occurred (Kees 2008). Content and context will influence knowledge about what is pertinent and what is not. "Knowledge is culturally situated and socially distributed as well as personal" (Bucciarelli 2001) and it depends on linguistics and social resources. Context dependent knowledge is partly theoretical, partly experiential and partly social (Bucciarelli 2001) with unclear boundaries among these parts. Thus the dichotomy between theory and practice just reinforces decontextualisation.

In architecture theory the distinction happens between form and symbolism. The idealisation of the primitive and elementary happens at the expense of the diverse and sophisticated. There is a "separation and exclusion of elements rather than inclusion of requirements and their juxtapositions" (Venturi 1977). Modernism is about primary forms, distinct and with no ambiguity with high selectivity in determining which problems to solve. The "less is more justifies exclusion" (Venturi 1977) allowing architects to be selective in the problems they solve. Simplification for the purpose of analysis is misinterpreted by simplification as an aim with "forced simplicity resulting in oversimplification" (Venturi 1977). Architects determine how problems should be solved within a specific doctrine without thinking about what problems they will solve.

In practice rationalism, with its emphasis on standardised process and structure, puts enormous emphasis on the construction industry (Lawson et al 2003). The majority of the work is focused on design process (to increase the process efficiency), tools and methods (Kees 2008). The separation between nature and technology, meaning and resources, science and arts and symbolism and function together with a generalised trend of behaviour results in disconnections in knowledge and society manifested through an extreme compartmentalization (Bachman 2003) leaving for the post-industrial and post-modern era the challenge to expand the scope of professional thinking (Bachman 2003).

6.1.3. The different reactions to rationalism

" 'Solutions' are viable in their environment, but say nothing about a reality independent of it nor about their own approach to this reality (...) Isn't it rather the case that the 'solutions' presented in society determine what is viable as a problem?" (Jonas 1993).

The different critics of rationalism rejected it through the proposition of different paradigms. Some theories, for instance phenomenology, hermeneutics and pragmatism focused on criticising heavily the idea of structures and the dialectics of subjective/objective, theory/practice as well as the separation of means from ends. More vanguard movements such as critical theory and deconstruction, with an extremely political basis, focused more on criticising control mechanisms behind structures either proposing a different paradigm or simply sustaining a constant critical attitude.

Phenomenology and Hermeneutics
Phenomenology and hermeneutics challenged the rationalistic dialectics and decontextualization by acknowledging the role of interpretation to think, understand and act (Winograd and Flores 1986).

In hermeneutics emphasis is given to the interpretation of texts. "Reading or hearing a text ... constitutes an act of giving meaning to it through interpretation" (Gadamer in Winograd and Flores 1986). Interpretation is based on prejudices and on assumptions implicit in the language that the person uses and everything depends on cultural background, as this is what forms the way individuals experience and live their language. However, "the individual is changed through the use of language and the language changes through its use by individuals" (Winograd and Flores 1986). As a consequence, the way language is experienced as well as the cultural background behind it cannot be made explicit within themselves. The result is "we are always within a situation" without the possibility of recognizing its objective part (Winograd and Flores 1986).

In phenomenology, all meaning is contextual and depends on the moment of interpretation and the "horizon brought to it by the interpreter" (Winograd and Flores 1986). The dualism of subjectivity and objectivity, the separation of subject from object are denied by Heidegger and Gadamer who state that "We would not stand back and apart from the world in order to understand it (…) and what we normally regard as an objective position is nothing more than a position prescribed within a particular horizon sanctioned by conventions of modern science" (Coyne and Snodgrass 1991). "Any individual in understanding his or her world is continuously involved in activities of interpretation" (Winograd and Flores 1986) and "interpretation is conducted from a base of prejudices on the part of the interpreter" (Coyne and Snodgrass 1991).

There is no neutrality in viewpoint and "understanding will never be objective or complete" (Winograd and Flores 1986). But because "meaning is fundamentally social and cannot be reduced to the meaning-giving activity of individual subjects" (Winograd and Flores 1986) and "a person is not an individual subject or ego, but a manifestation of Dasein (existence) within a space of possibilities, situated within a world, within a tradition" (Winograd and Flores 1986), both discourses tend to be intrinsically conformant to the zeitgeist, the spirit of the time.

Phenomenology and hermeneutics discourses are accused of excluding and concealing inherent judgements and action in situated human practices, they are considered "aloof from current events" (Coyne 1995). There is no asking 'why?' no looking for causes as we are always considered situated within a language and background or within the idea of simply 'Being' which cannot be made explicit within themselves.

Hermeneutics attempts to understand how language, thought and action operate in themselves. It does not deal with models but with explanations and interpretations because it believes all situations are unique. Phenomenology reiterates this position; everything is a matter of interpretation, therefore it is indeterminate, contingent and with a varied formulation (Coyne 2005). The central problem of interpretation is actually a circle in which "what we understand is based on what we already know and what we already know is based on what we understand" (Winograd and Flores 1986).

In hermeneutics and phenomenology the objective of learning is understanding, and understanding is the appropriation of experiences. "The application of rules is a matter of experiences and it is therefore hermeneutical" (Coyne and Snodgrass 1991). "It is meaningless to talk about the existence of objects and their properties in the absence of concernful activities" (Winograd and Flores 1986). "Practical understanding is more fundamental than detached theoretical understanding" (Winograd and Flores 1986) because "we do not relate to things primarily through having representations of them" (Winograd and Flores 1986). There is no stable representation of the situation. Things emerge while under development, things are fragmented and it is up to the agent to structure them. Every representation is an interpretation. "There is no ultimate way to determine that any one interpretation is really right or wrong" (Winograd and Flores 1986). In this sense, hermeneutics and phenomenology also challenge the dialectics of theory and practice. They preach the union of means and ends. They treat the technological objects as commodities or devices and consider things "situated, corporeal and involved in human practices" (Coyne 1995).

Pragmatism

Conforming to the viewpoint of phenomenology and hermeneutics in criticising the rationalistic dialectics, pragmatism effectively proposes a paradigm to replace the duality of theory and practice and of means separated from ends. Pragmatism is all about action (Coyne 1995); "theory is just another kind of practice" (Coyne 1995); it is all practice (Coyne 2005). Pragmatism is mainly concerned with "the practicalities of human involvement, the materiality of the world, the interaction of the senses and the formative power of technology" (Coyne 1995). "All enquiries begin with engagement. Reflection can be defined as the process of going outside the immediate situation and it involves the search for an appropriate tool" (Coyne 1995). "The applicability of the tool is worked out in the situation" (Coyne 1995). Theory is subservient to practice and facts, ideas and concepts are all tools. "Rules, formulas, frames, plans, scripts and semantic networks are not forms of knowledge but tools for research" (Coyne 1995) because thinking and doing are inseparable and doing is more important then developing theories. Practice is about the means best suited to achieve one's ends and cause/effect relationships are instrumental (Schon 1991). In this sense the pragmatic orientation appears to be concerned with context.

Pragmatism is heavily "oriented towards an engagement with materials and technologies" (Coyne 1995) and sees the medium as the message "rather than merely the carrier" (Coyne 1995). It is centred in the generation of information and everything that "enhances the flow of information is seen as beneficial" (Coyne 1995), but "to speak of passing information in a situation is to strip the experience of its context" (Coyne 1995) and the liberal view in which information is provided for each person to make meaning out of it can actually be an illusion. Information is always generated within a context even if separated from it to be delivered. The speed, the amount, the type and the apparently decontextualised nature of the information provided gives the false impression that technology and media are neutral. In this sense, pragmatism might be paradoxical with regards to its approach to context and it is accused by more vanguard movements of being conservative when, like phenomenology and hermeneutics, it does not look for causes.

Critical Theory

Looking for causes is the kernel of critical theory (Frankfurt School) which provides a continuous critical approach to social transformations with its basis on questioning to unfold new dimensions of discourse (Coyne 1995). It criticises the abstractions, indifferences and lack of context of rationalism and the rationalist structures. Its aims are "identifying the various means of domination" (Coyne 1995) in structures and systems by recursively asking 'why?' and looking for causes.

Critical theory also challenges the separation between means and ends but, contrarily to pragmatism, it sees the medium as far from being neutral but an instrument of domination. As no distinction can be made between technique and value, technology cannot be seen beyond the ethical. "Concepts become instruments of prediction and control... and technology in itself embodies and reproduces this domination" (Coyne 1995). "Proposition settles the matter" (Coyne 1995). The over-valorisation of information has the aim to "universalise and homogenise human practice" (Coyne 1995); the illusion of differentiation, of choice and of freedom simply mask the promotion of conformity. Critical theory does not propose any kind of analytical model but sustains "a critical attitude, keeping alive the suspicion of totalizing arguments, philosophies, systems and technologies" (Coyne 1995).

Deconstruction

Similarly to critical theory, deconstruction, one of the most important and influential philosophies since general system theory is heavily critical. It started in the literature and philosophy as a radical response to structuralism and phenomenology from which its most important proponent, Jacques Derrida, provided a method to "show how the literary and metaphysical work works" (Benedikt 1991). Deconstruction's mission is the exposure of "how we bend the language to our will, transmitting meaning and creating presence" (Benedikt 1991).

The objective of deconstruction was to demonstrate the elusive nature of meaning and the contingency of intentionality. "To deconstruct a text is not to read it linearly, or even to criticize what it says by finding objections relative to some other view on the truth claims made. It is to analyse and question a text as a 'block'" (Benedikt 1991). Deconstruction believes the meaning is in difference. For Derrida "to focus on difference is to embark on limitless discovery" (Coyne 1995). Derrida's strategy of deconstruction was to uncover oppositions in the text that betray the thesis to show that actually the opposite was the case (Coyne 1995). Once the oppositions were identified they were deconstructed to challenge hierarchy.

As with phenomenology, criteria make sense only in an interpretative context and intention is constructed in this context. While structuralism is about similarities, deconstruction is about differences. Differences are revealing. Deconstruction sets up different dualities: between present and absent, between essential and supplemental and the essence of its discourse is to "keep the terms in play rather than fixing them" (Coyne 1995).

6.1.4. The collection of worldviews underlying building design problem-solving

This section (6.1) illustrated that there is no overall philosophy behind building design problem-solving but a collection of different worldviews influenced by science, arts and humanities.

The post-modernist discourses

At the conceptual level, there are discourses connected to phenomenology and hermeneutics in which "the existence of essences independently of the horizon or background within which the search for such essences is undertaken" (Coyne and Snodgrass 1991) is heavily criticised. What actually gives a place its character are the social, cultural, political and physical forces acting upon us while interpreting and appreciating a situation (Coyne and Snodgrass 1991). There are also deconstructivist discourses in which Derrida's ideas of deconstruction are interpreted from the viewpoint of the fine arts rather than directly translated from the original philosophical discourse.

Most of the hermeneutical, phenomenological and deconstructivist discourses are used to set up a paradigm of 'architecture as a language' in which self referential statements and a distinction between form and figure has become very much the issue. In these discourses form is "a configuration with natural meaning" (Rowe 1987) or no meaning at all, and 'figure' is "a configuration whose meaning is given by culture" (Rowe 1987).

The emphasis on meaning is used to dismantle "the confidence placed in the doctrine of 'form follows function" (Rowe 1987). The orientation is "architecture for architecture's sake" (Rowe 1987). Architecture is "seen in relationship to itself and its constituent elements" (Rowe 1987) with the architectural object as the locus of enquiry. Architectural objects and organising compositional principles distinguish architecture from other disciplines (Rowe 1987). There is a "shift towards the world of architectural 'objects' and the use of its constituent elements as the primary focus of design" (Rowe 1987). Since Venturi 1977 demonstrated that the meaning of a building could be separated from its function, and that its public image need have very little connection with the technological content of its design" (Ward 1989), then image is what matters and it became the ultimate criterion against which good design was assessed.

Application of the hermeneutical circle then refers to aesthetics. "The relations of the parts to one another and to the whole constitute an essential aspect of their character as parts... and of the character of the whole" (Rowe 1987). "We cannot perceive the meaning of a part until we have grasped the meaning of a whole" (Hirsch 1967 in Rowe 1987). The process is circular "neither the parts-side nor the whole-side is totally determined by the other" (Rowe 1987) and for meaningful interpretation to ensue, the circle must not be a vicious one" (Rowe 1987). There is a dialectical relationship between the parts and the whole, both whole and parts need to be apprehended and understood for the architectural object to have meaning.

Everything becomes about form and meaning. "A valid architecture evokes many levels of meaning and combinations of focus; its space and its elements become readable and workable in several ways at once" (Venturi 1977). Complexity and contradictions are a special obligation towards the whole (Venturi 1977). In this same frame of mind deconstructivism is relegated to the aesthetic level mainly (Donn 2004) with "the excitement of a building lying in the difference between systems of order imposed on it, the destruction of the grid, and the deviations from regularity" (Coyne 1995).

In this sense, post-modernist theories "avoid discourse that trades in symbols and numbers other than for very pragmatic uses" (Coyne 1995) and are sceptical about universal principles mainly when they are extended towards human sciences and human cognition. References tend to be about "the building as an aesthetic object, a work of art" (Ward 1989) with a hyper-valorisation of the designer as a consequence. In the post modern age "architecture theories have fallen back upon the primacy of 'imagination', 'experience' and 'phenomenology'" (Ward 1989). There is a "primacy of self-expression, supported by a doctrine of value-relativity" (Ward 1989). There is an emphasis in the individual value expression with its basis on an egocentric value system. Aesthetics is reduced to looks, dressed up as art (Harris and Lipman 1989). The heart of theory, criticism and practice is the preoccupation with form. "Formalism, the currency of architectural thought, pervades modern as well as post modern discourse" (Harris and Lipman 1989) and architectural aesthetics have been reduced to the manipulation of formal effects (Harris and Lipman 1989).

The problem of understanding architecture as a language in itself is that another extreme is reached, the one of a complete subjectivism in which context and the background of the society involved in it are disconnected from the architecture object. In this sense meaning is paradoxical because it goes against Kunstgeschichte, in which a "concept is understood as having meaning only when we see it as an inherent part of the whole culture or age" (Capon 1983), as without social purpose it is difficult to imagine how a broad understanding of and meaning for architecture can be established" (Rowe 1987).

Apart from that, "architecture, like other cultural work ... can have a meaning independent of authorial intention and such meaning can change during the course of time" (Rowe 1987). Meaning is "that aspect of the designer's intention which, under architectural conventions, may be shared by others. Architecture is not a purely public object, whose character is solely determined by public norms ... many form-making strategies, axiomatically require a substantial measure of fixity of meaning; otherwise, the rhetoric and cultural continuity to which designers aspire would be totally ineffective" (Rowe 1987).

The pragmatic discourse

At the professional level the discourse is mainly pragmatic or, rarely, based on critical design theory. In the first case, the design "activity is immersed in practical concerns" (Coyne 1995). Design is a conversation in action activity in which designers can only gain understanding of what information is actually necessary by engaging in the activity. That is the way the designer becomes aware of his own prejudices, assumptions and also understands the scope, latitude and nature of the problem (Coyne and Snodgrass 1991). For the pragmatists "designers are not objective experts distant from the life and culture they are dealing with. The designer is also not the creative genius" (Coyne 1995). Practitioners deal with uncertainty, instability, uniqueness and values conflict. Knowing is in the practitioner's actions. Practitioners recognise phenomena without providing an accurate or complete description of them; make judgements of quality without being able to state adequate criteria; display skills without stating rules and procedures. (Schon 1991).

However, very few designers effectively incorporate research into their professional design practice. The whole practice is very oriented to become something to do with mass production and is organised similarly to an assembly line in which a network of consultants and experts are interconnected to materialise the 'object of design'. Donn 2004 suggests that architects quite comfortably acknowledge and accept an architecture oriented to nature and culture but do not think it is their job to understand the applications of these 'laws' to the design of their buildings. That means they passively conform to the fragmentation of the profession and the reinforcement of a structure with a well-ordered labour force skilled in the techniques of design, believing that their job is about dealing with meaning, understood as something beyond materialisation.

The criticism

In this context, critical design theory comes into place looking at design from a Marxist point of view interrogating "issues of fashion, consumerism, commodification, etc. as elements of a dynamic that is driven by the dominant culture in order to reproduce its own positions at the top of the social class" (Ward 2008) and proposing a different paradigm for practice. Critical design theory evolves and grows always criticising the current state of affairs, mainly what is critical at each specific moment in time. It believes that "all human beings shape the world and that in doing so they create themselves" (Ward 2008).

However, "in the modern capitalist society we have mostly been alienated from the capacity to shape our own world. That opportunity is taken from us by others – planners, architects, designers, politicians, developers and so on" (Ward 2008) and this is supported by an economy which transforms our capacity for creation into a capacity for consumption. In this context, critical theory preaches community design as an increase in public decision-making, in the creation of the physical environment. The ideology behind it is humanistic socialism and the theory is highly critical of postmodernism considering it reactionary and conservative.

"Efforts to separate form from content in architecture are but particular instances of the more general divorce of culture from society, of art from everyday life" (Harris and Lipman 1989). "The advent of post modernism has delegitimized the prior concern of schools with social and cultural aspects of design" (Ward 1990) making architects contribute to the propagation of the social, political and economic status quo by being omissive. The strong support for non-ideological, apolitical discourse and the transmission of social, cultural, economic and political values said to be value free, have in fact hidden agendas that come from tacit normative value structures from the social, professional and political milieu (Ward 1990). Knowledge is not neutral, it is produced and distributed according to particular voices and it is intimately related to power (Ward 1990).

For the criticizers, postmodernism "is the result of social, political and economic trends to which the profession of architecture has been increasingly subject to" (Ward 1990). It expresses the values of a professional elite deeply committed to the maintenance of its political and social power and aspirations (Ward 1990). The extreme preoccupation with meaning reinforces the division of labour and the mass production system of the construction industry. "Contemporary architectural practice is … an alienated practice: (Harris and Lipman 1989). It is drained of social content, particularity is ignored, occupancy is by-passed, history is overlooked and reality denied (Harris and Lipman 1989). It became "reduced to an alliance of taste and capital, of art and profit of style and power" (Harris and Lipman 1989).

The collection of worldviews underlying design problem-solving

From the previous discussion it was possible to see that rationalism, pragmatism and some post-modern theories are the main worldviews underlying building design problem-solving.

The discussion shown that although rationalism attempted to provide a unified worldview for building design, its criticism ended up originating different directions of thinking (Top of Figure 6.1). On one side, the reaction to rationalism was not inclusive; rationality was repudiated and irrationality celebrated through the claim that architecture design has never been rational even when claimed to be so (Ward 1989). On the other side, designers were free to go back into a defence of their work in the context of traditional arts and crafts (Buchanan 1995) once the activity is seen as immersed in practical concerns.

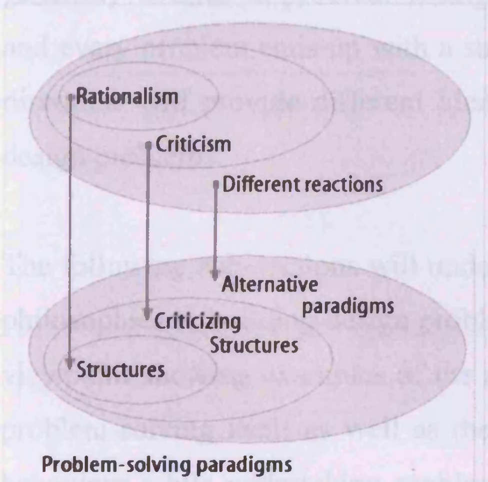


Figure 6.1 – Different worldviews originating different design problem-solving paradigms

The rationalist worldview as well as the different directions of thinking originated from its criticism strongly influence building design problem-solving paradigms. These influences are examined in detail the next section (6.2) which starts by analysing the influence of rationalism in design problem-solving structures, followed an analysis of the influence of pragmatic and post-modern theories in alternative design problem-solving paradigms (Figure 6.1).

6.2. Building design problem-solving paradigms

> *"The objective of the design problem and the design itself have a dialectic relationship, forcing designers to solve not only the problem at hand but also the problem of how to solve it, simultaneously" (Akin 1989).*

In building design, problem-solving paradigms will vary depending on which view of the world the designer subscribes to when interpreting and solving a problem, either consciously or unconsciously. As in human sciences, designers tend to question structures and their appropriateness as constructs mainly because many of the structures cannot be directly transposed to socio-cultural phenomena.

In any case, "the matter of control is already decided in the framing of the question" (Coyne 1995), i.e. the connections between design theories and the design artefact are generally defined in problem-setting. Although axioms and approaches are idiosyncratic and every problem ends up with a structure of its own (Lawson 1997), each philosophical discourse will provide different identifiable underlying philosophies to set up and solve design problems.

The following sub-sections will underline some of the most common applications of these philosophies to building design problem-solving paradigms. It will start with the rationalist viewpoint showing examples of the most common generic and specific structures used in problem-solving itself as well as the most common examples of structures of designer's behaviour while undertaking problem-solving activities. It will then outline the limits of rationalist structural and functional basis in dealing with problem-solving and show examples of pragmatic approaches that deal with 'subjects undertaking design activities' as well as post-modernist approaches that deal with the 'object of design' (Figure 6.1).

6.2.1. Rationalism and design problem-solving structures

The rationalist approach to design problem-solving is vast in its scope and encompasses prescriptive models, in which the aim is to prescribe how to deal with the 'object of design', up to descriptive models, in which the aim is to describe the subjects while undertaking design activities. In all cases, the paradigm tends to be structuralist and functionalist, i.e. it uses structures or models to deal with problem-solving.

Functionalism, made evident and instrumental by general system theory, is explored in all domains, from social to environmental and technical. Performance of activities, of structural systems and other sub-systems are paramount. Design is very much performance oriented in which the basic idea of problem-solving lies in the "selection of functional components that will perform as required and specify an arrangement of these parts that will allow them to interact as required" (Mitchell 1990). The aesthetics discourse also reflects this interrelationship as beauty is "taken to be a consequence of honest and direct response to necessity and to material" (Mitchell 1990).

The focus of discussion, when considering rationalist influences in design problem-solving, is about form and function with the connections and associations between the two studied and expressed in a rational way. Structures and models have their meaning attributed to metaphysics or complete subjectivism depending on the type or subject of structure and/or situation it is used. Connections between form and function appear in all structures analysed from models that deal with the objects of design, generic and specific, to models that deal with 'subjects undertaking design activities'. Models are used to "to reduce the apparent complexity of the observed world to a coherent and rigorous framework" (Rowe 1987) they are much more than simply aesthetic rules and constraints that provide guidance to solutions.

6.2.1.1. ***Models dealing with the 'object of design'***

Models dealing with the 'object of design' describe, or sometimes prescribe, how the problem-solving activity should evolve. They are used as guidelines or frameworks to organise problem-setting and problem-solving development in which the final aims are the creation of a resultant object that best meets all the performance requirements stated in the brief together with the ones unfolded by the designer along the process. Models can be generic, referring to the overall building design problem-solving paradigm, or specific, concentrating in specific aspects of problem-solving paradigms. Most generic models started with prescriptive aims but evolved to guidelines or loose descriptions of design problem-solving, whereas most specific models evolved either to new fields of studies, some producing computer tools, or were transformed into important organising concepts widely used by designers in many of their projects.

Some examples of generic models used to map the design process, used to reveal the structure of a design problem and used to describe a 'design language' are going to be provided in the following sub-sections, followed by some examples of specific models used to deal with performance of activities and environmental performance. These examples illustrate how descriptions of design problem-solving structures found in the literature actually subscribe to a rationalist worldview.

Jones' Design Method

A classic example of prescriptive models to map the design process is provided by Jones 1981 who, in "Design Methods", developed a catalogue of strategies to deal with design problem-solving, expanding and renaming the three stages (analysis, synthesis, evaluation) into: divergence, transformation, convergence. These three stages roughly correspond respectively to: "breaking the problem into pieces, putting the pieces together in a new way and testing to discover the consequences of putting the new arrangement into practice" (Jones 1981). This cycle is said to be happening from the conceptual stage up to the refinement stage.

The divergence stage corresponds to the very beginning of the process when the problem is ill-defined or wicked, therefore the objectives and boundaries are loose and the designer is searching for information and expanding his/her view of the problem in order to understand it better.

Strategies to be used as guidance in this situation are a mixture of: defining requirements, searching for further information about the object to be designed (from information about users behaviour up to technical information about products or systems to be potentially used), undertaking some tests to understand potential limits and complicated actions as well as selecting scales of measurement and making judgements about relevant data which critical design decisions depend upon.

The transformation stage is when solutions start to emerge from the results of the divergent search, when requirements, information collected and judgments about relevant data are made sense of. This is when the designer makes decisions about what is the relevant information to be used, when objectives and boundaries are fixed, when constraints and critical variables are identified and when judgements are made, allowing the problem to be split into sub-problems to be solved in series or parallel.

However, decisions are relatively loose in order to avoid major compromises. Strategies to be used as guidance in this stage consist of: topological models and interaction matrixes to classify and organise information, methods for searching for ideas such as brainstorming and the use of analogies and precedence together with morphological charts and further topological models to match requirements with possible solutions. Strategies for removing inherent faults, shifting boundaries of unresolved problems as well as finding radically new solutions in terms of patterns of behaviour and demand are also provided. Most of the guidance is compliant with a systemic worldview in which hierarchical structures, topological models and input/output functionalist procedures apply.

The convergence stage is when the problem becomes well-defined, the variables are identified and the objectives agreed. The process is about reducing uncertainties progressively towards either a final solution or a solution refinement. Strategies for convergence include checklists to match requirements and solutions, comparing alternatives using a common scale of measurement, fixing targets, applying decision support theories, applying cost analysis, undertaking performance tests and applying control strategies. In the convergence stage, strategies come from the several ramifications of general system theory and the ultimate aims are all about evaluating how the object will perform.

Design methods separate problem setting and problem structuring from solution generation and solution evaluation. They assume the process is linear in a micro-level, going from divergence to convergence, but that it becomes cyclical at a macro-level, repeating this serial process from conception to refinement (Figure 6.2). The aims of the model are to prescribe means and ends to fulfil performance aims.

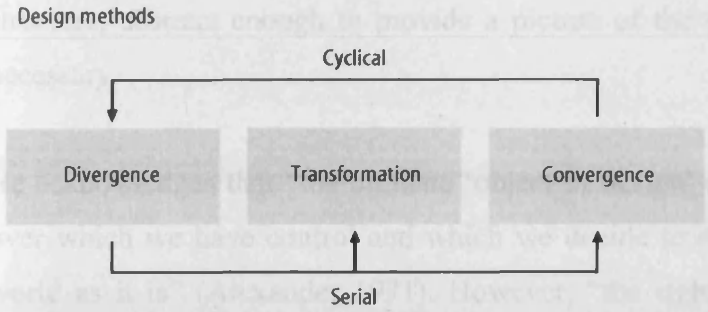


Figure 6.2 – Abstract illustration of design methods

Jones 1981 methods are generic and theoretically supposed to be applicable to all design domains. Design methods were highly useful to develop management methods used nowadays to manage team work, to plug consultants in and to agree on milestones with clients. However, they were not very popular among designers when undertaking design activities as they represent only one way of dealing with problem-solving, they are prescriptive and procedural. Apart from that, they assume the process is independent of the product which goes against most architects beliefs.

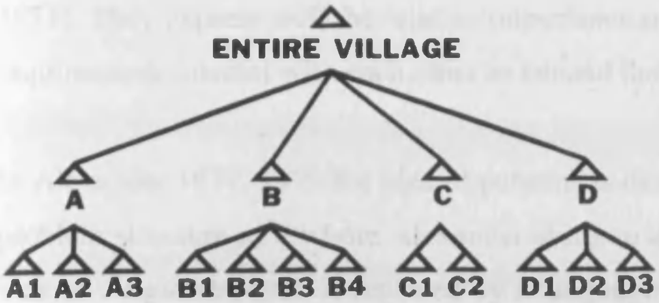
Alexander's models: design problem-solving structure and 'Pattern language'

Paradigms specifically proposed to deal with architecture design are provided by Alexander 1971, 1977 and 1979. In Alexander 1971, a prescriptive model is used to 'reveal' building design problem-solving structure. Knowledge about how to interpret problem setting using hierarchical diagrams to study interactions between variables is provided. The diagrams "represent an abstract pattern of physical relationships which resolve a small system of interacting and conflicting forces" (Alexander 1971).

The whole idea behind Alexander's diagrams is to propose a topological model to abstractly represent design problems, a logical structure, so that design can become something intellectual and able to be criticised. The complexity of design problems is becoming so huge that decisions should not be based on style anymore but have a scientific basis; "the designer's greatest gift, his intuitive ability to organise physical form, is being reduced to nothing by the size of the task in front of him" (Alexander 1971). As design problems cannot be solved piecemeal because the designer would go round in circles trying to correct problems generated from attempts to solve previous problems, a proper structure, abstract enough to provide a picture of the way designers see the problem, is necessary.

He acknowledges that "the ultimate 'object of design' is form (...) that part of the world over which we have control and which we decide to shape while leaving the rest of the world as it is" (Alexander 1971). However, "the rightness of the form depends on the degree to which it fits the rest of the ensemble" (Alexander 1971). The ensemble as a whole is composed of form and context, in which context is that "part of the world that puts demands on the form" (Alexander 1971) and fitness is that relation of mutual acceptability between form and context (Alexander 1971). "The form is the solution to the problem, the context defines the problem" (Alexander 1971). "Every design problem begins with an effort to achieve fitness between two entities: the form in question and its context" (Alexander 1971). In order to evaluate the fitness of a form to a context Alexander proposes to treat both as a diagram of forces by creating a diagram of forces for the context from which a complementary diagram of forces for the form can be derived.

From the previous description, it is clear that what Alexander means by context are actually design requirements. It makes also clear his approach to problem-solving structure: Once "designers translate requirements into diagrams which capture their physical implications" (Alexander 1971), they have the material to create diagrams for form and finally form itself as "form's basic organisation is born precisely in the constructive diagrams which precedes its design" (Alexander 1971). Diagrams for requirements summarise properties and constraints (Figure 6.3). Diagrams for form not only describe formal characteristics but also summarise the aspects involved in its physical structure, i.e. what it is as well as what it does (Figure 6.4). Form and function are interrelated; the latter is the ultimate aim of the solution, whereas the first provides the means for it to be materialised.



A1 contains requirements 7, 53, 57, 59, 60, 72, 125, 126, 128.
A2 contains requirements 31, 34, 36, 52, 54, 80, 94, 106, 136.
A3 contains requirements 37, 38, 50, 55, 77, 91, 103.
B1 contains requirements 39, 40, 41, 44, 51, 118, 127, 131, 138.
B2 contains requirements 30, 35, 46, 47, 61, 97, 98.

Figure 6.3 – Hierarchical structure of design requirements (Alexander 1971)

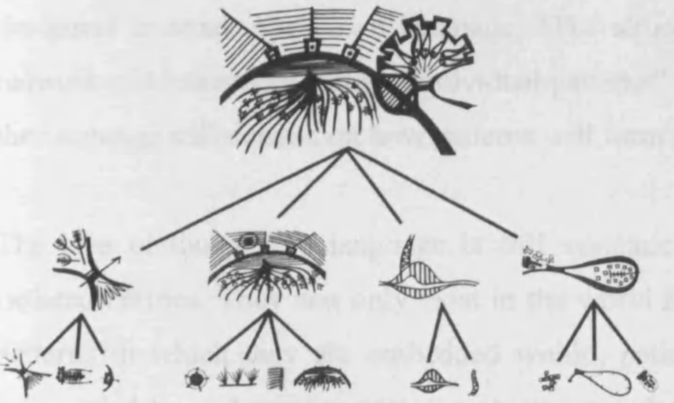


Figure 6.4 – Hierarchical structure of abstract forms (Alexander 1971)

Alexander's worldview is then heavily tied to functionalism and his diagrams are actually abstract descriptions of form following function. He believes that "designers first trace their design problem to its earliest functional origins" (Alexander 1971) to try and find some sort of pattern in them and that form is the part of the ensemble which designers have control over to create order in this ensemble. It is essential that a "structural correspondence between the pattern of a problem and the process of designing a physical form, which answers that problem (Alexander 1971), exists.

Patterns can be well expressed through hierarchical structures, meta-processes of the process to be modelled and controlled by the designer, powerful tools to describe the link between the variables according to the way designers see the problem (Alexander 1971). Hierarchical structures express order and control and facilitate the "search for the right components, and the right way to build the form up from these components" (Alexander

1971). They express well the relative importance of the different requirements and how the requirements interact with each other to control the form to be proposed.

In Alexander 1977, 1979 the idea of patterns is developed further. Instead of working with problem structure as a whole Alexander shifts to a more flexible proposition in which the idea of a rigid structure is replaced by a language with theory and instructions for its use (Alexander 1979) followed by a detailed description of its units, called patterns (Alexander 1977). "Patterns are atoms and molecules from which a building or a town is made" (Alexander 1979). Each pattern is a problem statement with its respective solution, both discussed and illustrated abstractly so that designers can create form from them. They are entities, elements of a language catalogued in Alexander 1977b to be put together by designers to create their own language. "The structure of the language is created by the network of connections among individual patterns" (Alexander 1979) and the liveliness of the language will depend on how patterns will form a whole.

The idea of the pattern language is still systemic in nature. Patterns are units but not isolated entities. They can only exist in the world if supported by another patterns: larger patterns in which they are embedded within, patterns of the same size which they are surrounded by and smaller patterns which are embedded within them (Alexander 1977b). The abstract and archetypal nature of the patterns together with the idea that they should be used by the designers to create their own unique and distinct pattern language intend to create an environment of unity, not fragmentation in which the structure is up to each designer to set up whereas the entities are "deeply rooted in the nature of things, ... a part of human nature, and human action..." (Alexander 1977b).

An interesting aspect of the language proposed by Alexander 1979 is the distinction between patterns of events and patterns of space. Patterns of events are similar episodes that happen along time and define the character of a place whereas patterns of space are geometric patterns that happen on a space interlocked with patterns of events. A structure of a building is made up of certain elements associated with certain patterns of events. However, "we don't have an obvious way of seeing how a building, its physical geometry is interlocked with the events that happen there" (Alexander 1979). "The pattern of space does not 'cause' the pattern of event. Neither does the pattern of space is ... the precondition which allows the pattern of event to happen" (Alexander 1979). Some relationships in the pattern of space will be congruent with the pattern of events. Some characteristics in the space are fundamental so that the pattern of events can happen, other ones will be only complementary without altering the essential nature of the space. Patterns of relationships will sustain patterns of events. Patterns of events and patterns of spaces can be understood as expanded concepts of function/ performance and form respectively, and pattern language is a rich design strategy that provides interesting insights and mechanisms to articulate both.

Alexander's prescriptive model of problem-solving structure (Alexander 1971) is actually a tool to analyse fits and misfits between problem requirements and abstract solutions, in different hierarchical levels. The hierarchical structure shows how requirements and solutions interact as well as how requirements interact with each other and how solutions interact with each other in the whole ensemble (Figure 6.5). This same basic idea is used to construct the patterns proposed in his later work (Alexander 1977 and 1979) in which the rigid overall structure is broken into unitary structures leaving up to each designer the job to put the pieces together, setting up their individual hierarchical structures (Figure 6.6).

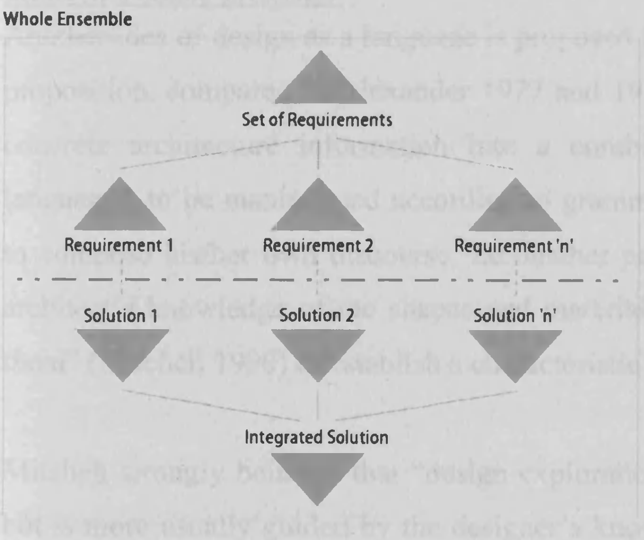


Figure 6.5 – Interpretation of Alexander's1971 ideal diagram for the whole ensemble

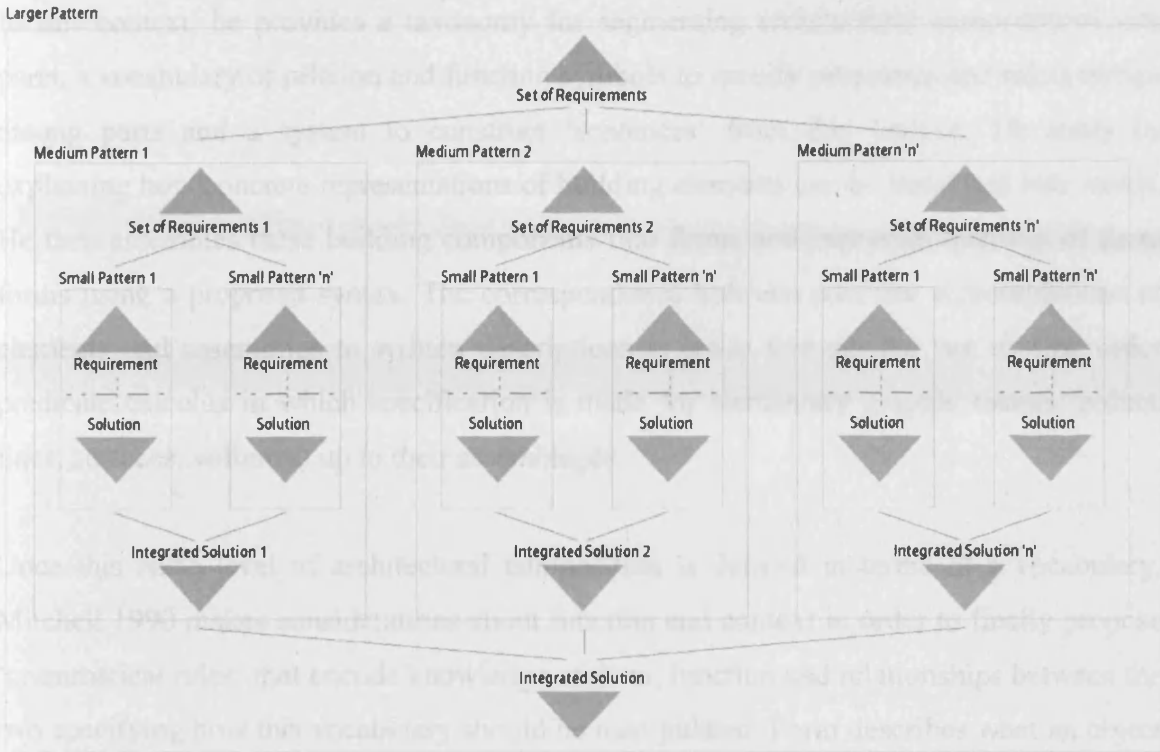


Figure 6.6 – Interpretation of Alexander's1977b ideal diagram for the patterns language

Mitchell's shape grammar

Another idea of design as a language is proposed by Mitchell 1990. He has a more abstract proposition, compared to Alexander 1977 and 1979, as he aims for a literal translation of concrete architecture information into a combination of mathematical and computer languages, to be manipulated according to grammatical rules to be used by each architect to compose his/her own discourse; i.e. his/her personal style. This personal style is "the architect's knowledge of the shapes and materials of available elements and how to use them" (Mitchell 1990) to establish a characteristic architectural language.

Mitchell strongly believes that "design exploration is rarely indiscriminate trial-and-error but is more usually guided by the designer's knowledge of how to efficiently put various types of compositions together that such knowledge can often be made explicit, in a concise and uniform format, by writing down shape rules" (Mitchell 1990). "Formally, design is execution of a computation in a shape algebra to produce required shape information, and the rules of a shape grammar specify how to carry out that computation" (Mitchell 1990).

In this context, he provides a taxonomy for segmenting architectural compositions into parts, a vocabulary of relation and function symbols to specify properties and relationships among parts and a system to construct 'sentences' from this lexicon. He starts by explaining how concrete representations of building elements can be translated into words. He then assembles these building components into forms and expresses qualities of these forms using a proposed syntax. The correspondence between concrete representations of elements and assemblies to written descriptions is made through the use of first order predicate calculus in which specification is made for elementary graphic tokens (points, lines, surfaces, volumes) up to their assemblages.

Once this basic level of architectural composition is defined in terms of a vocabulary, Mitchell 1990 makes considerations about function and context in order to finally propose 'grammatical rules' that encode knowledge of form, function and relationships between the two specifying how this vocabulary should be manipulated. Form describes what an object is whereas function describes what an object does. Functions make sense in contexts and both can be inferred by form. "What an object can be used as determines the type of thing it is: its architectural essence is its function together with the context, shape and material properties necessary for the performance of that function" (Mitchell 1990). However, "derivation of functional inferences requires applications of rules that relate observations about form and locations of architectural elements to conclusions about their functions" (Mitchell 1990).

As a result, rules to recognise situations, to watch out, to pay attention to, and to respond to, are provided as well as rules to specify responses to be considered or worth considering; both specified as rules of grammar. Interpretations and reflections about best matches and correspondence between the two are up to skilled designers to be resolved as it is "the conscious and informed play of intentions against a structure of givens to yield three-dimensional form, that gives a significant work of architecture its intellectual and emotional power" (Mitchell 1990).

In essence Mitchell's overall resultant idea of using rules to recognise situations and rules to propose responses for these situations is similar to Alexander's 1977 and 1979 propositions. An indirect match between requirements and solution is proposed. Grammatical rules are used instead of abstract hierarchical diagrams. The rationalist approach here is made clear as both authors believe the languages they are providing are objective and instrumental. Their basic elements and rules are set up to guarantee form/function matches, with the ultimate overall meaning to be conveyed by the designer, as infinite possibilities of assemblages and compositions are believed to be existent. It is important to point out that the main difference between the earlier (Jones 1981 and Alexander 1971) and the later works (Alexander 1977, 1979 and Mitchell 1990) lies in the shift from a top-down approach to a bottom-up approach in which order still exists but it is controlled from beneath (Dovey 1990). Overall there is more flexibility and structures are more comprehensive.

Formal languages

Another way of dealing with problem-solving structure is through the use of formal language mainly derived from typologies and environmental relations. These languages "possess guiding structures or rules that explicitly direct decisions about the 'correct' functioning and 'meaningful' ordering of formal elements" (Rowe 1987). They differ from the languages proposed by Alexander 1977, 1979 and Mitchell 1990 because they basically consist in a repertoire of formal, not abstract, solutions to be used in solving generic functional requirements.

One of the most famous examples of a concrete language is provided by Le Corbusier (Mitchell 1990) when summarising the 5 fundamental points of modern architecture:

(i) The pilotis,
(ii) The roof gardens,
(iii) The free plan,
(iv) The elongated window and
(v) The free façade (Figure 6.7).

The 5 points provide concrete solutions to abstract functional requirements through functional and formally specialized elements. The whole idea underlying the 5 principles is scientifically justified by Le Corbusier using rational arguments to construct and articulate an architectural vocabulary "of functionally and formally specialised elements ... to produce functionally expressive compositions" (Mitchell 1990).

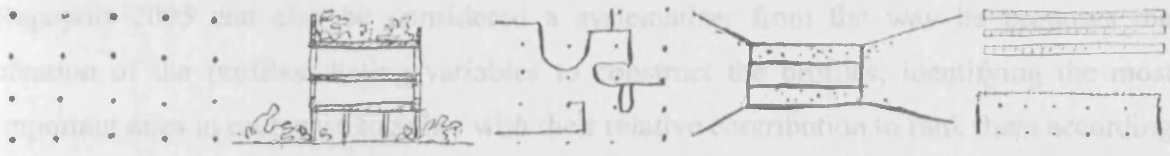


Figure 6.7 – Le Corbusier 5 points in architecture (Mitchell 1990)

Rationalist architects use a similar approach to the one illustrated in the 5 points. They have clear rules that address form/function requirements and at the same time act like a trade mark to distinguish their work from the others. The languages are developed "from a habitual way of doing things" (Rowe 1987) and like the previous languages exposed (Alexander 1977, 1979 and Mitchell 1990) they are bottom-up approaches to deal with problem-solving.

Mitchell 1990 rules as well as formal languages take into account architecture canons whereas Alexander 1977 and 1979 are based mainly on social sciences. Although "functionalist social sciences clearly has its limitations, … functions defined in relation to human activity systems, economic systems and cultural systems in relation to physical systems are fundamentally useful" (Mitchell 1990) and innumerous studies about classifications of buildings according to the types of functions they accommodate are available. Crucial roles were assigned to the architectural program in modern times but deep and interesting examples are provided by specific models that concentrate in connecting form and function with social systems and social activities.

Rapoport and the lifestyle profiles

Rapoport 2005 believes that requirements should be dictated not by function but by the meaning attributed to each function. Although meaning is something abstract it can be inferred by lifestyles, widely available due to marketing reasons, which contain descriptions of consumption patterns, activity systems, choices, etc. of the different groups of people within each culture. These lifestyles can be represented as profiles in which values, expressed through ideals, images, schemata, meanings, etc., are made explicit and then ranked. These profiles would actually provide patterns with requirements as well as solution targets, to be used as design guidance.

Rapoport 2005 can also be considered a systematiser from the way he proposes the creation of the profiles; listing variables to construct the profiles, identifying the most important ones in each case together with their relative contribution to rank them according to their importance in an assemblage or structure of linked relationships likely to be hierarchical. His model is prescriptive in which the subjective meaning of activities is made objective and instrumental to manipulate function requirements as well as to set up objective solution targets.

'Space Syntax'

Another example of rationalist model that focus on connections between form and function with social systems, provided initially by Hillier and Hanson 1984 and further developed into an independent field of study in design, is called Space Syntax which aims to understand spatial relationships from which, based on the analysis of spatial layouts, social patterns can be inferred. Although the model itself is descriptive it was developed to provide knowledge to be used prescriptively.

The model describes relationships between spaces in a system configuration, a space syntax, in order to study how movement and occupation, constrained by physical boundaries regulate the activities taking place in those spaces. The syntactic model describes the relation of one space to another taking into account other relations and laws are established based on analysis of movement. Integration of spaces with regards to movements in relation to an entire configuration are expressed through the easiness of access using as a basis the number of straight patterns of movement that intersect each other in the system (Figure 6.8). The results from the spatial analysis are translated into topological diagrams from which mathematical relationships are derived in order to quantify these levels of integration (Figure 6.8).

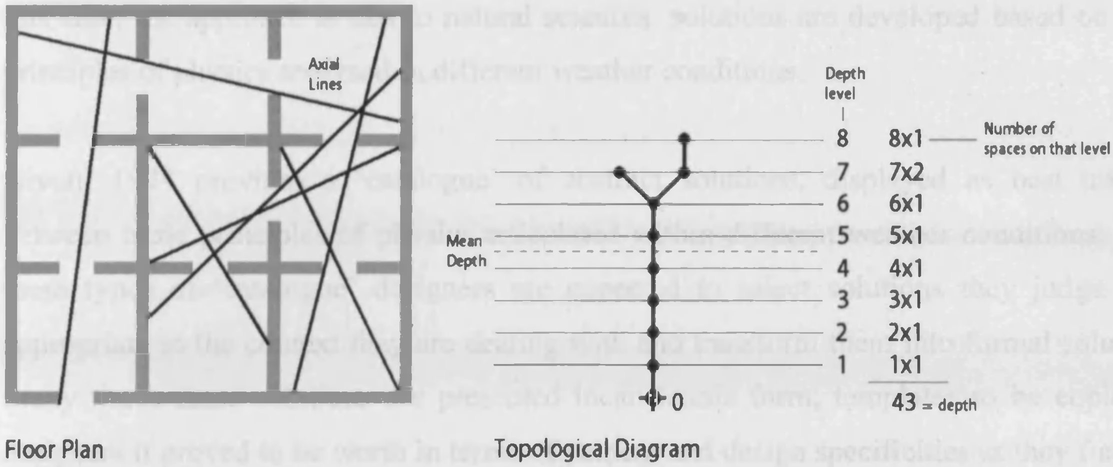


Figure 6.8 – Integration of spaces with regards to movement and topological diagram of different levels of integration (Aazam 2007)

The ultimate aim of space syntax models is to abstract information contained in layouts to identify genotypes from them. Genotypes are elaborated diagrams of configurations that display integration values. They are useful to analyse and evaluate the impacts of layout in the performance of social activities and social relationships (hierarchy and control) and are abstract and elaborate maps of typology that connect form and function with social systems and social activities.

Maps of typology that connect form and function with social systems and social activities are highly important to provide common sense knowledge, abstract and concrete, about past solutions with regards to characteristic needs, uses and customs found in a design situation that are useful to be conserved or reproduced. Simple maps are widely used as frameworks or references to solve problems "concerning spatial distribution and conformation of functional elements" (Rowe 1987), i.e. to deal with social and activity systems. As "typologies embody principles that designers consider unvarying" (Rowe 1987) they can be considered icons of successful functioning of spatial organisations. They tend to function as prescriptions about how the activities should be interconnected and distributed either in elaborated versions, such as when based on environmental profiles or space syntax, or in simple ones.

Iconic models of environmental science

A similar idea in terms of icons with successful functioning is found in examples of specific prescriptive models that refer to environmental performance. However, because in this case, the approach is tied to natural sciences, solutions are developed based on basic principles of physics analysed in different weather conditions.

Givoni 1994 provides a 'catalogue' of abstract solutions, displayed as best matches between basic principles of physics articulated within different weather conditions. From these types of 'catalogue' designers are expected to select solutions they judge more appropriate to the context they are dealing with and transform them into formal solutions. Many times these solutions are presented in an iconic form, templates to be copied by designers if proved to be worth in terms of context and design specificities as they function successfully (Broadbent 1988). A classical example of an iconic solution is the Trombe wall (Figure 6.9) which shows a combination of strategies for energy storage and ventilation systems, both applied principles of physics, to be used as a template for passive heating and cooling.

Figure 6.9 – Example of iconic solution: The Trombe wall

<u>*Szokolay system based model*</u>

More elaborated rationalist prescriptive models for environmental performance are the system based ones. These models are procedural as they provide targets to be achieved and means/models to calculate how far the current design propositions are from achieving these targets, leaving up to the designer to make decisions about where to act upon in his/her design in order to achieve the prescribed targets. Fundamentals of physics are generally provided together with these models so that the designer understands which variables are influencing each type of target being considered, by constraining design decisions to these variables and helping the decision making process. Examples of system based models are provided in Szokolay 1980 who presents fundamentals, targets and calculation procedures for performance in terms of lighting, acoustics and thermal comfort individually.

Szokolay 1980 not only works at an elemental level, dealing with each environmental condition individually, but also presents an overall model based on general system theory for the whole design process. His model is composed of four parts: the objective system, containing the "purposes of the organisation to be accommodated" (Szokolay 1980); the activity system, containing the activities to be accommodated as well as the conditions they require to be accommodated; the environmental system, containing all the elemental systems he developed extensively, and the building system, which actually provides the 'hardware' for the other three systems to exists. The first two systems are said to be of concern in social-sciences whereas the last two systems are in the territory of architecture, engineering and building physics.

Any proposed design will be concerned with "what things do and how they behave" (Szokolay 1980) in order to determine what things are. This concern is said to be a matter of coordinating controls to fulfil specific targets as well as a matter of using and articulating multifunctional components.

When coordinating controls to fulfil specific targets, the designer "must integrate the controls of the inanimate part of the building ... in such a way that it can accommodate the whole range of behaviour and respond to any likely state of the human subsystem in the appropriate purposeful manner" (Szokolay 1980). When using and articulating multifunctional components, the designer has to manipulate multifunctional components, which respond to many different functions at the same time, in an articulate way to compose a 'hardware' system that responds to all the needs of the objective system, activities system and environmental system. The last stage is the integration of controls and the 'hardware' system, which can either be accomplished through accommodation of building components and services or through the active use of building components as parts of the service systems.

Bachman system based model

A similar approach to treat and understand buildings as systems is proposed by Bachman 2003 who considers buildings have 5 fundamental systems to be addressed:

(i) Envelope, composed of the building shell and separating the indoors from the outdoors;

(ii) Structure, composed of the elements that provide static equilibrium against gravity and dynamic loads acting upon the building;

(iii) Interior, composed of the occupied and circulation spaces (including all its partitions, finishes, lighting, acoustics, furniture, etc.);

(iv) Site, consisting of the building surroundings, its landscape and support systems (parking, drainage, vegetation, utilities, etc.); and

(v) Services, consisting of HVAC, electrical, plumbing, vertical transportation, etc. all the equipment that complements the 'hardware' functions.

After the definition of these 5 systems, Bachman 2003 defines three types of integration to be accomplished in order to eliminate redundant resources and contribute to architectural success:

(i) Physical integration, in which components share the same space;

(ii) Visual integration, in which the arrangement of components is aesthetically resolved; and

(iii) Performance integration, in which the components work together to fulfil different needs or do not defeat each other when fulfilling specific needs

He then provides examples of architectural work highlighting how these 5 subsystems were articulated, based on these three criteria for integration, into different formal solutions. A table of potential integration relationships is provided (Figure 6.10) in which performance objectives for low energy consumption even if listed in an abstract way suggest possible aesthetic routes in which potential performative/functionalist compositions are valued.

	Site	Structure	Envelope	Services
Interior	Indoor/Outdoor relationships	Exposed structure Integrated lighting	Daylighting	Exposed ducts Masking bachground Air-handling luminaires
Services	Cooling ponds Earth tube cooling	Duct routes Interstitial mechanical Plenums	Passive cooling design Solar roofs Vented skin Double envelope	
Envelope	Earth sheltered Natural habitat Noise barriers Storm water	Building shell Shading Light diffusing		
Structure	Underground Terraced			

Figure 6.10 – Table of potential opportunities for integration (Bachman 2003)

The Szokolay 1980 and Bachman 2003 models are mainly models based in environmental performance, but developed further into models that reveal the structure of design problems. Their models, clearly systemic, were developed with their basis in natural sciences. Instead of exploring matches between requirements and solutions they tend to address solutions straight away based on abstractions of principles from observed phenomena. They "deal with complex patterns of relationships among a multitude of things, where the relationships are more important than the things and the patterns are more important than the single relationships" (Szokolay 1980). These patterns referred to, are clearly patterns of abstract solutions developed from understanding of natural sciences. They are understood as generic, context independent, widely applicable therefore difficult to be contested and presented as deterministic. They put more weight on the environmental aspects of performance rather than on the social aspects of performance, showing that propositions can have different orientations with regards to function and performance.

Models dealing with the' objects of design'

Commonalities can be found in either generic or specific examples of models dealing with the 'object of design' presented. In general the 'object of design' is accessed through methods that prescribe means and ends to fulfil performance aims, and hierarchical structures that either deal with problem-setting (making clear which requirements should be fulfilled in problem-solving) or create patterns to be combined in a higher level that guaranteed the match between requirement and solution through form and function. In all cases, there is a separation of problem setting from problem solving followed by an analysis of the relative importance of the elements of the object to be designed with regards to how they interact with each other and how they interact with the whole for the object to perform according to what is required.

Generic models provide structures to deal with requirements as a whole. As a consequence of that, they tend to be criticised as reductionistic, rigid and decontextualised. Some of the research on generic models shifted its focus from the 'object of design' to the 'subject undertaking design activities' and concentrated on understanding the creative process involved in problem-solving. These models tried to address some of the issues models dealing with the 'object of design' could not address, such as taking into account subjective issues as well as the context involved in design problem-solving. However, when trying not to be reductionist with regards to the information manipulated by designers while setting and solving design problems, they illustrated the same classical rationalist points, in which some of these points are simply transposed to a different level.

Specific models, evolved into different specialities, provided a number of important organising concepts that deal particularly with spatial organisation and environmental concerns. They inaugurated different types of design consultancy professions that not only participate into the design process but also develop sophisticated tools to assess its outcomes and provide advice.

6.2.1.2. ***Models dealing with 'subjects undertaking design activities'***

Descriptive models of cognitive processes used by people undertaking design activities have been one of the most important focuses of design research since the late 1980s. Mainly used to understand the creative problem-solving activity, cognitive models focus on a "small finite number of basic mechanisms for processing information that could be grouped or arranged into strategies ... that allowed complex problems to be solved" (Rowe 1987). Methods of examining, calibrating, and describing problem-solving behaviour through psychological experiments, formal and computer simulations have been extensively used in design research to "discern which fundamental information processing mechanisms appear to be involved" (Rowe 1987) in design to help improving artificial intelligence models and more effective methods of design teaching.

Several cognitive models are used to explain the 'creative problem-solving' activity. They generally assume the design development occurs in distinct phases, and from this assumption establish matches between the cognitive processes involved in each of these phases with their corresponding representation systems proposing a model that describes the problem solver's behaviour in terms of information transformations (Figure 6.11). They are all based on the fact that "designers usually face a problem without clearly defined objectives, methods or evaluation criteria" (Akin 1986), but that "there are things that are shared by many design problems and designers which characterise these processes and suggest the existence of normative methods and knowledge" (Akin 1986).

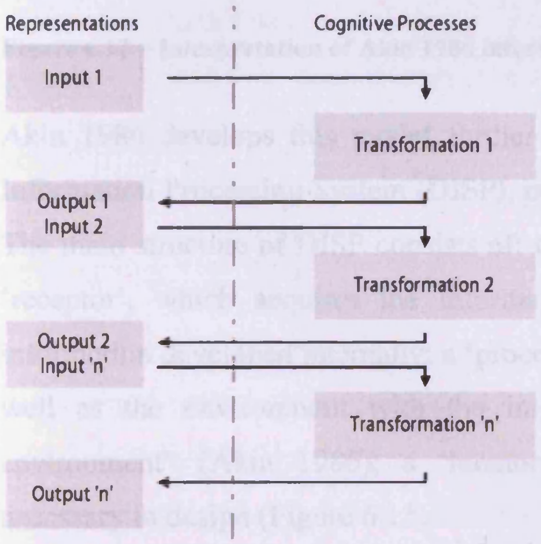


Figure 6.11 – Essence of information transformation models

Akin's cognitive model

A well known cognitive model is proposed by Akin 1986 who presents a paradigm which codifies the cognitive processes and employs information processing system to this process, setting up a computer simulation tool able to reproduce it. Akin's 1986 basic information transformation model is developed into three parts:

(i) A part which contains the external representations that result from design information transformations: background information, problem definition, problem structure, preliminary documents and construction documents;

(ii) A part which contains the processes used to generate and manipulate each of these representations: information acquisition, information representation, information projection, information confirmation, regulation of control;

(iii) A part related to the knowledge involved in the generation and manipulation of this information: representational, inferential and heuristics. The interconnection of these three parts is basically summarised in Figure 6.12 which shows that for each stage, knowledge is processed into an external representation system to be used as input for the following design stage.

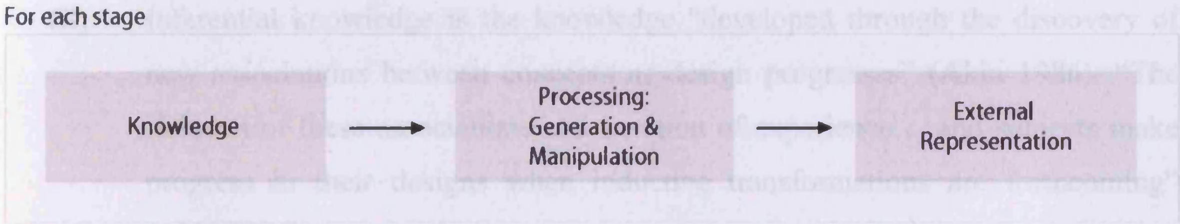


Figure 6.12 – Interpretation of Akin 1986 information transformation model

Akin 1986 develops this model further into a computer simulation tool called Design Information Processing System (DISP), presenting the architecture of this system in detail. The main structure of DISP consists of: two information sources, problem and solution; a 'receptor', which acquires the information needed; an 'effector' which encodes the information developed internally; a 'processor', which "alters the content of the memory as well as the environment with the intent of solving the problem described in the environment" (Akin 1986); a 'memory', which provides the long-term knowledge necessary in design (Figure 6.13).

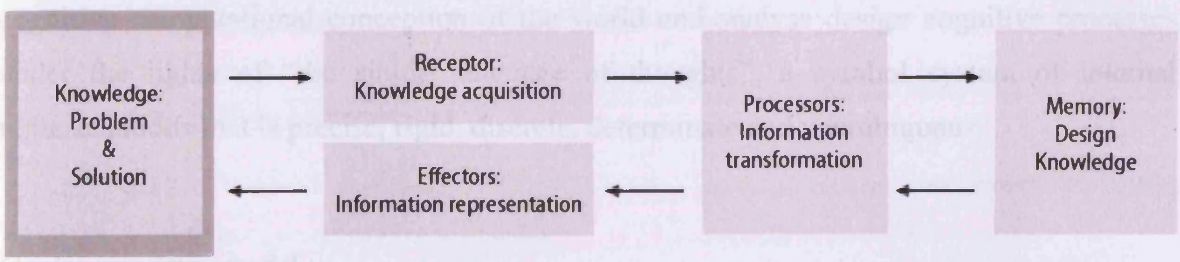


Figure 6.13 – Akin 1986 DISP model (Akin 1986)

In order to put the DISP model to work Akin 1986 concentrates his research into the identification of the types of knowledge involved in the process so that each part can be further detailed and calibrated. The most important types of knowledge identified are: representational knowledge, inferential knowledge and heuristics:

(i) Representational knowledge comprises dealing with structures used in representing, learning and recalling architectural drawings. Organisation of spatial information is multidimensional and is useful to evoke many associations during the process. This knowledge is tightly connected to inferential knowledge, "the driving force pushing the design process forward" (Akin 1986) which explains all the data manipulation and transformation of concepts during the design process.

(ii) Inferential knowledge is the knowledge "developed through the discovery of new associations between concepts as design progresses" (Akin 1986). "The richness of these associations is a function of experience... and subjects make progress in their designs when inductive transformations are forthcoming" (Akin 1986).

(iii) Whenever inductive reasoning fails to promote the design flow, heuristic reasoning comes into action to move design forward. Heuristic reasoning is a powerful search technique used to identify and refine solutions. Techniques used can be analogies, educated guesses, weighting decisions, generate-and-test, means-ends-analysis, depth-first search, breath-first search, hill climbing and back-tracking.

Akin's 1986 model is heavily reliant on representations and his main concern is to understand the types of knowledge involved in articulating these representations, the structures of concepts designers use. Goel 1995 goes deeper into the studies of the cognitive computational conception of the world and analyse design cognitive processes under the lights of "the single language of thoughts", a symbol system of internal representations that is precise, rigid, discrete, determinate and unambiguous.

Goel's cognitive model

Goel 1995 provides a model to characterise the design problems space based on the structure of the task environment and the information processing system. Characteristics of the task environment consist of: incompletely specified starting state, goals and transformation functions; in which it is up to the architect to set up most of the constraints of the project based on a combination of the interpretation of the brief, the discussion with all the agents involved in the process together with further relevant information consistent with the materialisation of the project. The information processing systems are based on physical symbol systems with syntax and semantic constraints and elementary processes operating in series. They are precise, rigid, discrete, determinate and unambiguous.

Goel's resulting list of the set of invariant features of design problem spaces are the following:

(i) Stopping rules and evaluation functions are dependant on the designer's view of the world and way of dealing with the problem;

(ii) Extensive use of memory retrieval and minimal use of deductive strategies occur due to the small number of logical constraints involved in the process;

(iii) Problem parameters are enlarged, narrowed or changed using transformation functions;

(iv) A problem is generally decomposed into modules, with contingent connections between these modules due to its complexity;

(v) There is a general tendency to incrementally develop ideas until an appropriate result is achieved,

(vi) A 'limited-commitment-mode' control strategy is used to generate and evaluate ideas,

(vii) Commitments are made, recorder and propagated up to the final product specification to be interpreted by third parties;

(viii) Problem structuring is differentiated from problem solving, with the latter further decomposed into: preliminary design, refinement and detailed design;

(ix) There is a qualitative difference between the input and output information in each stage of problem solving determined by a hierarchy of type and level of detail of information manipulated in each stage;

(x) The problem space is manipulated through the use of representations that include several symbol systems;

(xi) These symbol systems are used to generate external models of the manipulation of the problem space that vary from abstract to concrete and

(xii) Each symbols system, according to the properties they have, correlate with different cognitive processes.

As a cognitive scientist studying the design process, Goel 1995 is also after a match between the cognitive processes involved in design and the representation systems associated to them. However, his depth in analysing the rigidity of the symbol system involved in the information processing systems provides him with insights about the fact that this matching is done assuming classification schemes that are highly controversial with regards to the criteria and boundaries between categories. When analysing dense, ambiguous, and amorphous symbols systems used mainly in the early design stages such as sketches, he found it difficult to provide classifications for them that conform to the current "single language of thoughts". Further theories are necessary to account for vagueness, fluidity, ambiguity and amorphousness in the representations and cognitive processes that underlie them, as well as to the information processing so that these things can be modelled.

Akin 1986 and Goel 1995 reach the limits of cognitive science in explaining the design process. The first, through an analysis of the cognitive processes involved in design, noted that the most important process is inferential which makes associations between concepts contingent and idiosyncratic. The latter, through an analysis of the symbol system used in information processing, noted that the nature of representations used by designers did not conform to the imposed classification schemes which affects the association of these representations with the cognitive processes involved in their production.

These models are full examples of the way cognitive science views design. Many other models are proposed but mainly the non-exhaustive list of studies of design under the heading of cognitive sciences concentrates on the following aspects:

(i) Models for the whole design process;
(ii) Models for specific points of problem-solving paradigms;
(iii) Prior knowledge;
(iv) Models of specific transformation processes and
(v) Internal representation systems.

Cognitive models for the whole design process

Examples of models that deal with the whole design process are proposed by Gero and Kannengiesser 2004 among others. The work elaborates Gero's earlier studies about the whole design process by developing further the Function-Behaviour-Structure (FBS) framework. In this framework, function refers to the variables that describe what the object is for; structure refers to the variables that describe the components of the object and their relationships, what the object is; and behaviour refers to the variables that describe the attributes derived or expected to be derived from the structure, from what the object does. Connections between function-structure-behaviour are constructed through experience, but generally designers attribute function to behaviour and derive behaviour from structure. The model is quite simple and consists of:

(i) Formulation stage, in which designers transform requirements expressed in function into behaviour, expecting to enable them to function;
(ii) Synthesis stage, in which designers transform behaviour into a solution structure exhibiting the desired behaviour;
(iii) Analysis stage, in which the designers derive the actual behaviour from the synthesised structure;
(iv) Evaluation stage, in which the designers compares the behaviour derived from the structure with the expected behaviour to decide if the solution proposed is to be accepted;
(v) Reformulation stages, in which designers undertake changes in function, structure or behaviour variables if the result is not satisfactory; and
(vi) Documentation stage, in which designers produce a description to construct a product.

The whole process involves the interaction among three worlds:

(i) An external one, composed of representations outside the designers mind;
(ii) An interpreted one, build up from designer's experiences, perceptions and contexts;
(iii) An expected one, based on imagined actions in which effects are predicted according to aims.

These worlds are recursively linked by processes of interpretation, in which variables of the external world are transformed into interpretations to compose the internal world. Acts of the interpreted world are focused upon to be used as goals in expected worlds and suggest actions. These actions involve changes in the external world, according to goals in the expected worlds, to be made effective. By taking into account the processes involved in the interaction among different worlds as well as the worlds themselves, Gero and Kannengiesser 2004 believe to be taking into consideration the knowledge of the designer as well as the design context and the models is open enough to account for the fact that each designer will develop a different strategy to encode design information (Eastman 2001)

Cognitive models for specific points of design problem-solving paradigms

Examples of studies that focus on specific points of design problem-solving paradigms can be found in Ozkaya and Akin 2006 and Kim et al 2007. The first ones propose a model to deal with "requirement specification within design solution exploration" (Ozkaya and Akin 2006) which basically consists of a digital model of information management to understand needs of clients and users, generating from it information to be used in form generation. They develop a process framework with a requirement based core in which each design decision serves as a new requirement for the next design stage, redefining the problem with each decision. The model is not rigid as is takes into account the fact that requirements are used not only during the early design stages, but through and after the whole design process, not staying frozen in time due to the additions, modifications and deletions that happen while design progresses. The aim is to generate a design structure with traceable paths, recording criteria or requirements together with the formal solution investigated to attend these requirements so that both can be traced at the same time. Requirements are not only inputs of the process but also used as evaluation criteria to test the suitability of the proposed solution.

Ozkaya and Akin 2006 resultant model is then highly rational. It comprises:

(i) A 'constraint-satisfaction' space, with explicit statements of goals, objectives and constraints;

(ii) A rank of importance of these constraints and the definition of efficiency functions to establish formal descriptions of requirements, solutions and operations;

(iii) A 'generate-test' space, that contains a model to describe the interaction between design space and requirement space until a satisfactory solution is found using an evolutionary approach in which requirements are specified at the same time solutions are generated until convergence is reached.

Kim et al 2007 focus on problem-solving structure to understand how designers manage complexity by decomposing the problem into a number of interconnected sub-models, dealing with the decomposed problem in various contexts, efficiently tolerating ambiguity and resisting premature closures.

Ozkaya and Akin 2006 and Kim et al 2007 studies are almost reinterpretations of Alexander 1971. However, these 'reinterpretations' are done in the light of cognitive sciences, taking into account the designer's previous knowledge as well as the highly interactive and evolutionary nature of the process in which problem and solution co-evolve side by side. "Problem structuring requires the designer to draw on knowledge and information flows and diagrammatically map the information/issues in order to move towards and develop a solution" (Kokotovich 2008). Nevertheless, "the development of an understanding of the problem and its structure is by nature iterative and cyclical" (Kokotovich 2008).

Cognitive models and prior knowledge

Examples of use of prior knowledge and transformation processes can be found in many design studies. Prior knowledge in this case includes the designer's prior knowledge, as well as knowledge taken from references and precedence. Architects take decisions based mainly on precedents, either of their own work or somebody else's work (Simon 1996). They resort to references while designing mainly to have ideas about how to translate abstract requirements into a form. They look at references, similar buildings, specific architects, their own previous work, etc. to try and understand which approach was used in problem solving, getting inspiration from these several types of problem solving to set up their own problem-solving paradigm. Examples provide a strategy of learning by similarities but interpretation is completely dependant on the nature and amount of prior experience and training of the designer (Kuhn 1996), making it difficult to separate prior knowledge from specific transformation processes.

Craig 2001 in studying different strategies to map the design process, to identify the process itself as well as the reasoning and cognitive strategies involved in it, found that there is not one single strategy to map this process because "designers tend to structure their solutions on available exemplars rather than on a priori principles, and seek novelty by varying attribute values rather than structural relations" (Craig 2001). Precedence is used not only in the proposition of a solution but also in the understanding of a problem (Kokotovich 2008). Oxman 2001 emphasizes the use of precedence to construct a 'design kernel', the main idea to be used from selecting and putting relevant information together up to the proposition of a formal solution. The kernel is said to be identified from precedence, conceptually and formally. Links between these concepts and forms are established, and concepts are expanded in an abstract way so that new ideas can be explored from these abstractions.

Bachman 2003 believes references are material to be used in 're-invention' to add something to the state of the art, to get guidance about general characteristics of the type and get successful design approaches to it. Designers find in references technical systems, historical models, formal interpretations, parallel organizations, etc. Besides that, recourse to reference also means recognition of cumulative experiences of the past; "art build new ideas on old ones without rejecting the past" (Bachman 2003).

In seeking precedents, the architect looks for the "evolutionary progression of successful design solutions" (Bachman 2003), getting lessons an inspiration from them. Heylinghen and Verstijnen 2003 also reinforce the role of references and precedence as sources of inspiration, stating that the importance of 'base case' reasoning lies in "identifying issues to pay attention to, to form ideas about how to progress and to imagine the effect of potential design solutions" (Heylinghen and Verstijnen 2003). They highlight that the importance of reference and precedence "as a resource for solving new problems" (Heylinghen and Verstijnen 2003) is the essence of 'base case' reasoning.

Studies about different learning styles will actually show that different design stages can be associated with different learning styles, going from learning by doing up to learning by thinking (Demirbas and Demirkan 2003). Prior knowledge and transformation processes are part of a designer's skills. These skills comprise a complex interaction of structuring experiences, reflecting about design knowledge and recall in new design situations. The basis for recall and information association is also a topic of study of cognitive researchers who try to understand the use of analogies and metaphors in design.

Cognitive models of specific transformation processes

Analogies and metaphors, under the light of cognitive science, are mental constructions of associations between different phenomena with common properties or processes. When two things have common properties they are considered analogous, when they have a common semantic description they are considered metaphors. Analogies, when based on perceptual surface features of the phenomena (colour, shape) are said to be shallow, when based on abstractions of the phenomena (topological structure, function) are said to be deep. In any case their use will be contingent.

Oxman 2001 studied reasoning from past solutions with the use of analogies and metaphors through the proposition of the Issue-Concept-Form (ICF) model in which the issues of a design problem with particular solution concepts related to form descriptions are matched. This ICF model is used to represent and model visual conceptual ideation in precedent-based design, considering representation, indexation and organization of precedence to support exploration processes of analogies and metaphors.

Goldschmidt 2001 also talks about visual analogy and imagery in creative problem solving. "In a creative search analogies are not just identified, they are created as a result of the manipulation and transformation of images" (Goldschmidt 2001). She believes the designer uses images to reason about the problem as a consequence these images undergo transformations. Analogies have a decisive role in creative activity, discovery and invention and are a powerful reasoning artifice crucial in the acquisition of new concepts. She notices that they are the most common type of reasoning used in ill-defined problems, mainly in conceptual design stages.

Cognitive models and internal representation systems

Reasoning and manipulation of representation systems based on images are central to cognitive sciences when studying designers undertaking design activities. "Using mental imagery, we can often simulate experiences or events only conceived mentally, imagining how we might walk through a space or view a scene" (Eastman 2001). Designing is then extremely related to visual thinking (Huang 2008). "The purpose of visual thinking ... is primarily to enable the designer to identify clues for forming and emerging design ideas...

it occurs more frequently in creative thought, in problem-solving that requires insight" (Huang 2008).

Eastman 2001 comments about lots of studies concentrating on how people can reason using mental imagery, providing examples of operations on mental imaging, influences of mental imaging on learning attributes, types of mental imaging, functional capabilities involved in them, etc. concluding that complex images are not retrieved from memory but "are constructed from a collection of imagery information about the object of interest" (Eastman 2001), a construction that can happen in different ways depending upon the need.

Reasoning and manipulation of internal representations tend to be assessed by cognitive sciences through experimenting with and studying external representations. Cognitive science deals with the duality of internal versus external representations when studying designers undertaking design activities. It specifically concentrates on mental imagery as the form of reasoning underlying internal representations and sketches as the type of representation used externally.

Cognitive science investigates internal and external representation systems in multiple ways. These investigations comprise for instance interactions between internal and external representation system directly in which the aims are to know to what extent things are generated externally (composed and refined by manipulating drawings) and to what extent things are generated internally (built and manipulated mentally) and only expressed externally later on (Eastman 2001, Bilda et al 2006); they can approach the types of cognitive processes involved in design by assessing the way designers manipulate internal and external representations (Oxman 2001, Eastman 2001, Akin 2001, Goldschmidt 2001); to cite a few. In most cases, reasoning and manipulation of mental imagery tend to be used in support of studies about the role of reference and precedence as well as in support of studies that refer to the use of analogies and metaphors.

Models dealing with 'subjects undertaking design activities'

Commonalities can also be found in examples of models dealing with the 'subjects undertaking design activities' presented. Basically cognitive science understands designers abstract patterns to be used in their problem-structuring and problem-solving. These patterns are identified from references and precedence and are constructed based on analogies and metaphors. The most common use of references and precedence are for handling issues related to typology, generally in the early stages, but references and precedence can also be used as sources of inspiration for the design main idea and/or to solve specific parts of the problem. The importance of reference and precedence in architecture is evident in the way information about the domain is stored: reference books containing architects points of view about specific problems solved, materialized into formal solutions – the buildings.

Commonalities among cognitive models are based on assumptions that design development occurs in distinct phases which are constant in all design problems. In each of these phases identifiable patterns of knowledge, transformation processes and representation systems are commonly applied by all designers when working on a design problem. Types of knowledge involved in the process, as well as types of representation being manipulated are classified based on the assumption that all human beings have a "single language of thoughts" (Goel 1995) which is based on a rigid, precise, discrete, determinate and unambiguous symbol system of internal representations.

Patterns of knowledge, transformation processes and representation systems require the use of references and precedence as a basis to develop associations, analogies or metaphors used to translate abstract information into form and/or when further developing this form. Heuristic reasoning, a more objective type of reasoning, comes into the process near refinement stages when information processing techniques are said to be commonly applicable as goals can be clearly stated and means to achieve them clearly seen, allowing variables and operations to be selected in order to reach the targets.

References and precedence, associations, analogies and metaphors are in fact widely used in building design problem-solving as guiding principles to solve either generic or specific problems. However, attempts to describe the cognitive processes involved in them cannot cope with the dialectics underlying the rationalist viewpoint. Separations between subjective/objective, means/ends, theory/practice together with intentions to generalize the designer's behaviour prevent further understanding and description of these processes using the field of cognitive science but not under the pragmatic and post-rationalist viewpoints.

In any case, the rationalist viewpoint provides important insights in terms of reasoning as well as positive outputs in terms of manipulating structures and systems, an important legacy highly useful to deal with any type of design problem-solving activity.

6.2.1.3. Rationalist design problem-solving structures: The legacy and the criticism

This section outlines the legacy and ramifications of the rationalist design problem-solving structures based on the foregoing discussion. It outlines commonalities between the models referring to 'object of design' and the models referring to the 'subjects undertaking design activities'.

Rationalist design problem-solving structures: the legacy

Commonalities among the different rationalist models presented show clearly their basis in structuralism and general system theory in terms of ways of thinking. The advantages in using methods and structures to understand and solve problems are innumerous. They are powerful tools for organising and classifying information, allowing different levels of understanding and manipulation of this information, from expressing knowledge to conveying it in the form of organising concepts. Apart from that, if transformed into mathematical models, they can be used to predict, analyse and simulate behaviour advising and supporting the design process. In any case, models tend to be heavily tied to function and performance, displaying hierarchical structures that are either procedural or instrumental, to be used either directly in the 'object of design' or indirectly to understand and simulate the 'subject undertaking a design activity'.

Concrete legacies of rationalist thinking to be used when dealing with the 'object of design' are:

(i) Guiding principles and typologies;
(ii) Analogies and metaphors based on references and precedence and
(iii) Abstract and concrete organising principles.

The legacy: Guiding principles

Guiding principles are "a major source for the perspectives that guide the choice of organising principles and constraints" (Rowe 1987). Guiding principles support generative reasoning instead of deductive reasoning and are used as primary generators for setting problem boundaries and solution goals (Cross 2004). When coming from prescriptive models they generally lie within a theoretical discourse from architectural history and theory. A classical example of guiding principle which became a doctrine of the modernist and functionalist theoretical discourse is "Form is everything and anything...according to their nature...some forms are definite and some are nebulous...the form exists because of the function" (Sullivan 1934 in Rowe 1987). This principle is more than a simple idea, it is actually a philosophy to set and solve design problems to which modern architects subscribe. When coming from models of subjects undertaking design activities, guiding principles are also shown as idiosyncratic to the designer expressing simply a guiding idea, a kernel used to structure the solution as a whole.

A classic example of this type of guiding principle is found in the work of Calatrava (Zardini 1996) (Figure 6.14) who develops buildings based on iconic analogies in which the natural world is used as a source of inspiration to develop building shapes. He recognizes an underlying principle in the natural world but tends not to focus on the surface features of the problem, standing back "from specifics of accumulated examples and forming more abstract conceptualizations pertinent to his domain of expertise" (Cross 2004).

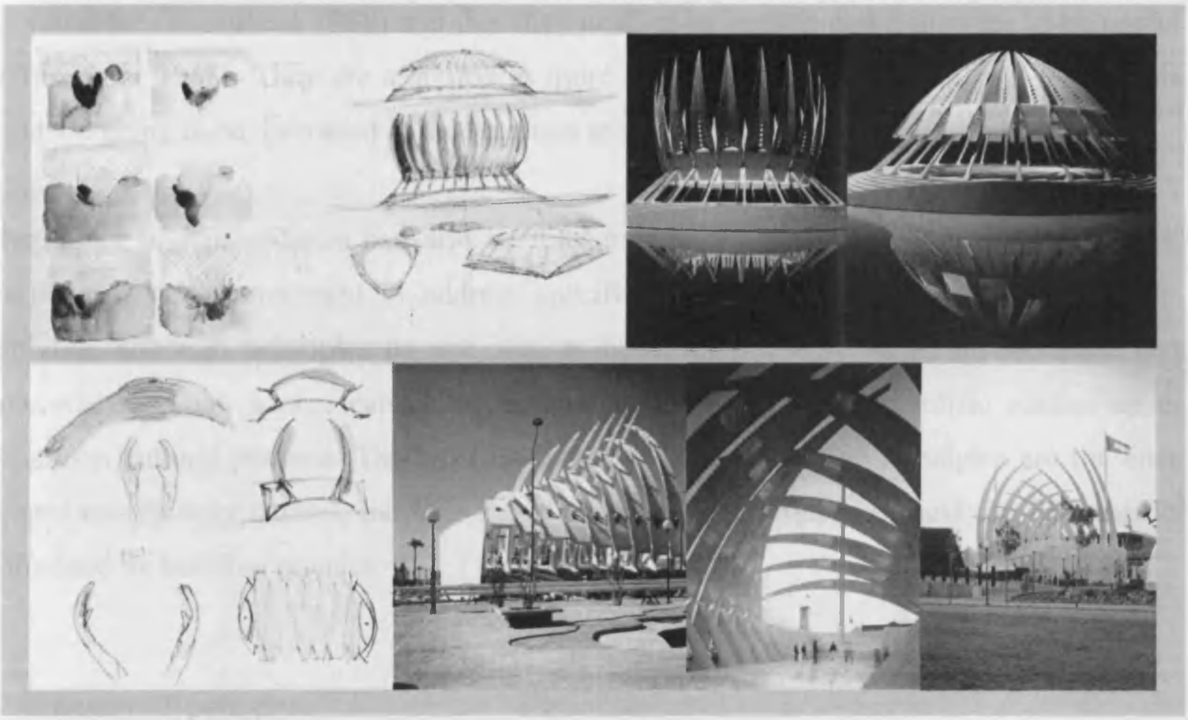


Figure 6.14 – Guiding principle based on iconic analogies with the natural world in the work of Calatrava (Zardini 1996)

The legacy: Analogies and metaphors based on reference and precedence

The importance of analogies and metaphors especially when guiding principles do not come from a strong theoretical discourse are paramount. They are considered the "central mechanism for creativity and … has been used intuitively by all architects we call creative" (Broadbent 1988). They are extensively studied by cognitive sciences, as already shown in the previous section, which try to describe and classify the mechanisms considered the most important ones involved in the creative process.

Outcomes of studies about analogies and metaphors show that, generally based on reference and precedence, these mechanisms are used by designers to provide conceptual and formal inspiration to structure solutions. Formal inspiration generally comes from iconic analogies such as the one from Calatrava presented in Figure 6.14. Conceptual inspiration comes from more abstract analogies in which rules, systems or patterns, to cite a few, are the most commonly used.

Metaphors are more subtle, and to discuss their meaning is beyond the scope of this study. Rationalists believe they are figures of speech "in which a name or descriptive term is transferred to some object different from, but analogous to, that to which it is properly applicable" (Broadbent 1988) and that they need to be broken down in order to be useful (Broadbent 1988). They are explored in more depth by pragmatists and post-modernists and are going to be discussed in the next two sections.

Reference and precedence can also be used to develop organising principles, concepts, structures or systems used to address specific parts of problem-setting and problem-solving, although principles do not need to be developed only based on reference and precedence. Their source can be wider than that, varying from scientific studies up to common cultural patterns. The most common types of organising principles are the ones based on typology studies, the ones based on systems of proportions and the frameworks provided by building physics.

The legacy: Typologies

Typologies are building classifications based on principles that connect form and function with social systems and social activities. They are widely used in building design as they provide information ranging from lists of types and number of activities to be accommodated up to operational frameworks, structures or systems to support the creation, organisation and spatial distribution of spaces to be accommodated by the building. The most common frameworks used for space organisation and space distribution are the bubble diagram and the zoning diagram (Figure 6.15). The first is a topological structure used to represent the activities and their interconnections. It is an aid to thinking and it is quick to produce (Szokolay 1980). It is an abstract representation of space arrangements that is generally further developed into a zoning diagram. A zoning diagram is a concrete structure used to place the activities in the site and work out their physical interconnections. Zoning diagrams are an important structure used in the generation of the floor plan.

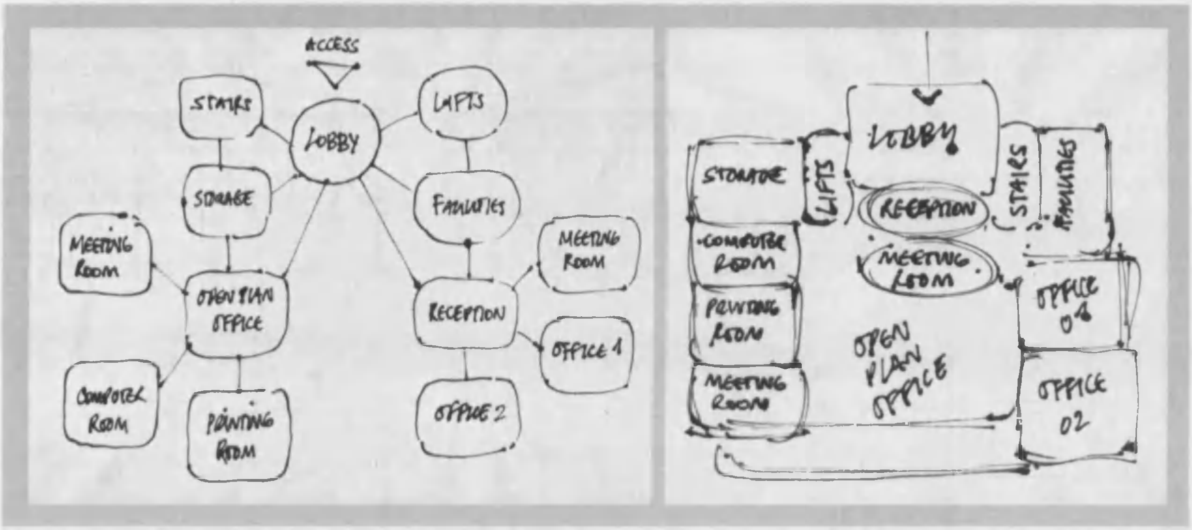


Figure 6.15 – Examples of a bubble diagram and zoning diagram

Other frameworks more abstract than the bubble diagram can be used when the complexity of the task is higher. These include frameworks such as interaction matrices, to list and show compatibilities of activities; link graphs, similar to the ones used in space syntax representations; and flow diagrams, useful to display flows of people and good (Szokolay 1980), to cite a few.

The legacy: Abstract and concrete organising principles

Systems of proportions are a set of geometric rules and structures used to create and articulate form, which vary from grids to geometrical rules expressed graphically and/or mathematically (Figure 6.16). They are also widely used by architects to create a 'geometrical discipline' that helps in starting to generate ideas about form or they can be used to create form directly. Systems of proportions can be developed based on innumerous fundamentals: a theoretical aesthetic discourse, environmental performance, structural performance, ergonomics, to cite a few. They can also be used with different purposes: to express a personal style, to follow a theoretical discourse, to articulate form and ergonomics, to comply with construction standards, etc. Their use and fundamentals are extensively explored in architecture history and theory books as well as in the work of architects individually.

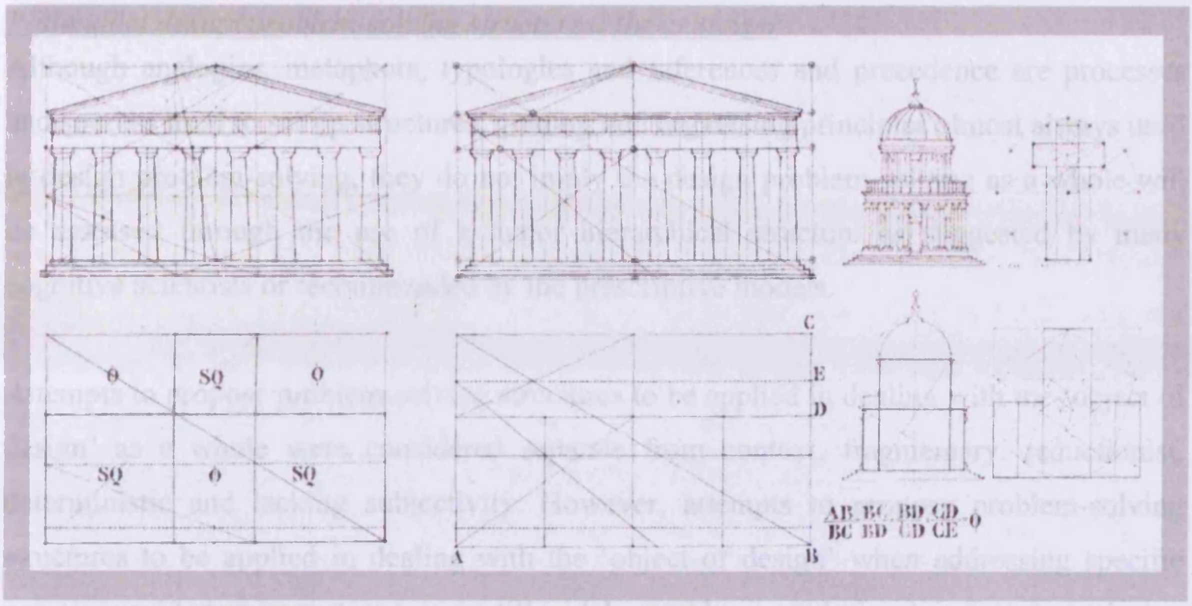


Figure 6.16 – Example of a system of proportions based on a theoretical discourse (Ching 1993).

Frameworks provided by building physics are much more analytical then generational and became extremely developed once transformed into computer tools. However, simple organising principles such as diagrams with directions of prevailing winds, to be used for natural ventilation purpose or wind protection; sun path diagrams, to be used for maximizing daylighting as well as allowing or protecting from direct sunlight inside the building (Figure 6.17); and abstracts or iconic passive design solutions to take maximum benefit of the climate are also used quite often by architects when designing.

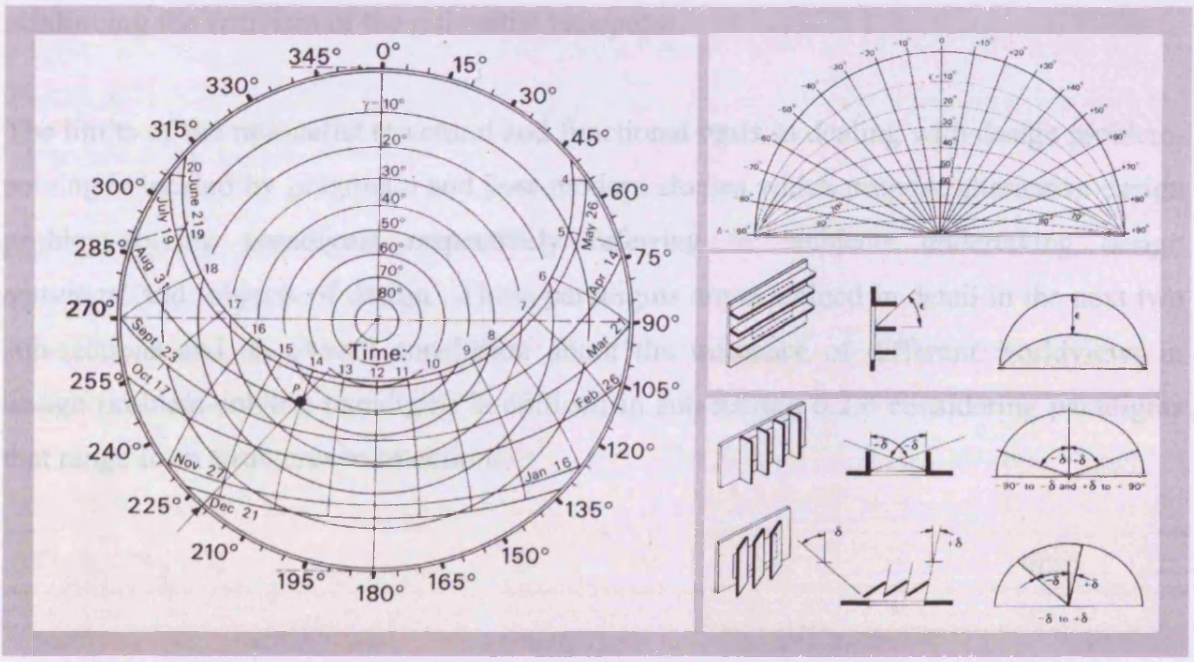


Figure 6.17 – Example of sun path and shading diagram (Szokolay 1980)

Rationalist design problem-solving structures: the criticism

Although analogies, metaphors, typologies and references and precedence are processes and sources used to set up structures, guiding and organising principles almost always used in design problem-solving, they do not imply the design problem-solving as a whole will be assessed through the use of a major hierarchical structure as suggested by many cognitive scientists or recommended by the prescriptive models.

Attempts to propose problem-solving structures to be applied in dealing with the 'object of design' as a whole were considered separate from context, fragmentary, reductionist, deterministic and lacking subjectivity. However, attempts to propose problem-solving structures to be applied in dealing with the 'object of design' when addressing specific points, provided an important legacy still widely used by most designers when designing.

Attempts to propose structures to be applied in dealing with 'subjects undertaking design activities' tried to address some of the aspects left behind by models dealing with the 'object of design'. There was a belief that a shift of focus from object to subject would allow for subjective issues as well as context related to the 'object of design' to be taken into account avoiding determinism and reductionism while manipulating information related to design problem-solving. However, assumptions about the fact that all subjects have a "single language of thoughts" transferred detachment from context, fragmentation, reductionism, determinism and lack of subjectivity from the object to the subject reinforcing the criticism of the rationalist viewpoint.

The limits of the rationalist structural and functional basis in dealing with design problem-solving is tackled by pragmatic and post-modern studies which propose alternative design problem-solving paradigms respectively referring to 'subjects undertaking design activities' and 'objects of design'. These paradigms are examined in detail in the next two sub-sections and an overall conclusion about the influence of different worldviews in design problem-solving paradigms is outlined in sub-section 6.2.4 considering paradigms that range form structures to intentions.

6.2.2. Pragmatism and a conversation with the materials of the situation

"Objectivity in design is not a given but an achievement" (Schon 1988).

Understanding the design problem-solving activity using a pragmatic paradigm was first proposed by Schon 1991 who observed designers in practice and concluded that although designers cannot properly express what they know nor put "their special skill and understanding into words ... their actual designing seems to reveal a great deal of intelligence" (Schon 1988). Pragmatist researchers such as Schon claimed that subject and object could not be separated and that problem-solving and problem-setting should be treated as a single thing, especially in the case of architecture in which ends are ambiguous, less systematic and less dependant on scientific knowledge base.

As a consequence, the focus of the pragmatic approach is on understanding the problem-solving activity as a combination of task and the subject undertaking it, without the assumption that subjects have the same "single language of thoughts" and that there is a single, specific and 'correct' structure to manipulate objects. Subjects are observed in action from which general rules involved in design, explanations about cumulative design knowledge and understating about how novelty arises from particular intuitions are identified. Each design is treated as a 'universe of one', considering designers "respond to the perceived uniqueness of a design situation" (Schon 1988) and principles are carried over from past experience, they "build up repertoires of broadly usable design knowledge" (Schon 1988). Problem and solution co-evolve as there is no analysis followed by synthesis in a rational, procedural way. Everything is a result of the conversation with the materials of the situation.

Schon's design problem-solving paradigm

One of the most important pragmatic frameworks that deals with architecture design is proposed by Schon 1988 after analyzing 7 expert designers performing in action. His framework considers what designers know, how they reason when facing uncertainty and how they deal with uniqueness and conflict and discusses design reasoning based on rules, types and worlds.

Design worlds are "environments entered into and inhabited by designers when designing" (Schon 1988). They are environments within which designers "instantiate a particular set of things to deal with" (Schon 1988), environments constructed with "processes of perception, cognition and notation" (Schon 1988). The idea of world is more comprehensive than a philosophy or simply a worldview, it is also more comprehensive than a kernel or guiding principles because it encompasses not only the designer's ideas or actions but also configurations of things, relations and qualities that are going to be dealt with. The idea of world puts together subjectivity and objectivity, theory and practice, means and ends.

Within design worlds, designers set and develop rules to manipulate types to construct a final object. "All designers make use of rules, as they reason their ways to moves, to draw out the consequences of possible moves, make and evaluate design decisions" (Schon 1988). However, "rules are almost always treated as contingent and contextual" (Schon 1988). They are "treated as relative to the features of the particular context of application, as the designer sees it; and the set of possibly relevant contextual features seem to be open-ended" (Schon 1988). That means rules are contingent, they are "largely implicit, overlapping, diverse, variously applied, contextually dependant, subject to exception and critical modification" (Schon 1988). Different rules might lead to similar decisions and similar rules might lead to different decisions.

Types are more than simple building classifications based on principles that connect form and function with social systems and social activities. They act like "generative abstractions". They are used as exemplars, patterns, analogies, prototypes or they can function as references in which something familiar is recognized "by forming representations of prototypes in relation to which we then recognize and reason about things we perceive" (Schon 1988).

Although Schon 1988 acknowledges that typologies are central to the design task and that the type of problem being solved relates to the functional typology directly, he identifies that it is the problem context and the designer's background that will influence the interpretation of the problem. From these observations he describes the four following 'types' used by designer:

(i) Functional types,

(ii) References,

(iii) Spatial gestalt and

(iv) Experiential archetypes.

Functional types are effectively the rationalist typologies. They act like functional guides from which buildings or physical environments (whole or parts) are used as primary sources of information to supply premises in chains of design reasoning. "Types are holding environments for contextual knowledge that can be 'read off' them ... they are used to make the design situation coherent, to frame it so that designers can reason about it" (Schon 1988). They are considered "as particulars that function in a general way or as general categories that have the 'fullness' of particulars" (Schon 1988).

References function as guides to designing. They are generally remembered buildings or kinds of buildings in particular that provide either leading or specific ideas suggesting or justifying moves. Their concept is very similar to the one provided by rationalists.

Spatial Gestalt is the spatial perception of the problem. It is a metaphorical description of the position, dimension and shape of a coherent figure, a "coherent whole perceived as such" (Schon 1988) used by designers to see configurations, patterns of elements forming a whole in which parts are so interconnected that the whole cannot be described as simply the sum of them.

Although the Gestalt psychology theoretical framework is not accepted anymore (Rowe 1987), its laws are still useful to empirical generalizations concerning figure perceptions. The four most important Gestalt laws useful to design are described in Mitchell 1990:

(i) Laws of similarity, in which "figures close to each other tend to be grouped into a unit" (Mitchell 1990);

(ii) Laws of closure, in which "shapes with closed contours tend to be seen as units" (Mitchell 1990);

(iii) Laws of good continuation, in which "relatively smooth, uninterrupted contours also help to define units" (Mitchell 1990) and

(iv) Laws of symmetry, in which "symmetrical objects tend to be seen as units" (Mitchell 1990).

Spatial Gestalt plays a crucial role in designing "they are literally the figures on which designers reason" (Schon 1988). Parts are not seen as conventional elements of Euclidean geometry (points, lines, angles) they are "constituent units that function in the designer's perception to make up the figure he sees in the works on the page" (Schon 1988). When laws are weak or contradictory figure-ground reversals happen and designers become aware of new figures (Mitchell 1990). Spatial Gestalt provides an explanation about how ideas are instantiated from ambiguous ways of seeing figures. The ability to see figures as aggregations of elements is essential, as figures have elements that function in the designer's perception to make up the figures designers see on the page (Schon 1992). Seeing a new figure might mean setting a new problem (Schon 1992). As rules that drive designers reasoning make reference to and depend on their way of seeing the perceptual geometry that has been acted upon, different designs arise from people constructing different figures.

Experiential archetypes are "images of experienced objects or settings in the built environment with experiential significance" (Schon 1992). Archetypes tend to be described through metaphors. They function as generative images for reasoning like references but instead of being used for workability purposes they are used as 'poetry'. They generally appear when the designers put themselves "in a position of moving through the spaces, feeling what it would be like to move in them" (Schon 1988), providing original models for patterns of experience. Experiential archetypes are used to rescue unworkable situations of reasoning.

Analogies and metaphors in pragmatic design problem-solving paradigms

In the same way that analogies are widely used by rationalists as one of the main resources of design reasoning, metaphors are used by the pragmatists mainly for reasoning about spatial Gestalt and when using references and experiential archetypes. There are many different philosophical theories about metaphor, and it is beyond the scope of this work to discuss them. However, because some pragmatists use metaphors as a counterview to method when talking about design (Coyne 1995), it is important to outline that the most important terms related to metaphors are analogy and simile and that its use is "essential to truth and understanding" (Coyne 1995). Metaphor is not purely a linguistic phenomenon but it is also implicated in perception, mainly in "seeing as" in which "one term, concept or situation is projected onto another" (Coyne 1995).

Metaphors have a wider meaning than analogies because they "elevate the role of imagination" (Coyne 1995) and they can be used either as models, like in science, or to convey a new and extended meaning like in literature and poetry. Contrarily to what is believed by rationalists, "they need not be broken down in order to be useful or meaningful" (Coyne 1995). They are irreducible. They need to be interpreted to be understood and their interpretation is contextual. They provide a different approach to practice in which fixed and predefined problem statements do not apply. They define orientations, provide insights into the workings of practitioners and suggest new action. They emerge from investigations of the problem and the designer's engagement with a situation enabling different ways of understanding a design in progress. "Metaphors assist us in setting the problem we try to solve" (Coyne 1995) by providing "different ways of understanding a design in progress as the designer shifts from one metaphor to another" (Coyne 1995). They provide examples of reasoning such as "space as fluid" which suggests and opens up possibilities for different ways of treating space; "building as a machine" used to make more evident the functional aspects of a design; among many others from playing with geometry and identifying shapes, to identify analogues from precedents (such as in the case of iconic analogies for instance).

Analogies and metaphors influencing Schon's design problem-solving paradigm

Functional types and references tend to be explicitly invoked whereas spatial Gestalts and experiential archetypes tend to be implicitly invoked. However, references and archetypes "guide the selection of rules to be taken as salient" (Schon 1988). They are leading ideas at various zones in the process, "used to generate sequences of design experiments, including chains of reasoning, consideration of possible moves, detection of consequences and implications and choices" (Schon 1988). In any case, types are used to derive rules, to test and criticise them. "Designers ability to apply a rule correctly depends on familiarity with an underlying type, by reference to which the designer judges whether the rule 'fits the case' and fill the inevitable gap between the abstract rule and the concrete context of its application" (Schon 1988). Types with their "constituent things and relations, forms, materials, construction methods, ways of organizing space and symbolic vocabularies ...

provide the furniture of a design world … to be assembled to produce an artefact that comes to function" (Schon 1988). They illuminate how designers go from abstract to concrete.

Schon's 1988 framework can be summarized in Figure 6.18, a non-hierarchical diagram that displays how each design world is composed of interrelated rules and types. In this framework there is no distinction between problem-setting and problem-solving as they are both embedded in the design world. Each world is contextual, contingent and design dependant, therefore there is not a single model of design world but a universe of types and rules that can be connected and interrelated according to different ways of reading and interpreting a design task producing, as a consequence, different objects of design.

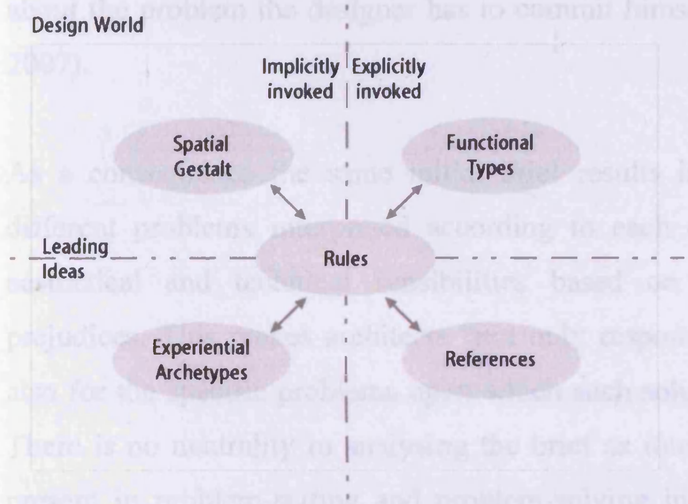


Figure 6.18 – Interpretation of Schon 1988 framework for architecture design

Schon 1988 framework is an example of how pragmatists see design problem-solving. Further studies under the same worldview will corroborate the fact that there is not one single problem structure. Structures are idiosyncratic to each designer and set up based on interpretations of the problem they have every time, the context of this problem and their previous experience in problem solving. Problem and solution are not two separated entities but they co-evolve into a proto-solution going from constant to discrete restructuring towards a final and coherent 'object of design'.

Problem framing – Co-evolution of problem and solution

Harfield 2007 demystifies the idea that there are many solutions to a single problem showing instead that there are actually many solutions to each different problem, after running an experiment using an architecture competition as a theme in which all designers analysed the same brief but each of them developed their own problem characterisation. Most studies assume the designer task is to solve a problem according to that determined in the brief. However, the brief is used only as a set of initially specified requirements. The designers will then particularise requirements, order them hierarchically, establishing criteria to set up the solution and to judge its satisfactoriness. Criteria are generally not part of the brief but "have been added by the individual designer in response to that brief" (Harfield 2007). In this sense there is a heavily ideological attitude to design and design thinking. "A design problem and its solution are linked in such a way that in order to think about the problem the designer has to commit himself to some sort of solution" (Harfield 2007).

As a consequence the same initial brief results in different solutions originated from different problems interpreted according to each designer viewpoint, position, formal, aesthetical and technical sensibilities based on prior experiences, preferences and prejudices. This makes architects "not only responsible for the solutions they create but also for the specific problems upon which such solutions are predicated" (Harfield 2007). There is no neutrality in analysing the brief as intentions and impositions of the self are present in problem-setting and problem-solving in architecture. Architects impose their views, positions and preferences in seeing the brief and in constructing the problems to be solved, defining and limiting the solution possibilities available to them (Harfield 2007).

Problem and solution co-evolve depending on the interpretation of the designer. They co-evolve through the designer's transaction with the situation in which the problem space is explored from a particular perspective "in order to frame the problem in a way that stimulates and pre-structures the emergence of design concepts" (Cross 2004). Problem setting involves naming the things to be attended and framing the context in which they will be attended. "It is rather through the non-technical process of framing the problematic situation that we may organise and clarify both the ends to be achieved and the possible means of achieving them" (Schon 1991). The enquirer imposes an order of his/her own and takes responsibility for the order he imposes. At the same time the enquirer tries to shape the situation to his frame, understanding that he must act in accordance with the view he has adopted but must recognize that he can always break it open later in order to make new sense of his transaction with the situation (Schon 1991).

Framing replaces structure in the pragmatic discourse. Framing is the way problem and solution are articulated. Framing is a tool used to intuitively or deliberately match problem and solution (Figure 6.19). “When shaping the situation to the frame (designers) evaluate the entire process by: whether they can solve the problem they set; whether they value what they get when they solve it; whether they achieve in the situation a coherence of artefacts and idea, a congruence with their fundamental theories and values; whether they can keep inquiry moving” (Schon 1991) towards refinement.

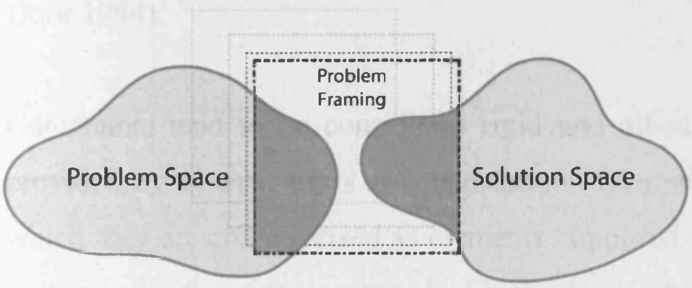


Figure 6.19 – A proposed diagram for problem framing

Framing is not as rigid as a structure, it involves a set of axioms used to perceive the problem and propose a solution to it (Schon 1984). Framing can be considered analogous to the idea of placement introduced by Buchanan 1995, tools used to provide a coherent starting point from which boundaries to shape and constrain meaning are also used to generate new ideas and possibilities. Frames or placements are used to discover or invent a working hypothesis, to establish “a principle of relevance for knowledge from the arts and sciences, determining how such knowledge may be useful to design thinking in a particular circumstance without immediately reducing design to one or another of these disciplines” (Buchanan 1995).

Framing can be understood as a tool used to construct a design world in which “underlying patterns or themes that enable a designer to recognize and make a connection with some precedent in episodic memory” (Lawson 2004) emerge as well as possibilities “to work with parallel lines of thought, to maintain openness, even an ambiguity, about features and aspects of design at different levels of detail, and to consider these levels simultaneously, as the design proceeds" (Cross 2004) are allowed to happen. They depend on rules to manipulate types and such rules might include either the legacies of rationalism or simply be based on constraints and criteria.

Constraints and criteria in design problem-solving

Constraints and criteria, useful elements to frame design problems are both contextual. The former are used to "organise internal relationships of objectives within a design problem and equally establish relationships between the design problems and its larger settings (Portillo and Dohr 1994). And the latter are "a measure of value used by the designer to conceptualise, test and evaluate the project purpose in the design process" (Portillo and Dohr 1994).

Constraints tend to be considered rigid and allied with specific requirements generally provided by clients, users and legislation. They are widely explore in Lawson 1997 in which they are characterised as elements "imposed to ensure the design system and object performs the function demanded of it as adequately as possible" (Lawson 1997). They are classified as internal and external in which the former comprise "all established relationships between elements of the object being designed" that are internal to the problem, mainly the brief, and the latter "relate the design object to its context, site, boundaries, sun, street, etc" elements that are external to the problem but set the circumstance that make the design unique. Besides that they are further classified according to the way they function to guarantee the object will perform as adequately as possible into:

(i) Radical constraints, which are fundamental and influential since the beginning of the process determining the reasons for having the design in first place;

(ii) Practical constraints, which deal with the reality of producing, making and building the 'object of design' but also consider the technical performance of this object during its working life;

(iii) Formal constraints, which include rules about form and aesthetic principles (grids, modular systems, geometrical rules, etc.); and

(iv) Symbolic constraints, which address the symbolic properties of design, its expressive qualities.

Criteria on the other hand tend to be flexible, used to reference functions to evaluative processes based on purposes. They are widely explored in Portillo and Dohr 1994 who acknowledge criteria as necessary to integrate process and solution, operationalizing different purpose levels of a problem that need to be translated into a physical form, as well as to help establishing "an initial conceptual direction to be referred to when testing and evaluating ideas and solution" (Portillo and Dohr 1994).

They are classified into 5 different types:

(i) Compositional criteria, used to manipulate form and space;

(ii) Symbolic criteria, used to represent design concepts;

(iii) Behavioural criteria, used to meet activity needs;

(iv) Preferential criteria, used to represent preferences of individuals of market trends; and

(v) Pragmatic criteria, used to consider economic or physical preconditions.

In any case, problem statement, criteria, and solutions all evolve together and have a symbiotic relationship (Harfield 2007). "Design problems are multidimensional and highly interactive" (Lawson 1997). "In design it is frequently necessary to devise an integrated solution to a whole cluster of requirements" (Lawson 1997). Stability, aesthetics, cost, availability of materials, etc. are not thought separately. "A good design is usually an integrated response to a whole series of issues ... It is often not possible to say which bit of the problem is solved by which bit of the solution ... the whole picture is in each fragment" (Lawson 1997).

Proto-solution and constant re-framing

Creative solutions arise especially from conflicts between designers own high-level problem goals and personal commitments with criteria for acceptable solutions established by clients. "Expert designers appear to be ill-behaved problem solvers" (Cross 2004) and a key feature of expertise is to spend time and attention in problem framing (Eastman 2001 and Cross 2004). Framing implies a connection with the designer's own views of the world and suggest not the setting of many alternatives but an upfront commitment to a specific one (Schon 1984).

In framing, problem and solution co-evolve into a proto-solution, a specific alternative used to initiate problem investigation. The analysis of problem and solution is mutually informative therefore a proto-solution is used for comparing goal state and problem state. "We can only commit to certain assessment criteria for a given solution once we have a proto-solution from which to generate such criteria ... The proto-solution is coextensive with the very problem it creates ... the problem as given necessitates a proto-solution that in turn becomes the design problem, the first in a series of developing problem-solution pairs" (Harfield 2007).

A proto-solution can also be understood as a design concept, a starting point from which the designer learns more about the problem but at the same time make appreciative judgements about how it is getting solved. This starting point is not fixed or rigid it acts like a hypothesis from which further moves are going to be undertaken and evaluated. Criteria, constrains, rules and types are constantly redefined through cyclical iterations of moves and appreciations putting the proto-solution under constant reframing, or according to a more rationalistic viewpoint, constant restructuring. Problem structuring is not exclusively an activity of the early stages of design but reoccurs periodically throughout the task (Cross 2001). The constant reframing reflects a shift from tentative adoption of a strategy to eventual commitment (Schon 1991). As the designer proceeds, the choices become more committing and the moves more nearly irreversible. The deepening of commitments to a chosen frame results in a broader coherence of the artefact and idea (Schon 1991).

Pragmatism and a conversation with the materials of the situation

In the pragmatic approach to design problem-solving, the unique features of a problematic situation lead practitioners to undertake problem-setting experiments. There is no room for applying a rule from past experience or the uniqueness of the situation will be ignored. But a brand new description of the problem is also not invented from scratch. Practitioners have a repertoire of examples, images, understandings and actions. Sites seen, buildings known, design problems encountered, solutions achieved are all used in framing the present, unique situation. Whenever seeing a situation the practitioner sees and acknowledges that unfamiliar, uniqueness as both similar to and different from a familiar one, not realising similarities and differences in respect to what. Seeing and doing proceed many times without conscious articulation. Unfamiliar situations are seen as familiar ones bringing past experiences to unique cases. It is about getting a feeling for the problem not trying to fit it into existing rules. Practitioners develop a varied repertoire to be brought into unfamiliar situations. They are able to see entities they are dealing with as elements of their own repertoire, to make sense of their uniqueness and to avoid reducing them into instances of standard categories. Each new experience enhances one's repertoire (Schon 1991). "A unique case may be generalised to other cases, not by giving rise to general principles, but by contributing to the practitioner's repertoire of exemplary themes from which he may compose new variations" (Schon 1991).

Artistic judgement is generally based on a sense of form that cannot be fully articulated. The reasoning is very much based on the fact that it is much easier and clearer to recognize what is bad, or a bad fit of a from into its context then recognize the corrected form to be good (Schon 1991). "Architectural design is ... a hybrid practice in which the problem-setting and –solving involved in making workable buildings overlaps and interacts with the development of architectural works of art" (Schon 1988).

In any case, design depends on abilities of designers to make normative judgments of quality based on a system of beliefs, values, norms and prizing possessed by individuals, shared by groups or cultures (Schon 1992). That means "criteria of success or acceptability for solutions are themselves similarly ill-defined and flexible ... significant aspects of acceptability criteria change and develop in response to parallel changes and developments in aspects of the emerging problem" (Harfield 2007). "As long as judgments of significant scale are internally consistent, at least in this design episode, their 'subjectivity' is no obstacle to designing" (Schon 1992).

In the pragmatic approach the idea of structuring problem-solving disappears in a conversation with the materials of the situation. A designer "through his transaction with the situation, shapes it and make himself part of it. The sense he makes of the situation must include his own contribution to it" (Schon 1991). "Architectural design is a dialogue with the phenomena of a particular site" (Schon 1988). Making involves appreciating the site as well as imagining a building. "Designers construct their design worlds not only through the shaping of materials but through interlocking processes of perception, cognition and notation" (Schon 1988). Things are not what they are independent of the way we see them, they are hermeneutic.

For the pragmatists there is no structure. There are idiosyncratic worlds subjects move within, populated by elements that help them shaping the object they are designing. Subjects interact, converse with these elements and the object is shaped while these conversations are undertaken.

6.2.3. Post-modernism and `meanings'

"Architecture does not bear its meaning primarily by conventional and arbitrary associations of signifier with signified as does language, but by re-creating, re-collecting, re-constructing and re-producing the structures of the vital settings and situations of our primeval past" (Benedikt 1991).

The post-modernist approach to architecture is also vast, with many different viewpoints as alternative reactions to rationalism. It also treats design problem-solving idiosyncratically and contingently not separating the objective from the subjective, means from ends and theory from practice but, contrarily to pragmatism, it focuses on the 'object of design' concentrating on its meaning rather than function. Post-modernism also strongly emphasises precedence, specifically historical precedence, and provides methods of analysis and makes extensive use of metaphors.

It is important to say that the post-modernist discourses come from post-modern philosophies applied in practise, not from design research. Therefore most of the literature about it comes from practised architects describing their way of thinking showing how this was transposed to their architectural work. This explains why the focus is generally on the 'object of design' and at the same time acknowledges the idiosyncrasies involved in these objects and the methods used to generate them. What under the rationalist view was generic under the post-modernist view is totally particular.

One of the most important expressions of the post-modernist discourse in architecture is Venturi's 1977 manifesto. His text is a reaction against Modern architecture, claimed to be extremely reductionist and deprived of meaning, followed by an apologia of a specific way of seeing architecture comparable to literary criticism. The use of literary criticism to analyse architecture provides a significant paradigm shift in understanding and working with the 'object of design'. Performance is replaced by meaning and the methods do not need to be scientific anymore but can explicitly follow what goes on with the arts and humanities.

Architecture can now be analysed using the philosophies of phenomenology, hermeneutics and deconstructivism if understood not as a language but as something analogous to a literary discourse. However, it can also be analysed in the light of critical theory and deconstruction if focusing on the socio-cultural aspects of design and criticising the current state of affairs of design practice.

Venturi and the post-modernist manifesto

Venturi 1977 brings a phenomenological and hermeneutic approach by comparing architecture with literary criticism. His discourse is based on thoughtful considerations of precedence populated by historical comparisons. "The historical sense involves perception, not only of the pastness of the past, but of its presence" (Venturi 1977).The historical sense is used to understand context also throughout time, paraphrasing Venturi 1977; compelling a designer not to design merely with his own generation in his bones, but with a feeling that the whole architecture of Europe… "has a simultaneous existence and composes a simultaneous order" (Venturi 1977). The historical sense is important because it makes the designer traditional and "at the same time conscious of his place in time, of his own contemporaneity" (Venturi 1977). Essentially there is no meaning alone, either in space or in time.

In this frame of mind Venturi 1977 re-examines mainly the Mannerist, Baroque and Rococo architecture styles "not to repeat its forms but rather in the expectation of feeding more amply new sensibilities that are wholly the product of the present" (Venturi 1977). His focus of analysis is in complexity and contradiction. He talks exclusively of architecture as something self-contained, not related to anything else, not connected with science and technologies or with humanities, leaving relationships and power to take care of themselves. He admittedly treats architecture purely as an art, concentrating on its particulars "because the arts belong to the practical and not the speculative intelligence, there is no surrogate for being on the job" (Venturi 1977). He deals with the past in relation to the present and attacks the limitations of modern architecture with regards to its rationale blaming it for suppressing complexities and contradictions involved in the arts.

In his manifesto, Venturi 1977 welcomes problems and exploits the uncertainties claiming richness of meaning rather than clarity through several readings and interpretations. He highlights the hybrid, compromising, distorted, ambiguous, personal, conventional, accommodating, redundant, inconsistent and unequivocal rather than the pure, clean, straightforward, articulated, impersonal, 'designed', excluding, simple, direct and clear Modern view of the world. He is in favour of an interdependence of form and function, exploring and acknowledging the variety inherent in the ambiguity of visual perception. This ambiguity is dealt with through exploring complexities and contradictions that result from a juxtaposition of what an image is and what is seems, i.e. between form and expression, as well as "complexities and contradictions related to form and content as a manifestation of problem and structure" (Venturi 1977). The whole idea is to rescue the unity of experience using paradox and ambiguities to intensify it.

Experience is intensified exploring complexities and contradictions, all expressed in form. Contradictory levels of meaning with basis on a hierarchy, "which yields several levels of meaning among elements with varying values" (Venturi 1977), are used to evoke simultaneous perception of a multiplicity of levels, for instance open and closed, structural and spatial, round and squared, etc. Apart from that, complexities and ambiguities involved in multi-functioning buildings, rooms and elements are extensively explored as opposed to the rigid specialization and limited functioning of Modern propositions (examples are: rooms with generic purposes, elements used for space enclosure and supporting purposes, etc.).

Exceptional inconsistencies that modify the consistent order or inconsistencies throughout the order as a whole are also explored. In the first case, "contradiction is adapted by accommodating and compromising its elements" (Venturi 1977) or contradiction is juxtaposed showing contrasts and violent oppositions. Examples of both are shown with regards to architectural elements in façade and structural composition. These same concepts are then expanded further into contradictions between the inside and the outside, varying from explorations of continuity between both, through subtle modification, little contrast, no surprise, up to expressive differentiation between both through enclosures within enclosures, spaces in between, etc.

In the second case, "the difficult whole in architecture of complexity and contradiction includes multiplicity and diversity of elements and relationships that are inconsistent or among the weaker kinds perceptually" (Venturi 1977). Multiplicity and diversity can be dealt by using complex and contrapuntal rhythms in positioning parts, by changing scale of parts for them to be perceived as overall textures or patterns, by exploring dualities, etc.

Venturi 1977 does not provide a concrete language with clear rules or a method with a clear general scheme for the whole. He provides a visual method based on a symbolic analysis of individual buildings from the past to be used as a source of inspiration to construct meaning when designing new buildings. Conceptually his emphasis is directed towards meaning conveyed by form. Methodologically it is fragmentary, based on a step-by-step sequence of relationships similar to the systematic analysis of the Beaux Arts in programmatic and visual terms (Scully in Venturi 1977). He claims it to be based on literary criticism and uses metaphors accordingly however the result is more an interpretation of architecture in the view of the Fine Arts.

Another important expression of post-modernist discourse is presented in the books of Peter Eisenman whose post-modernist 'manifesto' is inferred from his work together with the discourse that precedes it. His discourse, strongly based on post-modern philosophy translates into a design method in which the basic aim is to subvert the form to question its meaning. In order to do that he deconstructs his own way of designing, his design process, to show how the aims are expressed in the resultant 'object of design'.

Eisenman and Deconstructivism

Eisenman's method can be identified from his publications such as in Eisenman 2002a, 2002b, 2002c, 2002d, 2002e. Similarly to Venturi 1977, he refers to the literature when talking about his own design processes. His method starts with a concept, in the case of

Eisenman 2002a to e, the concept of blurring. This concept is philosophically explored in terms of meaning, producing a meta-narrative that might be used in a single building or many different buildings. This meta-narrative is the main source of inspiration to create different narratives (Figure 6.20) specifically developed into metaphors to produce disruption and subversion in the architecture form to be created.

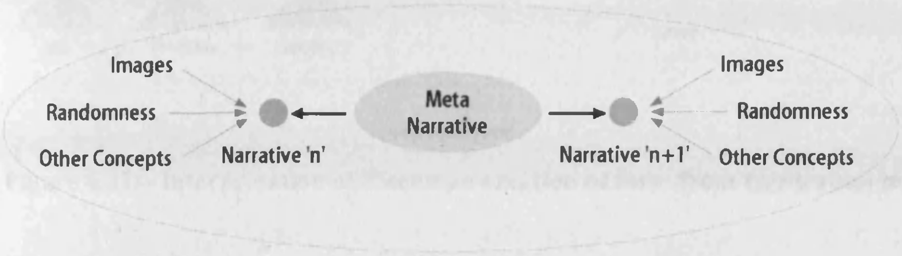


Figure 6.20 – Interpretation of Eisenman meta-narratives and narratives

Eisenman's method creates forms based on the relationship between three different textual materials:

(i) The first textual material is "the textual material with immediate information on which a specific design is based" (Eisenman 2002a) that is the site, the program and the function. It provides information similar to what is outlined in the rationalist models.

(ii) The second textual material is the textual material of interiority and anteriority, in which interiority defines "what it is that makes architecture singular (and) anteriority is the sedimented history of architecture, which has defined architecture at any given historical moment" (Eisenman 2002a). It provides information similar to the one outlined by Venturi 1977 when dealing with the past in relation to the present in order to express meaning, i.e. it acknowledges precedence to expand and give meaning to discourses that are going to be used to build up form. However, instead of using only these two textual materials to create and legitimise form (Figure 6.21), he proposes the introduction of a third textual material.

(iii) The third textual material contains a narrative (developed mainly from the meta-narrative) used to blur the relationship between the former two textual materials, a narrative that disrupts the idea that function and image are used to legitimise this form. He questions precedence and functionalism and introduces extra elements that can also be used to define the 'signature' of an architect (Figure 6.22).

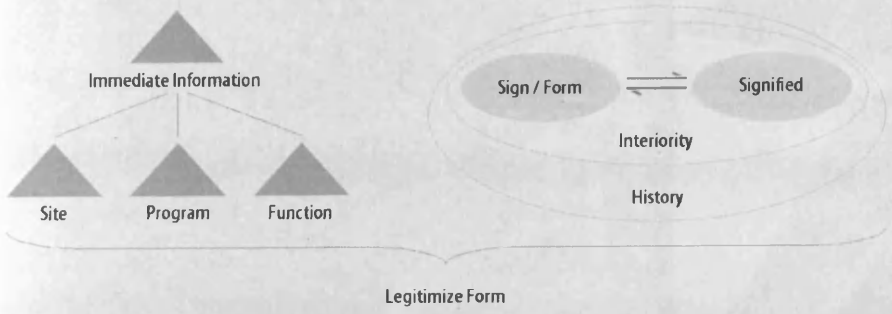


Figure 6.21 – Interpretation of Eisenman creation of form from two textual materials only

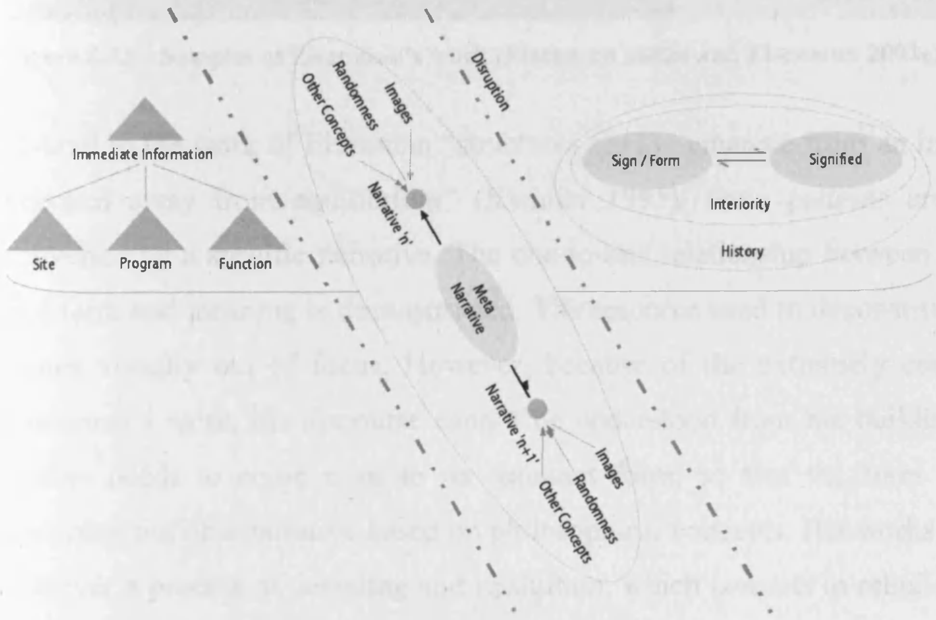


Figure 6.22 – Interpretation of Eisenman creation of form from three textual materials

Eisenman's intentions are clearly to blur the relationship between form, function and meaning by producing architectural effects to displace the 'traditional' ones. The result is that forms are no longer motivated by site, function, program, interiority and anteriority but appear to be 'out of focus' once the third narrative is superposed to them. Figure 6.23 illustrates some of the formal outcomes of this process. The first two images show how the concept of façade, which can be literally interpreted as the faces of a building expressed iconic and symbolically in its vertical planes, is blurred allowing the vertical planes to be something else. The last image shows how the solid/void relationships of a volume are disrupted, resulting in a figure containing "little resemblance to any known configuration" (Eisenman 2002e).

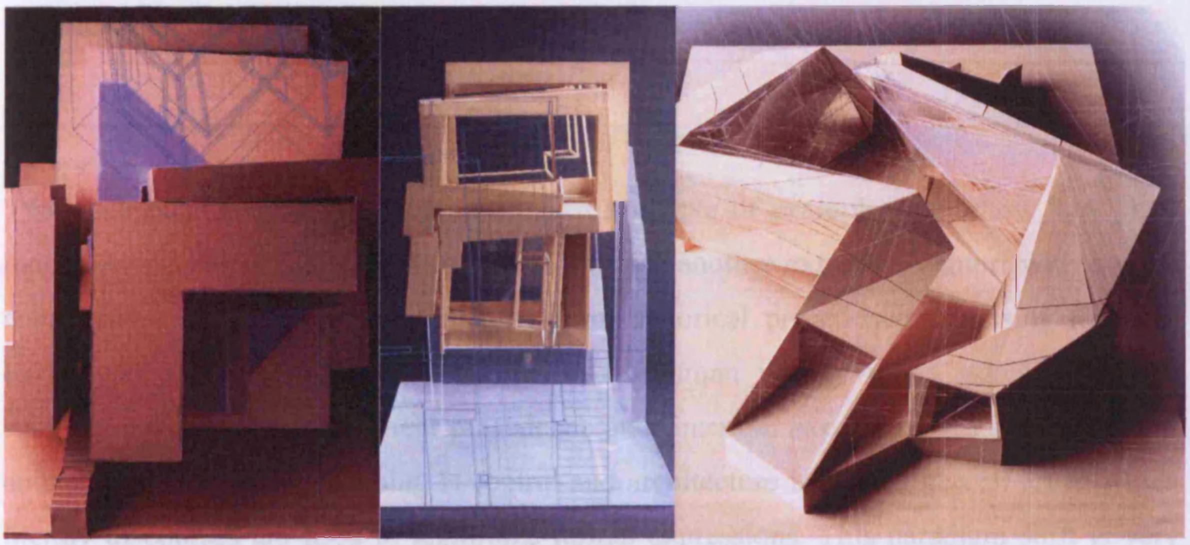


Figure 6.23 – Samples of Eisenman's work (Eisenman 2002a and Eisenman 2002e)

Overall in the work of Eisenman "structures always emanate from an initial pattern that is knocked away from equilibrium" (Kwinter 1995), basic patterns are always formally subverted by a specific narrative. The one-to-one relationship between form and function and form and meaning is deconstructed. The resource used to deconstruct is to blur, to put things visually out of focus. However, because of the extremely conceptual nature of Eisenman's work, his discourse cannot be understood from his buildings. The discourse always needs to come prior to its resultant form, so that the form makes sense as a metaphor out of a narrative based on philosophical concepts. His works "demand from the observer a process of decoding and restitution, which consists in rebuilding a sense of the compositional operation from its origin" (Purini 2002). Each building is a manifesto to be disclosed and interpreted in which the conventional status of architecture is deconstructed (Purini 2002).

Eisenman's ideas go beyond Venturi's ones. The past is not used as a source of inspiration about meaning conveyed by form. The past is used as the ground of something to be subverted. This subversion is considered by Eisenman himself as ultimately a subversion of the political system and transnational capital which demands clarity, utility, standardization and technological processing. The subversion is expressed in form and space. The past is expressed in the layers of superimposed grids and subversion happens in the fragmentary nature of architectural objects which became ambiguous in terms of their roles. A façade is not a 'face' anymore and the volumes cannot be easily read. Interstitial spaces cannot be consumed because they are no longer legitimised by utility and significance. (Eisenman 2002).

'Meaning' legitimizing formal expressions

The work of Eisenman and Venturi are just a couple of examples that show how post-modernist discourse in architecture has fallen into another extreme. Venturi with a more conservative discourse rescues meaning from historical precedence criticising meaning exclusively derived from function whereas Eisenman with a more radical discourse subverts meaning from historical precedence and function, expressing his subversions as an artist. In both cases, meaning is central and architecture is treated like an art in which literary discourses are used to legitimize formal expressions. This paradigm shift is very well illustrated and debated in Capon 1983 when analysing derivations and precedence in architectural theory and design. An interpretation of Capon's texts suggests Figure 6.24 which shows the emphasis of modernism and rationalism in form and function as opposed to the emphasis of post-modernism in form and meaning.

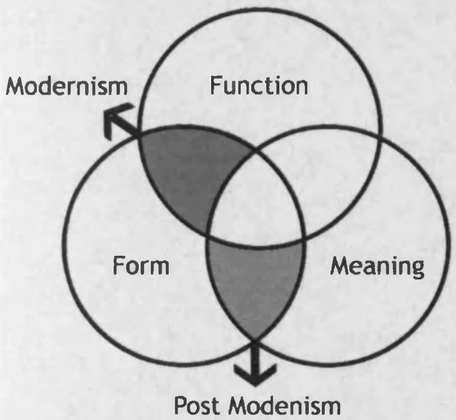


Figure 6.24 – Interpretation of Capon 1983 focus of architectural theory and design

The reorientation of the architectural discourse towards form and meaning suggests "functionalism as a formal device is … passé" (Harris and Lipman 1989). "Architecture stretches beyond the everyday, the mundane; it refers to the art of building … the product of an artistic intervention, not like, building of necessity" (Harris and Lipman 1989). "Architecture separates itself from the act of building" (Ward 1989). It is treated as an art.

When moved away from the act of building, from the craft of construction, from "knowledge and experience that man accumulates in dealing with the contingencies of providing shelter" (Harris and Lipman 1989), architecture started sharing the "extreme sophistication of the collective myth about art (which) relegates rationalism to an 'inferior' form of knowledge" (Ward 1989). The practices of the Beaux Arts are rescued and a trend to go back to "free expression of design concepts undiluted by practical constraints" (Ward 1989) becomes the norm. The ideas are all that matters and "paper architecture is once more a significant currency" (Ward 1989). There is a "primacy of self-expression, supported by a doctrine of value relativity" (Ward 1989). When moving towards art "the essential mystification of the architectural paradigm remains intact, since it is never possible to subject it to systematic analysis" (Ward 1989). Design under this paradigm is a non-analytical process, it is said to be liberating, non-objective, daydreaming encouraged, personal and extremely preoccupied with the visual.

An example of a reaction towards this is presented by thinkers who analyse architecture in the light of deconstruction and critical theory claiming that the post-modern discourse adopted in architecture was a copy of formal languages of visual arts, with some references to the literature instead of the discourse coming straight from philosophy and human sciences.

Deconstructionism rather than deconstructivism

Benedikt 1991 provides an example of deconstruction applied to architecture claiming that deconstructivism is only one way of reading deconstruction. Deconstructivism is an aesthetic style derived from principles of deconstruction, the philosophy. He questions how well Derrida's ideas are expressed in architecture and attempts to propose how these ideas could be applied to architecture. He questions deconstructivists: "If deconstructivist buildings are texts before they are buildings, why then are they not best left unbuilt, in the interest of not compromising their necessity rhetorical freedom?" (Benedikt 1991). After all "can anyone read this building with the building?" (Benedikt 1991). "The way architecture means is not a strong analogue to the way language means" (Benedikt 1991). Besides that, "deconstruction is not interested in the form per se" (Benedikt 1991). It is interested in the form and motion of the ideational content delivered by this language.

As a result, "the value of deconstruction for architects lies in the way it can suggest finer strategies for design and critical thoughts in architecture in general" (Benedikt 1991). He suggests deconstruction principles should be used to analyse design structures not to construct buildings that pose themselves as deconstructing texts. In this frame of mind he illustrates how four essential principles of deconstruction can be applied to analyse structures:

(i) Différance;

(ii) hierarchy reversal;

(iii) marginality and centrality;

(iv) Iterability and meaning.

Différance is a concept that means differences, distinction between things, "dimensions along which items in a vocabulary separate themselves from each other" (Benedikt 1991). It also means deferral, the process of postponing, "a spacing in time" (Benedikt 1991) and differing, as in disagreeing, dissembling. "Différance exists as a primary shift, as a distinction making" (Benedikt 1991) with its most common example and most fundamental distinction in 'presence and absence' in which difference is in their interdependence, in the fact that one cannot exist without the other. Without difference there is no meaning. "Absence lies behind and mirrors presence always" (Benedikt 1991). This concept can be widely explored in architecture from the setting up of benchmarks, the representation of presence of an absent scale that conveys quantitative meaning about something, to combinations of form in which minimally indicated elements, most intensely undetermined, questioned or obliterated, have greatest presence. Presence and absences are also extremely useful to manipulate structures used for problem-solving suggesting what should and shouldn't be included as well as how things should be included and left behind.

"The idealisation of presence in Western metaphysics ... causes all systems of distinctions and categories to be hierarchical, hierarchical in the sense that one term dominates by overshadowing or occluding the others with its 'extra' presence" (Benedikt 1991). "Différance is the source of all categories and oppositions" (Benedikt 1991). Opposite, absent and 'lowly' members are subordinated or suppressed, even when logically necessary and logically preconditioned to the same whole scheme. That means not only that any structure is excludent but also that in order to set up a structure it is necessary to suppress or subordinate opposite, absent or lowly members.

Deconstruction then proposes to "identify what is being suppressed in some hierarchy or bifurcation of ideas" (Benedikt 1991) and undo it, overturn it, run backwards, reverse the polarity of the hierarchy to reach a better truth. The aim of hierarchy reversal is to see the idea behind the idea, to see things upside-down, to see "what was at stake for the author" (Benedikt 1991). This concept can also be applied in architecture to see how structures of these oppositions proliferate and reappear in different contexts and to address the management of oppositions within structures. Using the principle of hierarchy reversal "buildings can be analysed along a number of dimensions into a number of clusters or systems, or aspects, ideas, parts, categories" (Benedikt 1991).Styles can be constructed based on a set of principles of expression/suppression of elements within different taxonomies, i.e. different hierarchical organisation of terms. Originality lies in the invention of new structures or in the revision and enlargement of old ones opening up "new opportunities for valorisations and repressions" (Benedikt 1991). The whole idea is to make clear that metaphysics is not in structures and that the form and content of structures should be analysed and criticised.

Marginality and centrality are presented as the interdependencies of the essential and the supplement, ideas that are complementary to hierarchy reversal and difference. This idea is explored by Benedikt 1991 as a metaphor to analyse space in which marginality can be understood as the frame, boundary "along which what is 'inside' becomes 'outside'" (Benedikt 1991) and centrality implies the notion of heart, "the place of concentrated meaning, ... the points at which action originates from within and the destination at which finally arrives from without" (Benedikt 1991). Many other metaphors can be derived from this concept. The idea of essential and supplement can also be used to manipulate a whole discourse for instance organising principles, typologies, etc. when manipulating problem-solving structure.

"Architecture is hardly possible ... without the extensive repetition of material components, geometrical configurations and cyclical acts of fabrication" (Benedikt 1991). A designer seeks to convey intentionality by repetition. This intentionality comes from a repertoire of formal solutions from outside the problem as well as from inside the designer's own practice together with the discipline of architecture he has studied (Benedikt 1991). In this sense, "the design process is one of iteration over time" (Benedikt 1991) in which configurations that survive are held on to from the first to the final design and gain their weight in meaning in good part by virtue of that very survival. This survival can happen in a single piece of design, throughout the whole work of a single designer or even throughout the whole history of architecture. Repetition creates the possibility for meaning. It is a tool.

"The very essence and source of meaning is the image pictured in/of/by the metaphor" (Benedikt 1991). For the post-modernist "the meaning of architecture lies in the history of architecture" (Benedikt 1991) as "architecture begins not with the construction of shelter per se, or the conscious creation of sacred places, but with the transposition and preservation of certain patterns of shelter-making across different and inappropriate contexts" (Benedikt 1991). In this sense, "meaning in-forms the moment" (Benedikt 1991).

Meaning "is not an object or something that can be grasped once and for all; it is the very flow, and the very sensing of this flow, of in-formation" (Benedikt 1991). Meanings of new works can be uncovered by deconstruction as meaning is in every principle of deconstruction. The biggest mistake of deconstructivists is that they ended up being superficial and not original once they only got the image of things and used them as sources of form, discussing only the most conventional symbolic meaning and its compositional aspects.

Meaning can also be interpreted with regards to its socio-cultural and ideological content, Derrida himself explores that in his writings, and when understood under this frame of mind it can shape design processes quite differently. Critical design theorists explore that by proposing a method to constantly question problem-solving structure over a very large scope, including who makes decisions, who shapes the public domain as well as how this right was acquired and exercised. This criticism is based on the assumption that any structure is a product of a socio-political construct and therefore expresses power and control which are unconsciously reproduced by designers if not questioned appropriately.

Critical design theory

Critical design theory looks at the history of design in the light of a socio-cultural perspective contextualising the emergence of the autonomous designer within the development of capitalism (Ward 2008). It heavily criticises design when seen as purely an art claiming that the "aesthetic paradigm is morally vacuous because it excludes social, political and ethical considerations" (Ward 1989) and that architects "by maintaining their collective belief in the essential abstractness of the aesthetic values, ... collude with a social and economic system based upon deep principles of the status quo" (Ward 1989). Ultimately it claims that "art and architecture are defined by the ruling class whom they also define" (Ward 1989) and because of that "art and architecture are ... political phenomena par excellence, dealing, as they do with the structure and processes of power relationships in society" (Ward 1989).

In this spirit, critical design theory proposes a paradigm in which the 'object of design' should be socially responsible and the subject undertaking the design activity should criticise his/her own methods, constantly reflecting about his/her own actions. For critical design theory design is about "helping people to shape their own world in their own way by their own efforts somehow conflicted with the perceived role of the architect as an expert in aesthetics or more precisely, design" (Ward 1989). The practical result of critical design theory is generally presented as a collection of case studies that deal with people who have building, design or environmental problems and on the top of that no resources to pay professional fees for the work they need. The case studies are either from practiced architects or academics that set up design exercises using real world contexts in order to develop student's reflective and cooperative skills.

Critical design theory explicitly acknowledges ideological and political motivations in design and goes in a complete opposite direction of the plastic and artistic postmodern discourse. Architects trying to express subversion as artists showing "florid and anarchic plastic inventions" (Purini 2002) like Eisenman are actually seen as advertisers of the values of an elite deeply bound up with the maintenance of its political and social power and aspirations (Ward 1990). Allied to that, these architects practise their architectures in the wealthiest countries in the world, within which many of the problems that architects should respond to are already solved. "Therefore the present condition of architecture is superfluous. For this reason architecture identifies itself directly with art, since art has no apparent utilitarian ends" (Purini 2002). Besides that "the definition of what is good in design in European (and North American) terms is 'canonised'... through a subtle political and ideological dialectic" (Ward 1990). The question is "to what extent meaning inheres in form versus the manner and extent to which people bring meaning to form" (Dovey 1990). "Good form while not culturally determined, is culturally relative" (Dovey 1990).

Although "the advent of post-modernism has delegitimized the prior concerns of schools with social and cultural aspects of design" (Ward 1990) it also fomented extremely radical discourses against it as "the aesthetic paradigm with which the profession is engaged, while presenting itself as essentially apolitical, is on the contrary, unequivocally political" (Ward 1990). In one side, the idea of structures is replaced by the idea of narratives once comparison with literary criticism is used as a method of analysis. "Professional expertise involves a trade of narratives" (Coyne 2005) in which analysis is not based on layers of meaning but on a "series of emerging narrative constructions on the part of the analyst in the context of rival propositions, a great deal of work in revising and adjusting these narratives to something mutually agreeable, an inevitable resistance to one or other narrative" (Coyne 2005). On the other hand, methods were developed to understand or question the several different types of structures created and manipulated to be used in problem-solving. So on the one side, design is purely about art, on the other side, design is a powerful means of socio-cultural and political control.

Post-modernism and 'meaning'

In the post-modernist approach to design problem-solving the idea of meaning is expanded far beyond functionality and performance. Either in the history of architecture or in the metaphor of the artist, the concept of meaning when expanded from its scientific basis and made central to the post-modern discourse sets up a complete paradigm shift in problem-structure.

Thus Post-modernism questions not only the diagnosis of the problem but also the rational basis of professionalism (Coyne 2005). Rationalism from design methods has been usurped by the cultural theorists, which are interested in other questions and formulate other problems (Coyne 2005).

However, lots of post-modern discourse is badly received because of the strong self-expression allowed to the architect, which leaves no room for nature or social content (Dovey 1990). Although the integration with local culture and everyday life, potential for user's participation, appropriate technology and political commitment were all forgotten, this was not the intention of many of the post-modern discourse from philosophy or human sciences.

In the philosophical sense post-modernism is actually about "an incredulity towards meta-narratives, a rejection of all-embracing modernist themes of universal structure, reason, enlightment and progress" (Dovey 1990). "Post-modernism represents a resurgence from relativism" (Dovey 1990) as it considers that "all meta-narratives are totalitarian, either the empirical ones or the structural ones" (Dovey 1990). "Relativism is a powerful enemy, which in the current context would seem to have the power to marginalise any grand theory of design" (Dovey 1990). "However post-modern relativism has its own logical inconsistencies, primarily due to the fact that, in its own terms, it can only be relatively valid ... in the lost of a basis for a rational communication, everything becomes valid in its own terms ... as relativism is a commitment to a lack of commitment " (Dovey 1990).

Post-modernism in its essence is not about rejecting structures and going towards pure self-expression and formalism transforming everything into art. It is fundamentally about consciously manipulating structures and understanding there is no universal meta-narrative behind them but meta-structures of power and control to be acknowledged, criticised and changed. If the expression of this manipulation is purely artistic or not, is something else to be discussed.

6.2.4. Building design problem-solving paradigms: From structures to intentions

> *"Creativity (is) the ability to problematicize, that is to create problems and to increase awareness, though always this side of emergencies" (Jonas 1993).*

The previous sub-sections of this chapter presented an overview of how different philosophies influence building design problem-solving paradigms. Rationalist different design problem-solving structures dealing with the 'object of design' as well as the 'subjects undertaking design activities' were explored followed by examples of pragmatic and examples of post-modern paradigms. In all of these philosophies the designer not only solves the design problem itself but also the problem of how to solve the design problem at hand.

Rationalism proposes structures to be used as tools for the design problems at hand to be re-written accordingly. The aim is to guarantee that minimum requirements will be fulfilled and that functionality will be achieved. The focus is always function, with form following it in order to acquire its meaning. Structures provide a solid framework to map requirements. They are useful tools to well-define the ill-defined objectively, as they allow problem statements to be mapped consciously into a known template in order for it to be solved acknowledging the functions it should fulfil. The aims of rationalism are then to discuss and define different types of structures to be used in well-defining the ill-defined.

In dealing with the 'object of design', rationalism started with procedures which evolved into hierarchical structures, and then developed further into language structures, a combination of procedures and structures in which only very basic entities are defined so that more flexibility in terms of combinations can be achieved. Flexibility is necessary to account for different contexts and different types of problems as well as to achieve aims that are far from being static. Function can be extremely comprehensive including building structures, all types of costs, manufacturing, ergonomics, activities, comfort, etc., they can be understood as synonymous of performance and encompass phenomena that do not only develop in space but also in time.

Hierarchical structures are static, rigid and inflexible as they attempt to define the whole whereas languages are dynamic and more flexible as they only provide definitions for the elemental entities, leaving the whole to be assembled based on rules. Space elements can be broken down into elemental units and then described by static structures. Elemental units allow for different possibilities of assemblages and can be combined using rules. Rules are less rigid than structures and can accommodate different contexts, types of problems and dynamic aims allowing for different possibilities of assemblages to form the whole. Languages are then a much more comprehensive and flexible system and can be based in different criteria to define rules and elemental units. Alexander 1977 and 1979 for instance defines elemental units based on archetypes, which invoke images; Mitchell 1990 defines elemental units based on abstract signs, which invoke words to describe form; and modernist formal languages define repertoires of formal solutions to be used in solving generic functional requirements.

Besides that, rationalism also deals with specific structures. These types of structures can be seen as having their reasoning lying between elemental units and rules of assemblage and are developed to deal with specific requirements such as space activities and environmental concerns. They mainly focus on analysing specific types of problems, using information from the correspondent science domain they tend to be more related to, in order to categorise information and provide abstract or concrete prototypical solutions to be developed further by designers.

In either dealing with the 'object of design' as a whole, or with specific structures to apply scientific knowledge to deal with critical aspects of problem-solving, rationalism's basic reasoning assumes requirements invoke functional needs that, once identified objectively in problem-setting, provide a rational basis for describing what would be an appropriate solution. Problem-solving is then summarised into identifying a suitable form that functions according to these pre-specified requirements. A separation of problem-setting from problem-solving, a separation of form from function, and a separation of the whole from the parts in order for the complexities of the problem to be fully acknowledged prior to the proposition of any type of solution, imply paradoxical situations.

The rational decomposition of the problem into parts exposes multiple objectives to be addressed and makes it easier to visualise and deal with parts individually. Once the parts are specialised and form separated from function, functional equivalences can be explored. Two or more objects with different forms but able to perform the same type of function provide possibilities to explore different types of solutions without compromising the fulfilment of requirements. However, this situation can be paradoxical. Different elements playing individual roles need to be put together into a coherent solution, which will require an extreme control of function articulations in order not to fall into the dangers of starting to recursively solve problems created by the solutions provided to other problems. Apart from that, this type of reasoning makes it difficult to deal with multi-functionality in which parts are not specialised and few elements play several different roles simultaneously.

Splitting the process into different specialities to scientifically analyse problems and propose a basis to develop solutions to them can be very narrow in scope. Providing abstract problem-solving structures generic enough in order to allow them to be applied to any context necessarily involves losing information (a condition to be generic is to be reductionist) as assumptions to reduce the complexities of reality into something that can be applicable to all contexts need to be made. This assumes that "the model is more important than the data" (Braham 2005), that the model is based on metaphysical principles that account for all the types of problem to be solved and provide the best means to solve these problems as the structures are always set assuming they are products of purely objective thinking. It also exposes a "limited significance of functional concerns" (Leatherbarrow 2005). The result is that "the building is its effects, and is known primarily through them, through its actions and performances" (Leatherbarrow 2005).

Another paradox arises in which "the interest in performance clearly draws on the long history of determinism and functionalism in architecture, understood in a large part through the mechanical and organic analogies" (Braham 2005) but forgets to acknowledge that the "objectivity of functional methods depends on the assessment of subjective needs" (Braham 2005). These subjective needs derive from ideas about health, wealth and pleasure based on social, cultural and political factors, which are far from being a consensus let alone metaphysical.

Therefore, the idea that rationalism provides means to deal with the 'object of design' using a basically neutral objective reasoning, in which the ultimate design ends are up to each designer to make sense of and opened enough to allow different meanings to be conveyed through the use of different styles, is actually a fallacy.

Most of the rationalist theories referring to the 'object of design' as a whole are heavily criticised by pragmatic and post-modern theories. This probably explains why designers mainly prefer to use specific structures, rather than structures that address the 'object of design' as a whole, as well as why these structures are continuously under development by specialised fields of knowledge. It also explains why design methods are used for management purposes rather than design purposes and why rationalist design research shifted its focus from the 'object of design' to 'subjects undertaking design activities'. This research contains lots of a priori assumptions based on rationalist theories such as the behaviour of a designer solving a problem is independent of the problem being solved; the behaviour observed from a sample of designers can be generalised to all designers independently of culture, and context designers are working in; and finally that there are clear stages followed by designers when undertaking design activities which require specific types of reasoning and representation that can be clearly related, described and explained.

However, rationalist design research dealing with 'subjects undertaking design activities' fails to explain the use of reference and precedence as a basis to the development of associations, analogies and metaphors, resources widely used in problem solving to set up formal solutions.

Post-modern theories refuted the dialectics of rationalism, showing that problem-setting and problem-solving cannot be separated, that means and ends are tightly interrelated and that there is no model for the 'object of design' independently of the subject undertaking the design activity. Conservative theories denied the use of structures in favour of the use of narratives and metaphors. Pragmatism approaches the design activity from the perspective of the subject and phenomenology and hermeneutics from the perspective of the object.

In the case of pragmatism, a less rigid framework and set of assumptions were used to derive conclusions from observing designers working in practice. The lack of separation between subject and object prevents generalisations in terms of procedures to be derived from observations, leaving each situation to be treated as a universe of one. The lack of separation between problem-setting and problem-solving suggests a paradigm in which problem and solution co-evolve. The designer sets up a frame, not a structure, to assist in the creation of the 'object of design'. This frame is a tool to deal with the environment the designer is moving within. It contains rules, constraints and criteria that are set on the go to develop proto-solutions that act like hypothesis which are abandoned or developed further according to the results from conversation with the material of the situation. There is no attempt for a problem statement to be re-written consciously into a known structure, quite the opposite, structures, when provided, tend to be broken in order to allow for creative ideas to arise.

In the case of post-modern theories, the focus is to contradict the dualities of form and function as well as the separation of the problem into its constituent parts. The intention is to acknowledge complexities and contradictions without using the clear methods provided by science, as they are reductionist and deterministic, but by moving architecture closer to the fine arts and literature. Multi-functionality, interdependences of parts and diversity of relationships are discussed to understand meaning conveyed by form. Function and performance are just a part of the overall meaning which can only be found in its fullness once looking at historical precedents.

Post-modern radical theories provide methods to analyse and criticise structures either by subverting them completely trying to convey some meaning through the creation of an object of art, or by reviewing, enlarging, adapting or creating new structures to solve practical problems acknowledging social, political and cultural contexts. Deconstructivism is just one way of seeing deconstruction, which tried to convey subversion through form and "proved to be incapable of instrumentalizing complexity itself as a tool that was material and architectural" (Spuybroek 2005), having every subversive formal act silently repaired by engineers. However, deconstructionism provides a method to deconstruct structures in order for them to be understood. Its aims are to understand the meaning behind hierarchies showing how this meaning can be subverted. Deconstruction is not dialectic, it deals with oppositions such as present and absent not as simple antonyms but as complementary concepts used to analyse the reductions involved in structures, i.e. what is present as opposed to what was left behind. It analyses how the parts are articulated and ranked defining what is more important than what in the whole as well as what is purposefully repeated to be reinforced.

Meaning lies in every principle of deconstruction and deconstructionists claim meaning in every structure. Designers when reviewing, enlarging, adapting or creating new structures need to have in mind what are the meta-narratives they are indirectly manipulating. In order for this to be achieved the proposition is to deconstruct the constructed, to criticise it and consciously construct it again. Besides that, because every structure is reductionist it is important to understand what was left behind, how the complex levels of reality are being reduced to a model in order to interpret and make use of the information being manipulated.

Similarly to deconstruction, critical design theory is also concerned with the meaning behind structures. Although it does not provide a method to analyse structures it approaches it through constant questioning. Structures are all mechanisms of oppression suitable to the distribution of power. Therefore all assumptions should be questioned if the aims of designers are to help people in shaping their world. Designers should be very conscious about structures and the meta-narratives underlying them in order to manipulate them properly.

The "construction of meaning ... involves more than the mere accretion of facts, or information. They also involve significant conceptual change, including, on some occasions at least, the acquisition of new concepts" (Liddament 1994). "Conceptual growth is less a matter of serendipity than of pedagogic insight" (Liddament 1994) that means that "to appreciate ... post-modernism we must have some understanding of the modernist positions it combats" (Liddament 1994). For post-modernism design is not about well-defining the ill-defined, it is about working with the wickedness. For pragmatism, phenomenology and hermeneutics the wickedness is many times treated unconsciously whereas for critical theory and deconstruction the wickedness is consciously acknowledged and all "design is political" (Rith and Dubberly 2007).

This sub-section illustrated how different worldviews influence and produce different building design problem-solving paradigms. The impact of these paradigms in representation systems used by designers while designing is analysed in the next section 6.3 which starts with exploring the influence of rationalist problems-solving structures, followed by pragmatic and post-modern problem-solving paradigms.

6.3. Representation systems used by designers while designing

"Designers manipulate representations of the world rather than the world itself ... all the reasoning and decision making is done through the construction and manipulation of models of various sorts" (Goel 1995).

Representation systems in building design are rich and varied. Most of them are generally visual, abstract or concrete, mainly used to manipulate functional requirements, to express design intentions as well as to manipulate and display form in space. In any situation they tend to start with a brief, in which goals and requirements are outlined by the client, generally in a textual format, and finish up with contract documents, in which drawings and specifications for the 'object of design' to be materialised are provided.

Representations are multipurpose. They are instruments of communication as well as instruments used by designers to manipulate and work upon design problems when designing. When used as an instrument of communication, representations start generally in a textual format, the brief, with the information presented in it conveyed in an ambiguous way allowing for a large number of possible solutions to be derived from it. As design progresses the levels of ambiguity conveyed by the representation systems need to be reduced so that the 'object of design' can be materialised according to its conception. Information used as an instrument of communication at the end of the process is then unambiguous and precise.

Although information about the 'object of design' when used for communication purposes needs to become less ambiguous as design progresses, this might not be the case when this information is manipulated for designers when designing. Representation systems used along the way to develop the 'object of design' can be varied and ambiguous up to the end of the building design process, and might well be used as complementary information to communicate with third parties, depending on idiosyncrasies and contingencies involved in specific design situations.

In spite of being contingent and idiosyncratic, representation systems, when used as instruments to work upon design problem-solving, can be roughly classified in order to be related to the thought processes involved in building design. According to what has been previously discussed in this chapter, these thought processes are embedded within worldviews which provide commonalities in terms of how to approach problem-solving.

As the whole idea behind this chapter is to outline how different worldviews affect building design to show there is no consensus about the activity of building design as a whole, this section continues this discussion by attempting to illustrate how building design representation systems interact with problem-solving paradigms. The interactions are explored through a discussion about which representation systems illustrate the most important points involved in problem-solving according to the different worldviews underlying building design.

An overview of the emphasis given to specific types of representation systems as a reflex of how rationalist, pragmatic and post-modern worldviews approach problem-solving paradigms is presented. This emphasis is provided based on a combination of aspects of the previous review of the literature about building design problem-solving, which discusses the role of representation systems in assisting the design process, together with the most important aspects involved in problem-solving according to each of the worldviews.

6.3.1. Rationalist topological structures and technical drawings

When dealing with the 'object of design', rationalism emphasises the technical aspects of representation systems. These comprises, representation systems that extract design requirements from the brief, representation systems that depict further information collected by designers to assist problem-solving, representation systems that express underlying guiding and organising principles involved in the solution and representation systems that convey design ideas in a clear and unambiguous way for designers to work upon the materialisation of the proposed artefact. These representation systems reflect how important it is for the rationalists to clearly relate form and function as well as how important it is to clearly communicate the data about the 'object of design' to be materialised.

Structuring design problem-solving

Representation systems that depict functional requirements involved in problem-setting and representation systems that express conceptual solutions that are going to underlie problem-solving tend to be many times intertwined. Although rationalists tend to prefer working with the problem statement separated from problem-solving in theory, in practice things happen to be a bit less dissociated, merged together in a problem-solving structure. The emphasis tends to be more in representations that convey the functional requirements to be fulfilled, the design aims which will also act as a tool to assess design decisions, together with conceptual solutions to respond to the aims and trigger shape explorations. Although the media used in this type of representation is varied, in general there is a trend to either work with textual information or preferably different types of abstract diagrams.

Textual information tends to be arranged in interaction matrixes (Figure 6.25) mainly when the amount of information is large and therefore difficult to be visualised spatially without prior analytical organisation. Relationships among the parts are explored based on value judgements, represented using a symbol system or weighting systems in order to structure the designer's thinking.

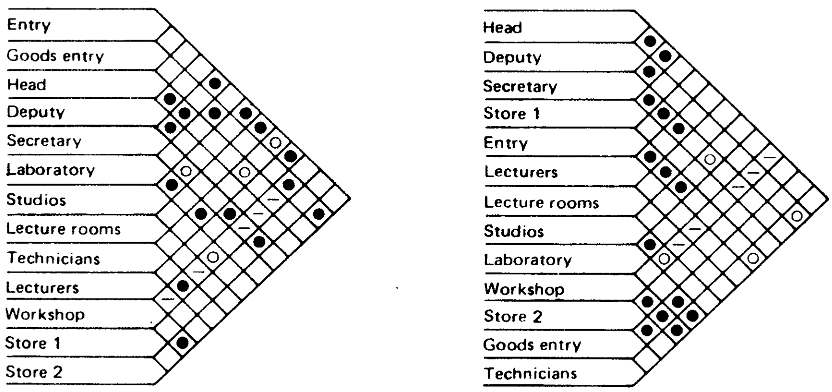


Figure 6.25 – Example of interaction matrix (Szokolay 1980)

Abstract diagrams are central to rationalists. They are said to be the key to the process of creating form (Alexander 1971). They express abstract patterns of physical relationships that allow designers to clearly and objectively control the creation of the whole as well as the interconnections between parts and whole, and parts with themselves. They can be used also as sources of knowledge once they become part of a designers repertoire serving either as a template to deal with similar problems or as a type of reasoning to assess new complex problems.

Abstracts diagrams can be of various types ranging from topological diagrams, which can be used for instance to organise overall design ideas in an abstract way (Figure 6.3 and Figure 6.4) or activity arrangements before working with their distribution in space (Figure 6.15 – bubble diagram), or sketches, which can be used for instance to work on conceptual functional arrangements in space (Figure 6.26) or to develop formal ideas from conceptual guiding principles (Figure 6.14).

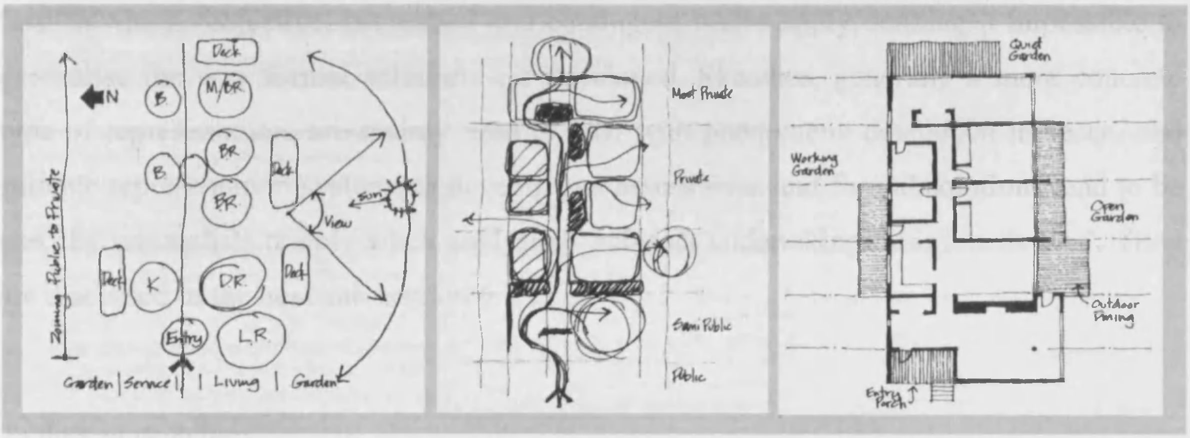


Figure 6.26 – Conceptual sketches to work on conceptual functional arrangements (Goel 1995).

Topological diagrams are useful representations to manipulate ill-defined problems abstractly. Rationalists are keen to use this type of representation as they are suitable to outline and manage functional requirements independently of formal solutions. These representations are a starting point to deal with design problem-solving in the early design stages as they provide the rational basis to develop formal responses allowing for ideas to be clearly articulated prior to any formal commitment.

According to Kokotovich 2008, there is a trend for grouping problems into themes and one of the simplest ways to express that is through the use of topological structures, abstract diagrams that express connections of ideas and describe symbolic relationships. These types of representation are good for managing different contexts and domains and can provide good benchmarks for validation processes. They are useful instruments to analyse problems as they allow the articulation of themes and the raising of issues clearly in the early stages of the process providing further creative inputs for final design solutions.

"When designers are able to raise, consider and clearly articulate complex dynamic interrelationships between design issues in the early stage of the design process, they are better prepared to present a highly regarded reasoned analysis of their final design proposal" (Kokotovich 2008). Thinking through and mapping the issues of a design problem greatly assist in the development of a creative well-considered design.

When dealing with the 'object of design', rationalists tend to discuss mainly the initial parts of the process, i.e. how to structure problem solving, and then move straight to the manipulation of representation systems that deal with the materialisations of the proposed artefact. Whatever happens between those two stages is seen as something within a black box, in which subjective, contextual and contingent issues apply, making it impossible to generalise the way formal solutions are developed. Sketches, generally a more concrete type of representation, are mainly used to deal with phenomena developed in space, and suitable representation systems to develop and assess form and formal solutions tend to be used by rationalists mainly when analysing 'subjects undertaking design activities'. They are discussed in the next sub-section 6.3.2.

Technical drawings

When discussing the manipulation of representation systems that deal with the materialisations of the proposed artefact, rationalists refer mainly to technical drawings, the most important type of representation system used by architects which also forms an intrinsic part of their reasoning capability (Eastman 2001).

Rationalists believe that when dealing with the 'object of design', designers describe constructions of their imagination, models that represent a real building (Mitchell 1990). Therefore how to represent things in space and how to give form to materials is a central problem for designers. The visual perceptions of things are very important and geometric considerations are prominent (Simon 1996). In this context, design ultimate types of representation for rationalists are systems that convey ideas in a clear and unambiguous way so that the proposed artefact can be simulated and evaluated before its materialisation. These representation systems are the technical drawings, models composed of a "collection of graphic tokens, such as points, lines and polygons, forming 2D or 3D arrangements"

(Mitchell 1990) which have associated to them properties and relations that allow them to correspond to objects in the real world.

Technical drawings are full of technical conventions used to depict site, construction components and materials. In these conventions “lines stand for boundaries, edges of solids or division between different materials. Often there are conventions under which colours and patterns stand for materials” (Mitchell 1990). Apart from that, specific symbols and textual annotations are also used in association with the graphic conventions, especially to fix references, specify material properties, equipment, space activities, space dimensions, etc.

The most common types of technical drawings are the ones displaying two dimensional shapes from projections of three dimensional objects (Mitchell 1990). Two dimensional parallel projections originate plans, elevations and sections when the projection plane is positioned to minimise foreshortening of shapes (Figure 6.27). Plans are parallel projections created based on a section taken at a height of 1.5m above each of the floors to be depicted; “elevations are parallel projections, seen from the side, onto a building façade” (Bielefeld and Skiba 2006); and sections are parallel projections created by making a vertical cut through the building. When the projection plane is rotated to show perpendicular lines and surfaces the two dimensional parallel projections originate axonometric drawings (Figure 6.28) and when the projection rays diverge from the viewer’s eye the two dimensional projection originates perspective drawings (Figure 6.29). Axonometric and perspective projections provide an idea of depth, especially in the latter case in which this idea is further emphasised by shape distortions.

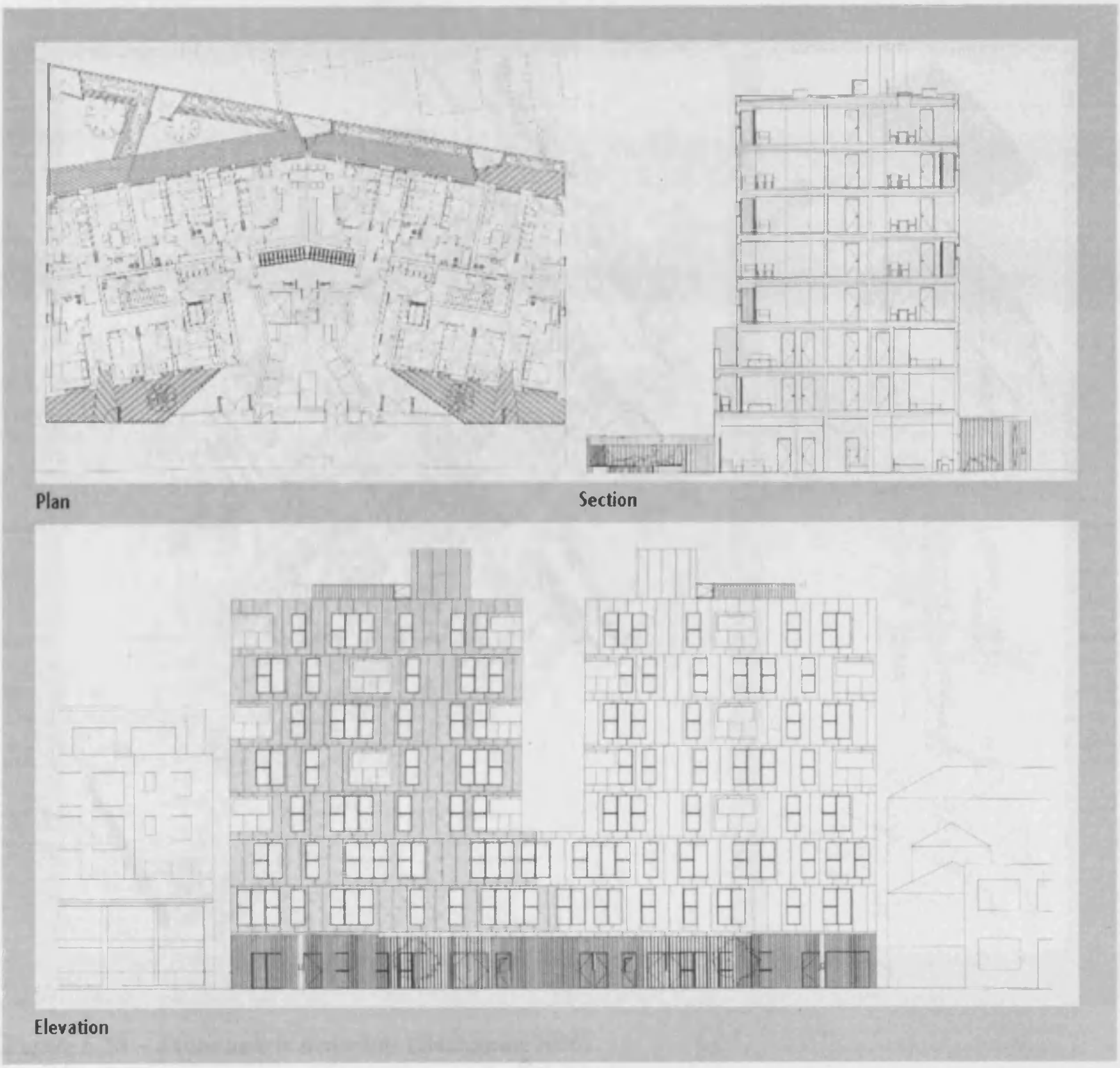


Figure 6.27 – Plans, elevations and sections (Adjaye 2006)

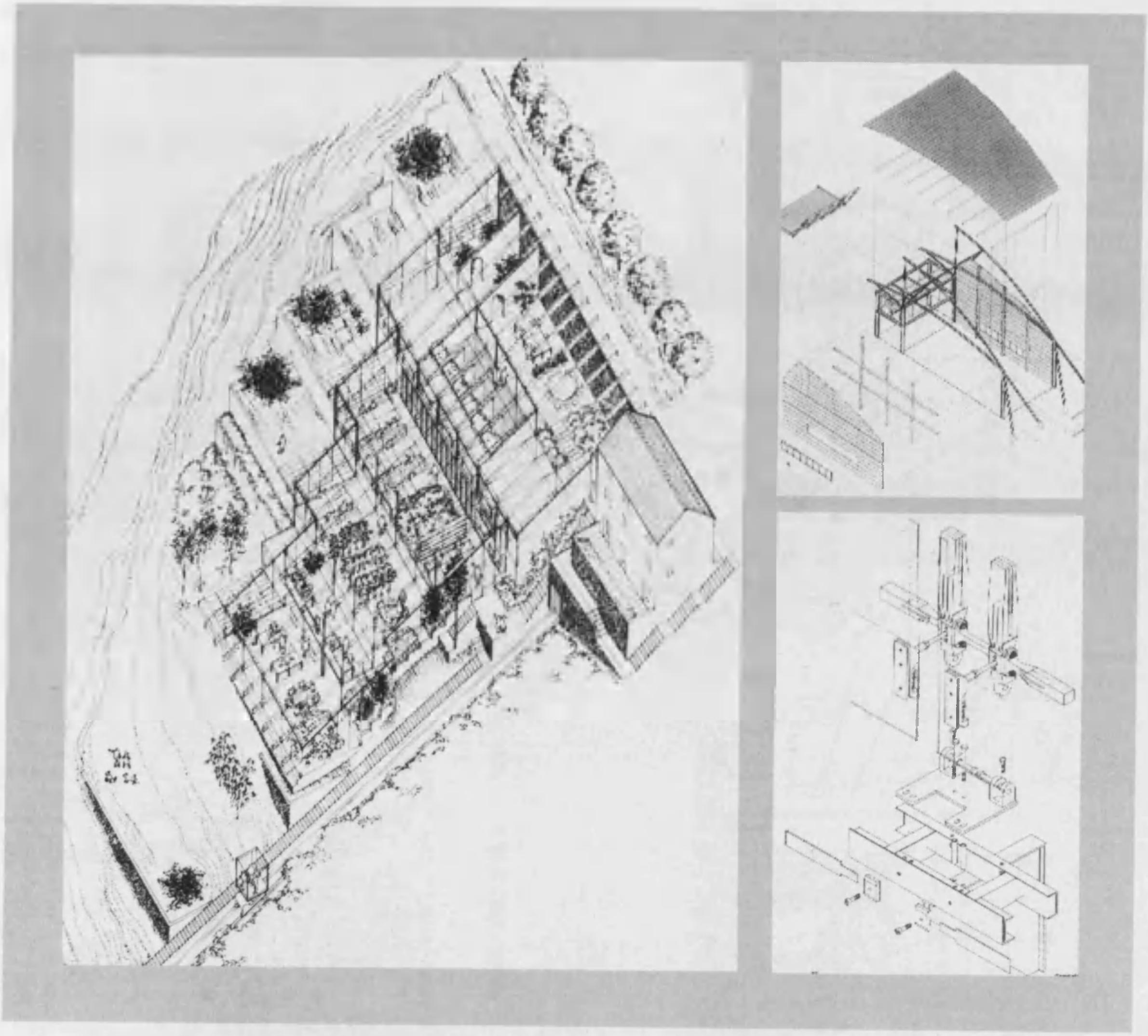


Figure 6.28 – Axonometric drawings (Buchanan 2000)

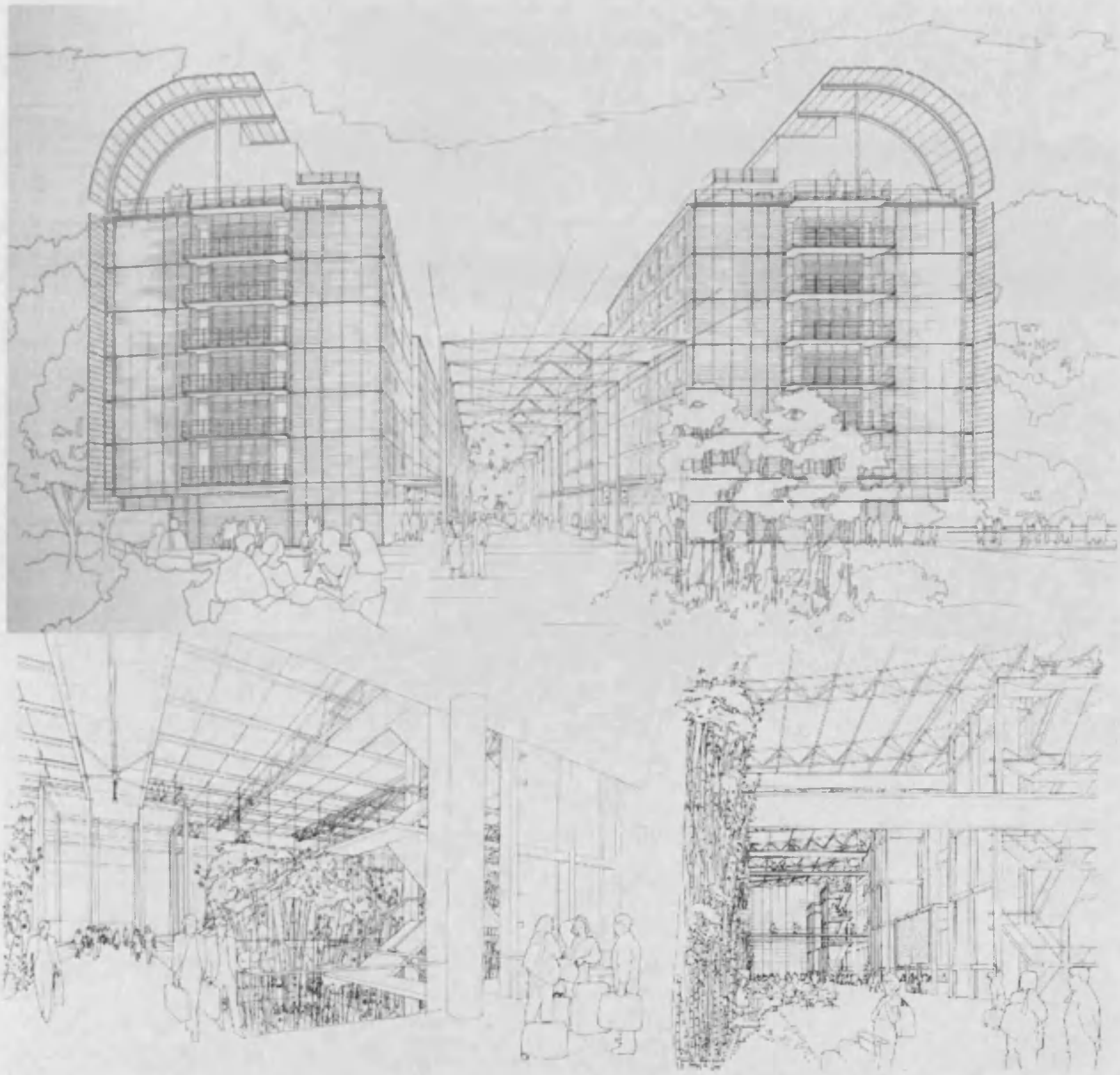


Figure 6.29 – Perspective projections (Buchanan 2000)

As technical drawings are the most important type of representation used to convey information for the 'object of design' to be materialised they need to be faithful to real world objects in terms of dimensions and proportions. Three dimensional real shapes when transformed into two dimensional drawings need to bear correspondence with their equivalent real world shapes. In order to do so, all dimensions of the proposed object are scaled to keep proportions and consistency between the object to be constructed and its representation. Different scale factors provide different levels of detail about the information displayed and are widely explored by designers to evaluate relationships between the whole and the parts as well as to explore specific relationships among the parts (Figure 6.30).

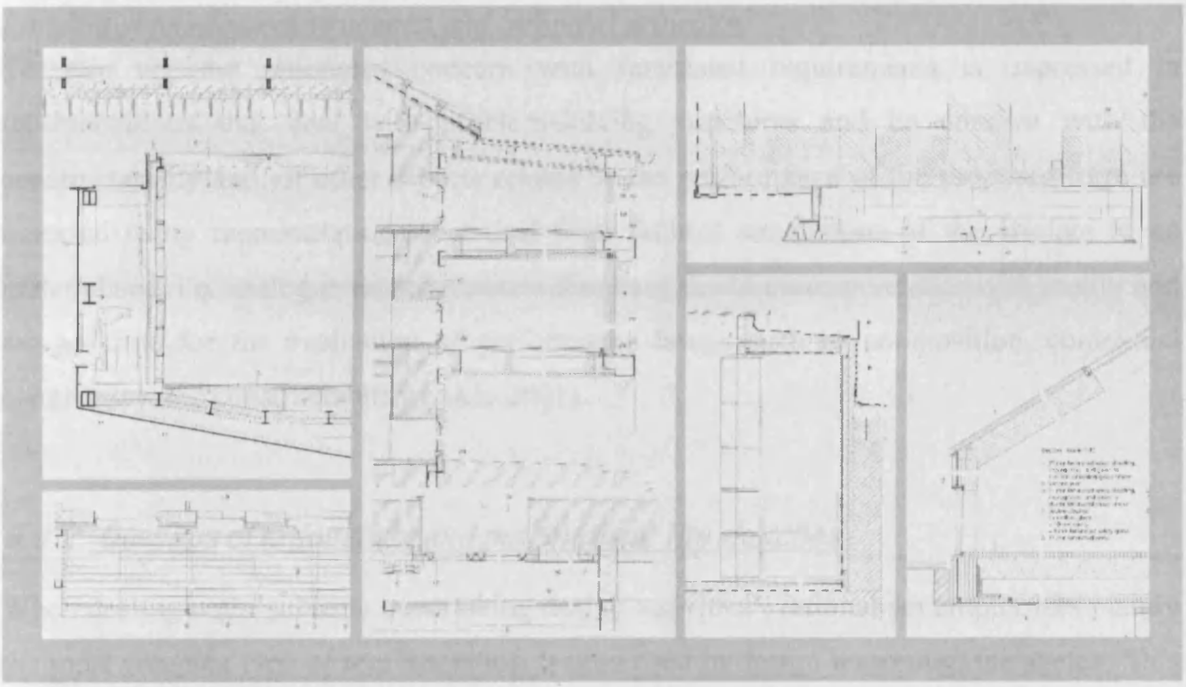


Figure 6.30 – Technical drawings in different scales (Schittich 2003)

Plans mainly provide information about horizontal dimensions, space distribution, circulation, construction, etc. Elevations mainly provide information about relationships with environment, form, proportions, materials, etc. Sections mainly provide information about floor heights, material qualities, construction systems, etc. And 3D views convey spatial impressions of the building, of its construction system, etc. Two dimensional representations are of immense use in providing spatial understanding (Eastman 2001) and three dimensional views provide a more perceptual type of representation useful to asses the object sensorial and aesthetically.

Rationalists discuss reading and interpretation of architectural technical drawings in terms of geometry and entities, in terms of layouts and circulation, in terms of their integration to derive 3D layouts, in terms of imagination of 3D form defined in drawings, as well as in terms of the simulation of construction operations and activities defined in the 3D space (Eastman 2001). Even capabilities such as functional and cultural interpretations of buildings, capabilities to deal with reasoning about spatial qualities, functionality and other uses of space "are based upon the ability to automatically read architectural drawings" (Eastman 2001)

Rationalist topological structures and technical drawings

To sum up, the rationalist concern with functional requirements is expressed in representations that deal with problem-solving structures and its concern with the constructability and all other aspects related to the performance of the proposed form are assessed using representations that deal with faithful simulations of the artefact to be materialised, i.e. analogue representations that have direct correspondence with reality and are accurate for the evaluation of performance issues such as composition, contextual congruency and constructability (Akin 2001).

6.3.2. Overlaps of rationalism and pragmatism: The sketches

When dealing with 'subjects undertaking design activities', rationalism emphasises mainly the most complex type of representation system used in design reasoning, the sketch. This type of representation is also considered the central one for the pragmatists as it is the media most commonly used to develop conversations with the materials of the situation. This representation system reflects how rationalists believe designers manipulate the object being designed. It also reflects how pragmatists believe designers not simply manipulate the 'object of design' detached from it, but actually interact with it during its manipulation.

Sketches are the representation system that starts being used right after, or even during, abstract problem-solving to assist the development of formal responses and is carried over throughout the whole design process up to the level of specifications (Figure 6.31). They are said to be the most important type of representation used in building design as they support and assist the whole design problem-solving reasoning. Therefore studies that deal with 'subjects undertaking design activities' widely explore the role and the use of sketches in design.

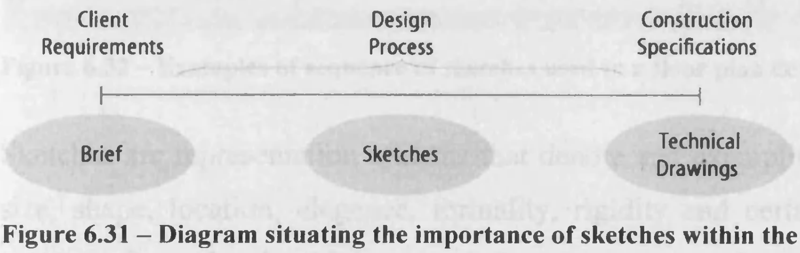


Figure 6.31 – Diagram situating the importance of sketches within the whole design problem solving activity

Sketches in cognitive sciences

Cognitive sciences understand sketches as external representation systems that assist in the manipulation and evaluation of sequences of moves in design problem-solving. Contrarily to the position stated by Eastman 1999 and Akin 2001, sketches are not naïve representations. They are symbol or representation systems able to cope with imprecise, ambiguous, fluid, amorphous, indeterminate, etc. properties of mental states (Goel 1995). They are representations that are suitable to explore ideas because they have exemplification and expressive properties. They fail to be clearly defined because they can have multiple and ambiguous meaning, objects can belong to intersecting classes or "it might not be possible to tell which class a particular object belongs to" (Goel 1995). And they do not possess a regular syntactic structure that can be recognized as "characters do not have the same referent or content in every context in which they appear" (Goel 1995).

Sketches are then non-notational symbol systems, in which each token may belong to many characters at the same time. They are not restricted to drawing (Figure 6.32), having extremely powerful intersecting, undifferentiated and ambiguous properties that play an important role in human creativity. They provide the necessary conditions for non-commitment, they help transformation processes to occur and they allow ideas to be worked upon without needing to be too early crystallized as different type and nature of overlaps keep lots of possibilities opened.

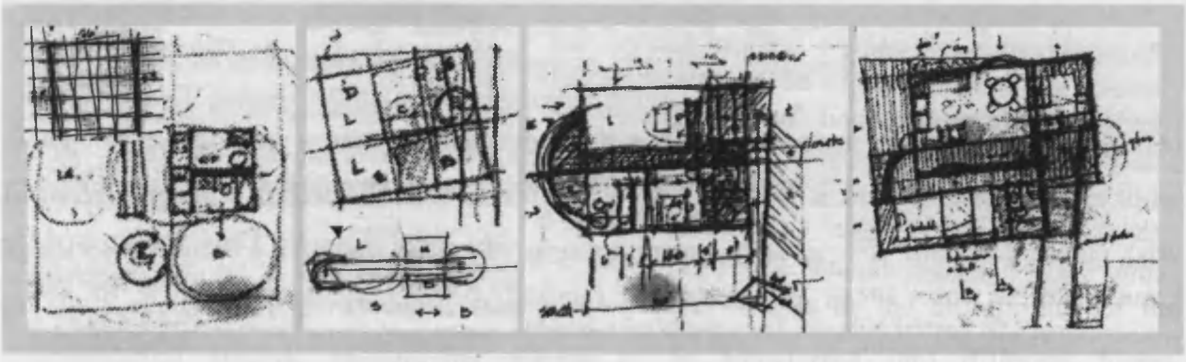


Figure 6.32 – Examples of sequence of sketches used in a floor plan development (Akin 2001)

Sketches are representation systems that denote and exemplify properties such as relative size, shape, location, elegance, formality, rigidity and certainty relieving the cognitive system of overhead without preventing these properties to be directly accessed and manipulated (Goel 1995). Ambiguities allow for different types of meaning to be embedded and the lack of regularity to recognize a syntactic structure allow for different properties to be expressed all at once. In this sense, sketches allow for the manipulation of complex forms, "forms that would be challenging to generate or maintain mentally" (Eastman 2001). They help seeing design as parts and seeing design as a whole, simultaneously. This make sketches powerful tools to "explore the contribution of mental imagery to creative efforts" (Eastman 2001). They are an instrument to record externally different instants of mental imagery operations, capturing the moment and storing it, synthesising partial thoughts. Perceptual processes invoked by the interpretation of these records enrich reasoning as they can retrieve ideas, suggest different ideas, help to transform one idea into another, point out future problems, express qualities not seen before, etc.

In this context, "sketching and conceptual designing are two inseparable acts for most architects ... because sketches are the tools they ... use to progress their designs" (Bilda et al 2006). "Architects learn to think with drawings, develop their ideas and solve complex problems with them" (Bilda et al 2006). Sketches are then the most powerful representation system used to define and develop design formal solutions, to assist the whole building design problem solving. They are central to creativity as they trigger a process cognitive scientist call 'interactive imagery'. "Interactive imagery enables the designer to converse with the materials ... in a dynamic manner, taking advantage of the speed with which images and sketches can be generated and transformed" (Goldschmidt 2001).

Designers externalise a mental image through a sketch and then reinterpret the sketched form developing it further. This further development result in another externalisation to be again re-interpreted (Figure 6.33). In re-interpreting, they revisit the idea seeing new possibilities, generating concepts, seeing meaningful shapes in the ambiguities of the representation system, recognizing shapes to be transferred into different forms, recognizing sub-shapes in hidden shapes, making associations, using the shapes to search for transformation rules, transforming shapes to satisfy design functions, and refining ideas. They keep this process going within a speed compatible with design thinking. As they allow quick generation and manipulation of information, they are economical and easy to manage over time (Eastman 2001).

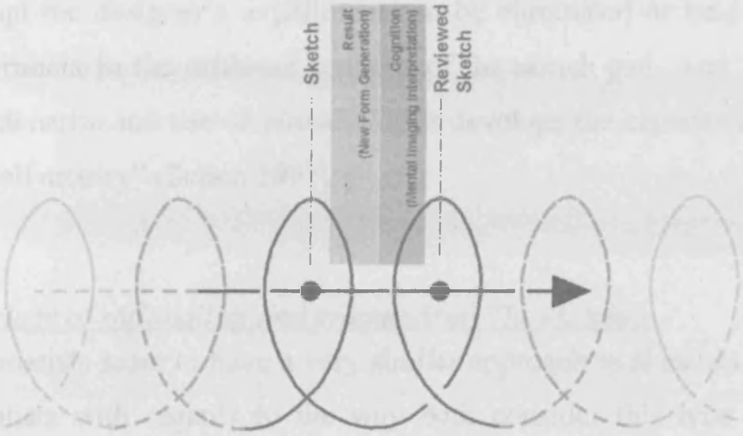


Figure 6.33 – Diagram representing the role of sketches in assisting building design problem-solving.

Sketches in pragmatic design problem-solving

Sketches are also the central representation system for the pragmatists which view them as the media to develop reflective conversations with the design situation. Practitioners do not deal with real situations but operate in a virtual world, a construction of the real world of practice. "Virtual worlds are context for experiment within which practitioners can suspend or control some of the everyday impediments to rigorous reflection in action" (Schon 1991).

The medium for architects to communicate with this virtual world is the sketch pad, in which designers "draw and talk their moves in spatial-action language, learning traces which represent the forms of the building on the site" (Schon 1991). "Drawings reveal qualities and relations unimagined beforehand, moves can function as experiments" (Schon 1991). The act of drawing is rapid and spontaneous and its result is stable which allows designers to examine them at leisure. Designers can try, look and, on another sheet of paper, try again. They can perform sequences of learning in which they can correct errors as well as take into account "previously unanticipated results of the moves" (Schon 1991).

The sketch pad is extremely flexible as a medium as it allows for interlocked variables to be separated from one another (geometry and site can be for instance separated from construction) as the media can be selectively used to address the issues of priority at each stage of the design process. Features of the real world, situations that might confound or disrupt the designer's experiment can be eliminated or held constant for the designer to experiment in the different contexts of the sketch pad. And "practice in the construction, maintenance and use of virtual worlds develops the capacity for reflection in action which we call artistry" (Schon 1991)..

Overlaps of rationalism and pragmatism: The sketches

Pragmatists seem to have a very similar approach to sketches when compared to cognitive scientists with regards to the way both consider this type of representation system as crucial in dealing with design problem-solving. However, the idea of assisting and evaluating sequences of moves in problem-solving interpreted within the central ideas of rationalism differs quite significantly to the idea of conversing with the materials of the situation interpreted within the central ideas of pragmatism.

In the first case, the representation system is used to manipulate an object being designed in an objective way. By externalising the form from his/her mind and acting upon it once re-interpreting what he sees on the paper, the designer is seen as an agent manipulating some piece of objective information. Cognitive studies make clear the separation of subject from object when dealing with design representations as they constantly refer to designers manipulating shapes of an imagined object, designers manipulating wholes and parts of an imagined object, and so on.

In the second case, the representation system is seen as a medium for experience. The media is a point of connection between the real world and the virtual world designers inhabit. It is used for designers to experiment how they view themselves within the design situation. It is used not only to set experiments with shapes, as extensively suggested in cognitive studies, but also to experiment with archetypes and other types of symbolic relationships for instance when used to set up experiments in felt-path mode, i.e. experiments that simulate the designer "moving through the spaces, feeling what it would be like to move in them" (Schon 1988). Pragmatism makes clear there is no separation of subject from object when dealing with design representation and expands the ideas of rationalism when discussing about sketches.

Thus, pragmatic studies and rationalist studies referring to designers undertaking design activities differ with regards to the way they approach the relationship between the object and the subject in relation to the representation system. However, they both recognise sketches are the most important representation system involved in building design as they support design reasoning from throughout the whole design process.

6.3.3. Post-modernism and the fine arts

The Post-modern worldviews emphasize all types of representations systems that are useful to explore and manipulate meaning involved in the object to be designed, i.e. representations that are useful to create and evaluate experiences of designers within design worlds acknowledging the meaning involved and conveyed by these experiences. As this is the case, postmodern representations tend to be conceptual involving textual and/or any type of visual media that is useful to refer to historical precedence, artistic or aesthetic discourses as well as philosophical and human science discourses. These representation systems reflect how post-modern theories view subjects and object as completely interrelated when dealing with problem-solving paradigms as well as how the design object has a wider meaning that goes far beyond the object itself and the intentions of the subject when defining it.

Textual material can be narratives; texts of architectural history; text of architectural theory; aesthetic, political or philosophical discourses; manifestos; metaphors; etc. any kind of written material that can be used to inspire, suggest or convey meaning to a piece of design or to the way this piece of design is experienced by the designer. The way textual material is translated into a visual media and or the way visual media will be used to extract textual material will depend more on which postmodern discourse is underlying this translation.

Postmodern discourses that are based on acknowledgement of historical precedence such as Venturi 1977 generally identify aspects of precedence, abstract them into a discourse and then apply this discourse into the new object being designed. The visual media used to abstract the discourse from precedence can be photographs, sketches, drawings underlying relationships between systems of proportions, etc. anything that can be used to extract information that will support the underlying discourse being developed, which will be used to inspire, suggest or convey meaning to a proposed piece of design.

In the design of the Pearson House (1957), for instance, Venturi uses the concept of "things in things and things behind things" (Venturi 1977) from a reinterpretation of precedence in which he identified the concept of spaces within spaces as a formal mechanism to express a sense of privacy as well as articulations and contrasts between the inside and the outside. Figure 6.34 provides examples of images from precedence used to derive these ideas as well as sketches used to abstract meaning from these images. Figure 6.35 illustrates how the discourse, used to explain how the meaning underlying his proposition is accomplished with the articulation of the proposed spaces, is an important element of design development.

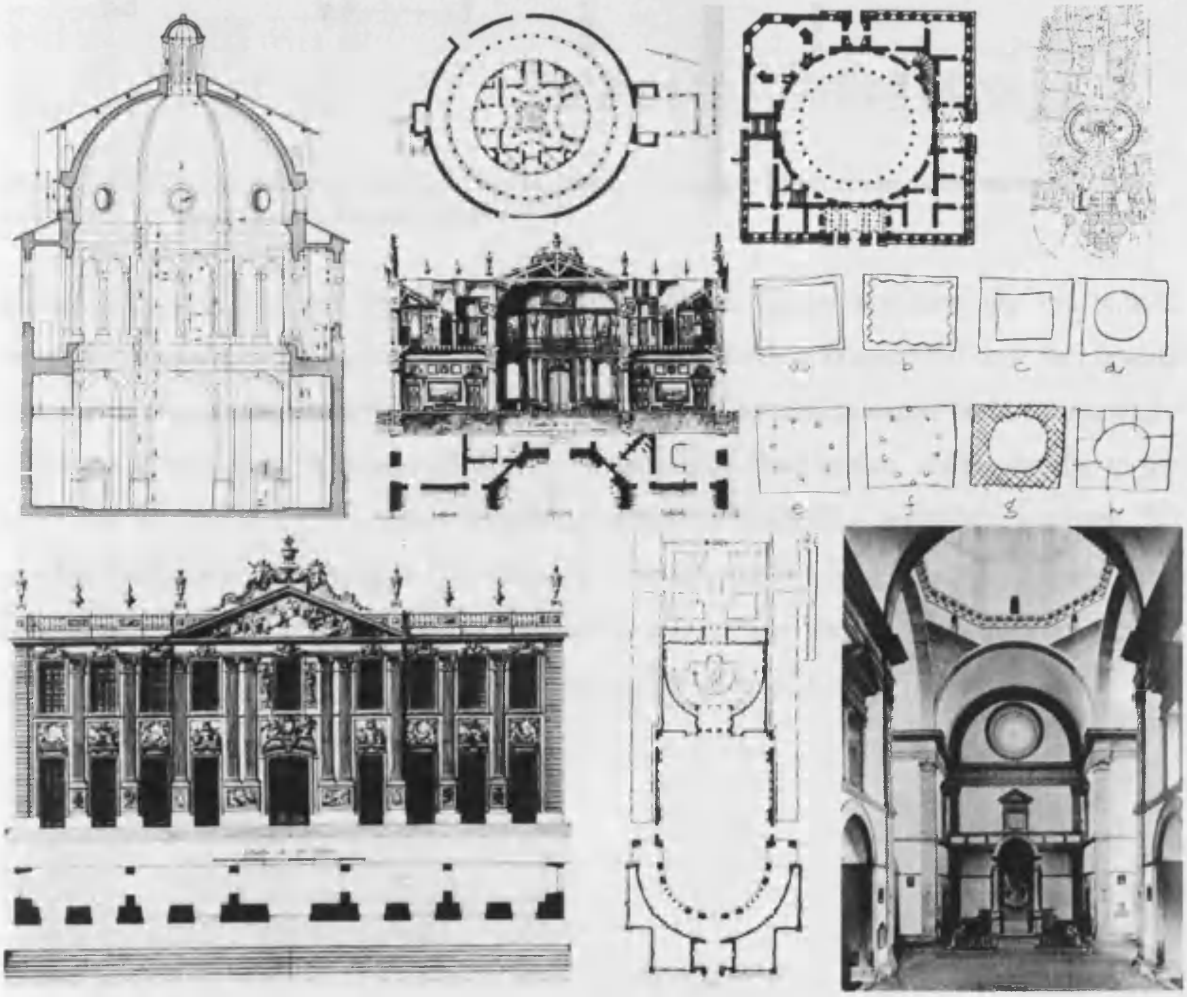
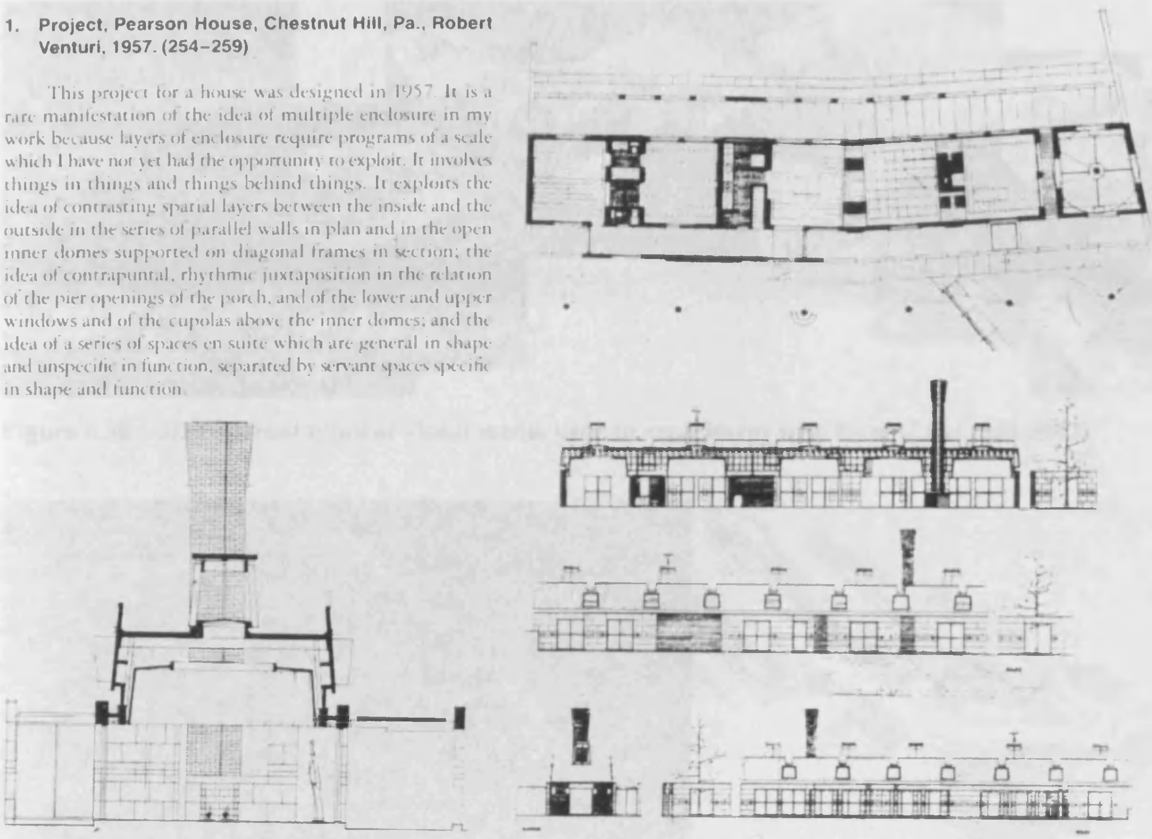


Figure 6.34 – Visual media used to interpret historical precedence (Venturi 1977)



1. **Project, Pearson House, Chestnut Hill, Pa., Robert Venturi, 1957. (254–259)**

This project for a house was designed in 1957. It is a rare manifestation of the idea of multiple enclosure in my work because layers of enclosure require programs of a scale which I have not yet had the opportunity to exploit. It involves things in things and things behind things. It exploits the idea of contrasting spatial layers between the inside and the outside in the series of parallel walls in plan and in the open inner domes supported on diagonal frames in section; the idea of contrapuntal, rhythmic juxtaposition in the relation of the pier openings of the porch, and of the lower and upper windows and of the cupolas above the inner domes; and the idea of a series of spaces en suite which are general in shape and unspecific in function, separated by servant spaces specific in shape and function.

Figure 6.35 – Textual material important in the design development that explains the meaning underlying the design proposition (Venturi 1977)

Postmodern ideas that are based on artistic or aesthetic discourses generally use textual material as a starting point from which visual media is used to experiment how this textual material is translated into a visual 'discourse', how this textual material can be concretely transformed into form is widely explored. Visual media used in this case is similar to the one used in fine arts, 3D models, exploring different modelling materials, textures, 2D graphic representations, etc. any type of media that allows easy manipulation of shapes and images so that designers can express themselves similarly to artists when conceiving and investigating ideas about the object being designed (Figure 6.36 and Figure 6.37).

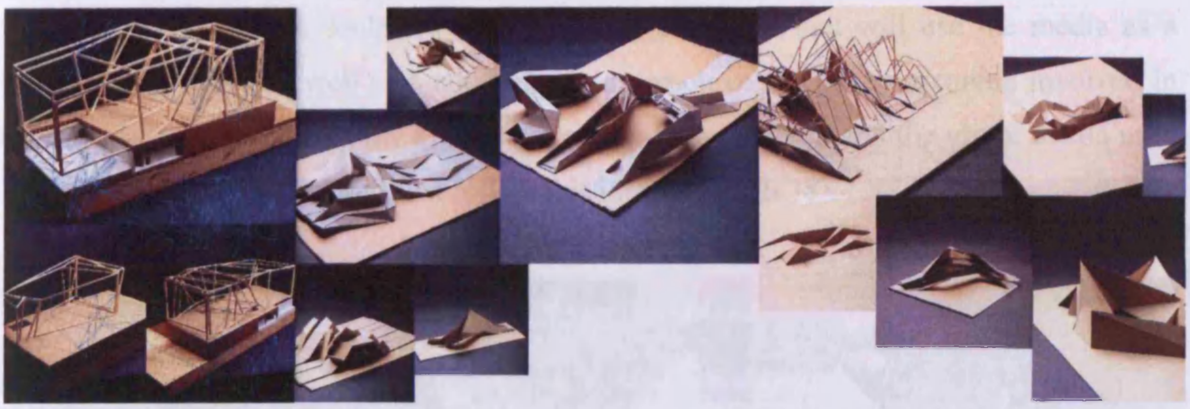


Figure 6.36 – 3D Different types of visual media used to experiment with form (Eisenman 2002)

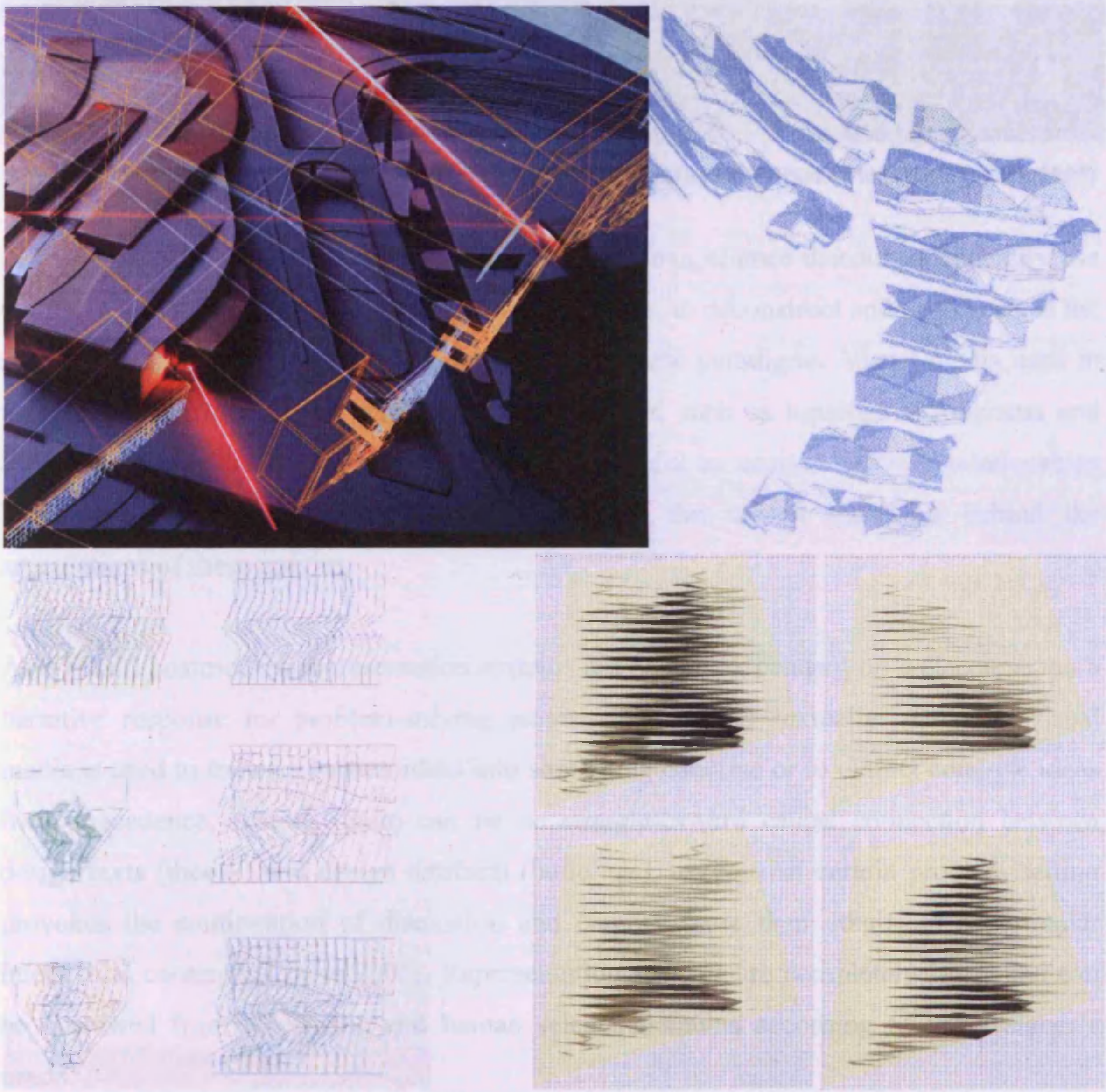


Figure 6.37 – 2D Different types of visual media used to experiment with form (Eisenman 2002)

Architects will act like sculptors and/or graphic designers and will use the media as a generative resource as well as a communication resource to convey meaning involved in the object being designed. Any kind of experimentation is valid and the visual media used to undertake experimentations just follow this idea (Figure 6.38).

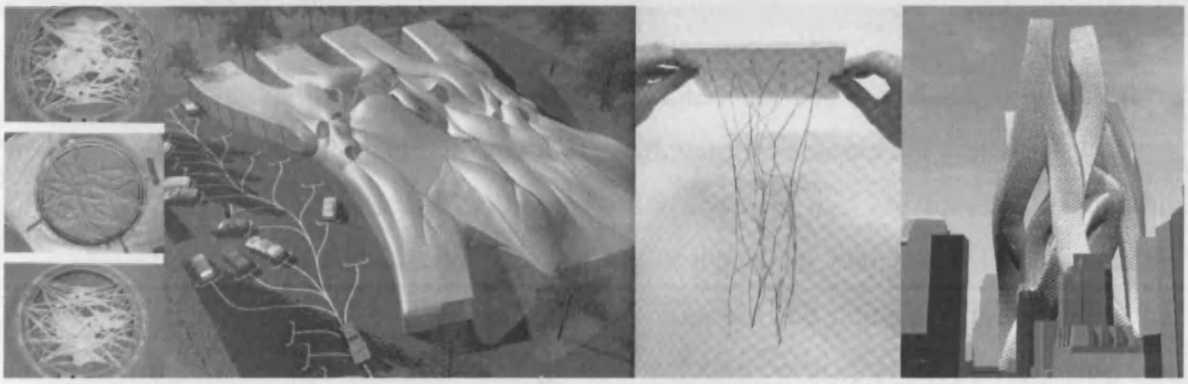


Figure 6.38 – Visual media used to convey meaning and undertake experimentations (Spuybroek 2005)

Post modern ideas based on philosophical and/or human science discourses generally use textual material to analyse problem-solving paradigms, to deconstruct and/or to analyse the socio-cultural and ideological meaning underlying these paradigms. Visual media used in these situations tends to be graphic abstract material such as topological diagrams and conceptual diagrams, any kind of media that is useful to analyse abstract relationships between the design entities in order to identify the hidden meanings behind the articulations of these entities.

As a result, postmodern representation systems are heavily dependant on a discourse, on a narrative response for problem-solving expressed above all textually. Although visual media is used to transfer written ideas into something concrete or to extract concrete ideas from precedence, "clearly there can be no straightforward causal connection between design texts (theory) and design artefacts (buildings), except that certain problem setting provokes the continuation of discussion and enquiry more than others, in a particular intellectual content" (Coyne 2005). Representation systems are completely 'free' and can be borrowed from all artistic and human science domains according to the designer's needs.

6.3.4. Representing building design throughout the design process

Section 6.3 presents an overview of how the different types of representation systems used by designers when designing are related to problem-solving paradigms. It outlined which representation systems reflect better the rationalist, pragmatic and post-modern ideas about problem-solving paradigms.

The essence of rationalism when dealing with problem-solving structures, in which form needs to respond to function, is reflected in the following representation systems:

(i) Diagrams and sketches: Representation systems that are focused on making functional requirements clear for the designer, so that forms that adequately respond to these requirements can be proposed and representation systems that are also focused on making the solution concepts clear, allowing the development of form to come naturally from them;

(ii) Sketches: Representation systems used to manipulate form, to develop design ideas, imprecise, amorphous, indeterminate, ambiguous and fluid enough for the designer to externalise forms from his/her mind and reinterpret them, developing them further;

(iii) Technical drawings: Representation systems that are as faithful as possible to reality, used to simulate and evaluate the materialisation of the proposed artefact in a clear and unambiguous way.

The essence of pragmatism when dealing with problem-solving paradigms is to emphasize the use of representation systems that are a medium for designers to express, develop and test their ideas, a medium for designers to communicate with the design world they are inhabiting: the sketches. A pragmatic view about sketches shows how this type of representation system is more than simply used to work upon the proposed design object. A pragmatic view about sketches show they are also representations used to explore how the proposed object can be experienced by the users.

The essence of postmodern discourses when dealing with problem-solving paradigms is to explore representation systems that are used to manipulate design meaning. Narratives and discourses are central as they bridge gaps between building design and its wider context either by connecting the object being designed with architectural history, with the visual arts or with human science and philosophy. Connections are reinforced by any type of visual media that clearly allows the textual concepts to be better manipulated and translated into spatial phenomena.

From this and the previous discussions, it is possible to conclude that, "in architecture the range and scope of representations used during different stages of the process are broader than they are in other design domains" (Akin 2001). Representations are multi-faceted and multi-media driven throughout the whole design process. There are no representation standards because problems are site specific and need to be integrated with physical context; they are socially situated and user dependant, needing to fit a social context to varying degrees; they need to accommodate the user along many dimensions, functional, psychological, cognitive, economic, climatic, ergonomic, among others in which user behaviour is an integral part of the functionality of the object being designed (Akin 2001); and finally they depend on the way the designer interprets and decides to act upon the object being designed.

As a result, building design problems require a great variety of representation systems to be used along the process (Akin 2001). However, although architecture is considered "a representation saturated problem domain" (Akin 2001) certain commonalities among the representation systems used can be identified. In most of the cases, representation systems are used to manipulate phenomena that develop in space either in an abstract or concrete way. The nature of these phenomena and the fact that representation systems are visual, enable intuition about quantitative results to be developed as interactions between the whole and the parts can be easily visualised. As a result, concerns tend to be about form, dimensions, proportions, usage, visual effects, scale, disposition of elements, organisation of activities, accesses, circulations, and so on in which the end data is mainly geometrical and material, concrete, for the object to be materialised, to be constructed.

As the ultimate product is form, representations tend to be highly visual, most of the time static and dynamic effects are acknowledged mainly in connection with perception, walkthroughs inside the building and in its surroundings, sunshine effects, textural effects, to cite a few. In any case, there is not an underlying unique model to be used every time a problem is to be solved. There is not even a set of standard representation formats to develop a design idea. There are simply multiple ways of representing ideas too comprehensive to be generalised either in terms of format or in terms of application, but possible to be connected to the different worldviews involved in building design if used to reflect different approaches to problem-solving activities.

6.4. Architectural design and the computer

"There is a symbolic value in our choice of media, one that reveals a great deal about what we regards as important and what we don't find so important" (Rowe 1987)

Thousands of computer tools are available to be used through the design process as well as to communicate building design information to third parties. In spite of the fact that most of them in essence tend to bear correspondence with the ways building design information is represented, i.e. they tend to emphasize visual capabilities and are used to manipulate aspects involved in the materialisation of the artefact (construction, costs, structure, etc.), to express designer's intentions, to manipulate and display form in space, etc… there is much more involved in them compared to what is involved in simple representation systems. "Technologies are implicated in our whole way of being" (Coyne 1995).

Tools are always conceived in a rational way with a starting point in General System Theory. "Computer programs and hardware are undeniably systems" (Coyne 1995), as they exhibit hierarchical structures, with interdependent components and nested subsystems, used to store and manipulate data, following control procedures, processing inputs into outputs. Computer tools are developed using a representation system composed of structured languages with fixed and unambiguous properties that enable a machine to handle the storage and manipulation of different types of representations of many phenomena. This means that tools "neither consider nor generate facts, they manipulate symbolic representations that some person generated in the belief that they correspond to facts" (Winograd and Flores 1986).

People generate and manipulate symbolic representations by interacting with an interface. This interface translates user domain information into machine domain information, it needs to be simplified and domain customised if the tool is to be useful. In order to provide the right coupling between the person and the machine, the starting point of interface development tends to be a mirror of the representation system users feel comfortable and confident to manipulate. Adjustments in the interface and development of capabilities to generate, store and manipulate information in these representation systems are undertaken based on feedback coming from practice, from observing and testing user's interacting with the proposed software.

Having a representation system as a starting point, makes it easier to relate the existing types of tools to problem-solving paradigms in order to discuss how the computer interacts with these different types of paradigms. The aim of this section is then, to outline the role of computers in rationalist, pragmatic and postmodern problem-solving paradigms. A short discussion followed by examples of applications is undertaken based on a combination of aspects from the previous review of the literature about building design problem-solving, which discuss the role of technology in assisting the design process, together with the different types of representation systems as well as the most important aspects involved in problem-solving according to each of the worldviews.

In any case, as has been already mentioned, there is much more involved in the use of computer tools throughout the design process compared to what is involved into the use of simple representation systems. Computers are not purely used to represent or to manipulate phenomena, they affect the whole way designers think in relation to the phenomena being manipulated and as a consequence, the way designers interact with their piece of design.

6.4.1. Rationalism and objective performance

Computer tools are essentially rational. Information manipulated, stored and retrieved by computers needs to be clearly defined, classifiable and unambiguous so that it can be objectively modelled and represented symbolically and mathematically for systematic rules to be applied to evaluate possibilities and compare alternatives. In this sense, computers tools are philosophically consonant with rationalist building design and the computer is seen as a potential advisor during the design process enhancing performance based design capabilities.

Rationalist models that deal with 'subjects undertaking design activities' envision the computer as a potential advisor in problem-solving structuring from the early design stages, when information about requirements involved in problem setting as well as conceptual solutions are being explored. Models that deal with the object being designed envision the computer as a powerful advisor to assist in form generation, evaluation and refinement of the proposed artefact.

Structuring design problem-solving

Tools that handle representations used to structure problem-solving, i.e. tools that basically simulate environments for digitally represented information manipulation, not the pure act of form generation (Ozkaya and Akin 2006) are more commonly developed and studied by design researchers for educational purposes. They tend to derive from a mixture of educational constructivist theories and cognitive science concept mapping theories, generally originating from idea association tools which provide abstract representation environments in which topological relationships can be explored, ideas brainstormed, reflected upon and recorded; or originating databases of precedence, simple computer case-based libraries developed to assist in case based reasoning.

Case-base libraries

An example of a case-based library can be found in Heylighen and Verstijnen 2003 who propose the Dynamic Architectural Memory On-line (DYNAMO) a web-based "growing collection of concrete design cases" (Heylighen and Verstijnen 2003), a database of case studies, that can be changed and improved. As solutions tend to be developed based on available exemplars, precedence is a powerful source of inspiration to form. However, it is up to the user to organise and structure this information as the way precedence is retrieved to inspire new pieces of design is completely contingent and idiosyncratic. Under this circumstances, DYNAMO allows the user to build his/her own catalogue of references, organised according to the way he thinks they better suit his/her way of designing. The collection of case studies is structured into a Microsoft Access Database which is connected to a browser interface that allows information to be retrieved based on specific search criteria (Heylighen and Neuckermans 2000). Users can consult and modify the collection as well as make links between the cases and create different indexations for them (Figure 6.39). The catalogue of cases can then be expanded and consulted, organised and re-organised according to the user's need and the tool can be used to specifically "clarify and support the use of cases in architectural education and practice" (Heylighen and Neuckermans 2000).

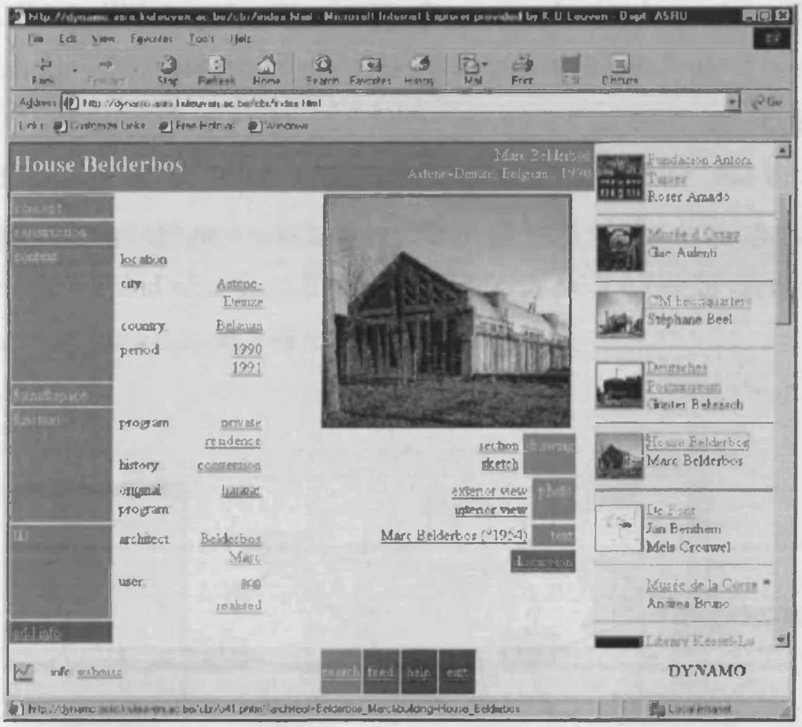


Figure 6.39 – DYNAMO user interface (Heylighen and Verstijnen 2003).

<u>Idea associations</u>

Examples of idea association tools can also be found in Lai and Chang 2006 and Tweed and Bijl 1989. Both are computer tools that directly handle the functional requirements involved in problem-setting as well as the conceptual solutions that are going to underlie problem-solving based on representation systems in which topological relationships are central.

Linkography is a cognitive science technique used to map 'design moves' in which associations between moves are represented graphically through links (Kan and Gero 2008). Originally developed as a topological mapping system used to record design productivity and look at patterns that display the structure of design reasoning (Kan and Gero 2008), this representation system is made digital to allow designers to "decompose a design into several architectural elements and use the attributes of these elements as keys to search for relevant ideas within a particular design case" (Lai and Chang 2006). Using as a basis the Issue-Concept-Form model proposed by Oxman 2001 and the linkography representation system, Lai and Chang 2006 propose DIM-2, Dynamic Idea Maps II, a digital tool to support idea associations acknowledging requirements and precedence.

DIM-2 differs quite drastically from simple databases like DYNAMO as information is manipulated and structured using a totally different type of representation system. The tool is not simply a catalogue with enhanced capabilities it enables abstract topological diagrams to be connected with brainstormed ideas and/or with ideas extracted from precedence (Figure 6.40). Precedence as well as the new ideas brainstormed can be stored, retrieved and also visually connected with each other in an environment that puts together textual information and topological diagrams.

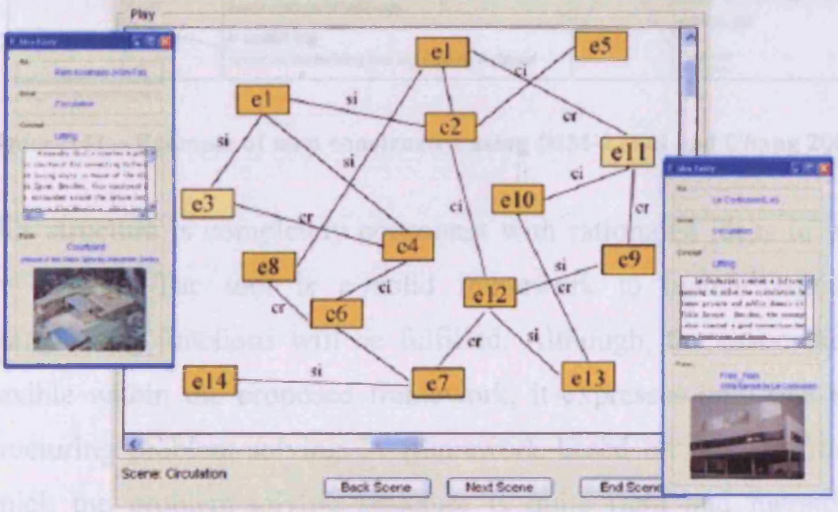


Figure 6.40 – Example of the handling of an issue in DIM-2 (Lai and Chang 2006).

DIM-2 allows information from precedence to be stored and retrieved, serving as a source of inspiration to develop new ideas and creative concepts, it allows new information to be manipulated and integrated and it can also be used to communicate with different agents involved in the process. However, it is quite restrictive with regards to non-sequential links among design issues, as the interface allows one issue to be handled at a time; it can produce maps that are too large, in which information overload and graph problems occur; but most of all it requires information to be clearly defined in the terms of the Issue-Concept-Form (ICF) format, in order for it to be related, stored and retrieved. Designers have to clearly understand and classify ideas and concepts they are relating to considering: the issues they are addressing, the concepts that are possible to be explored to address the issues as well as the possible forms that can resolve the issue being addressed (Figure 6.41).

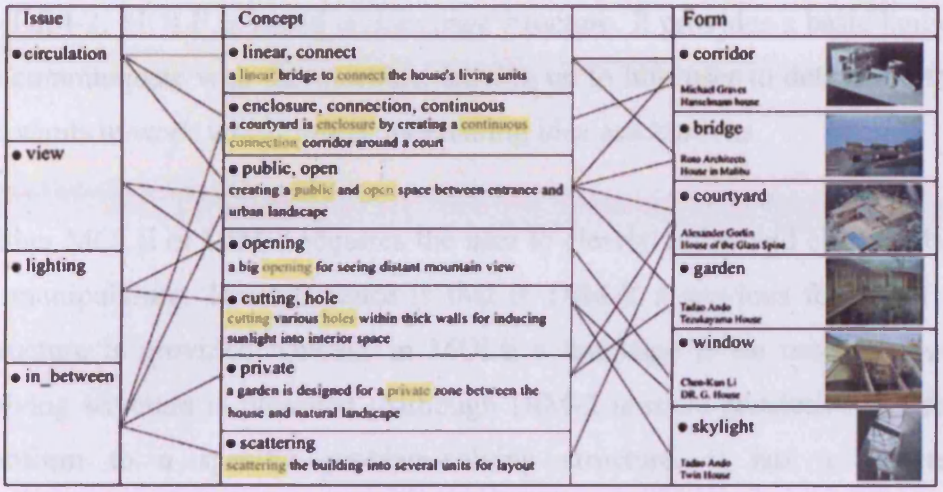


Figure 6.41 – Example of map constructed using DIM-2 (Lai and Chang 2006).

This structure is completely consonant with rationalist ideas in which form and function are central. The tool is a solid framework to match requirements with solutions, guaranteeing functions will be fulfilled. Although, the association of ideas is relatively flexible within the proposed framework, it expresses only one rationalist framework of structuring problem-solving. A framework based on models from cognitive sciences in which the problem-solving structure is quite rigid and hierarchical. Many others are possible according to what was discussed in section 6.2.1, including more dynamic language structures, which are less hierarchical and more procedure-based.

An example of a tool that has a different structure for designers to work with association of ideas is provided by Tweed and Bijl 1989. Although MOLE has a representation environment also based on topological diagrams, it was designed to "accommodate user's descriptions without conditioning their content" (Tweed and Bijl 1989). The idea behind MOLE is the production of a tool that is similar to a word processor in which users "structure their words to form descriptions" (Tweed and Bijl 1989). Descriptions can be represented either as texts or drawings (or both) and general functionalities, domain independent, are provided to users to accommodate descriptions according to their needs (Tweed and Bijl 1989). MOLE's framework is composed of 'kinds' which can be used to define things; 'fillers' which are the parts that describe the 'kinds' and 'slots' which are the connectors between 'kinds' and 'fillers'. Numbers and strings are the basic tokens for users to choose the way they want to represent things and at the same time are used to define operations that are possible to be undertaken with the structure that was defined. Contrarily to DIM-2, MOLE is based on language structure. It provides a basic language for the user to communicate with the machine, leaving up to him user to define the format of the tool he wants to work within when undertaking idea associations.

Either MOLE or DIM-2 requires the user to clearly define and classify the information he is manipulating. The difference is that in DIM-2 a previous format of problem-solving structure is provided whereas in MOLE a language to be used to develop a problem-solving structure is provided. Although DIM-2 is more restrictive and forces the user to conform to a specific problem-solving structure, it has a representation system ontologically clearer to designers when compared to MOLE. Designers can set up their own problem-solving structures in MOLE so long as they can design a program that allows them to do so. The user is usually faced with an extra task far beyond his/her capabilities in terms of time and expertise as he needs to create a program to assist him in problem-solving prior to starting to solve the problem at hand.

As problem-solving structure can be approached in many ways under the rationalist viewpoint it becomes extremely difficult to develop a tool comprehensive enough to assist the early design stages. The fact that information when manipulated, stored and retrieved by computers needs to be clearly defined and unambiguously classified either makes it possible to develop tools that make the user conform to a specific structure or a specific set of structures, or tools that transform the user into a programmer so that theoretically any type of structure can be developed. The level of freedom allowed in paper-based schemes is far beyond what computers can do in these situations. The user is not forced to rationalise the very beginning of the design process while manipulating information because he does not have to either conform to or create an environment for this to happen. Paper-based media is comprehensive enough in terms of the type and nature of information being manipulated and at the same time it allows for ambiguity, flexibility and fluidity in exploring ideas.

Acting on the 'object of design'

The same cannot be said about tools that assist in form generation, evaluation and refinement of the proposed artefact. When the information being stored, manipulated and retrieved refers to form and representation systems used are concrete and visual, most of the information can be transformed into mathematical models and therefore represented in computer environments. The problem of integrating computer tools into the design process becomes much more a matter of designing an interface with a clear ontology reproducing as much as possible the "language that creates the world in which the user operates" (Winograd and Flores 1986).

Initially developed to mirror representation systems that deal with the materialisation of the artefact, CAD (Computer Assisted Design) tools used to have command based interfaces based on Euclidean geometry to input and manipulate data. CAD tools provided an environment in which points, lines and polygons were used to construct plans, sections and elevations that could be stored, manipulated, retrieved and send to third parties to be further developed. Once interfaces evolved towards a more visual approach in which command lines were replaced by basic shapes and properties, reaching a better coupling between designers and machines, representation systems to input and manipulate data became more compatible with the representation systems designers were used to manipulating. Possibilities of using the computer capabilities further in the design process could be envisioned, and CAD tools became much more than simple representation systems.

From descriptive models with geometrical rendering algorithms useful to manipulate graphical representations of digital objects, CAD tools were transformed into predictive models with analytical processes applied to geometrical models, integrated with material logic and manufacturing processes used for collaboration between different design team participants (Oxman 2006). Structural behaviour, cost estimates, photorealistic rendering and innumerous other capabilities such as shared databases between representations and evaluations to re-asses changes are now part of many of these tools impacting hugely in design development. When CAD transcended their initial descriptive and evaluative purpose and could assist in shape formation, generation processes and parametric design, i.e. when CAD tools became performance based design tools, a real 'digital revolution' was reached as the computer capabilities started going beyond what could be done in a conventional paper-based scheme.

Shape formation tools

Tools that assist in shape formation simulate external forces acting upon the object being designed in order to shape it. Analytical simulation techniques produce parametric expressions of performance, and shapes that respond to specific performance criteria are used to transform and/or deform a model, reflecting a complex behaviour (Oxman 2006). New form generation possibilities emerge with hyper-surfaces, and different types of interactions in manipulating these forms are enabled with modifiers such as nurbs, b-splines, scripts, etc. Shape formation tools can either interact with users through a mixture of graphic/visual with a numeric/rule based interface (Figure 6.42) or through a main graphic interface directly. In any case the idea is to provide real time feedback in terms of form response to the application of parametric expressions of performance in the object being designed.

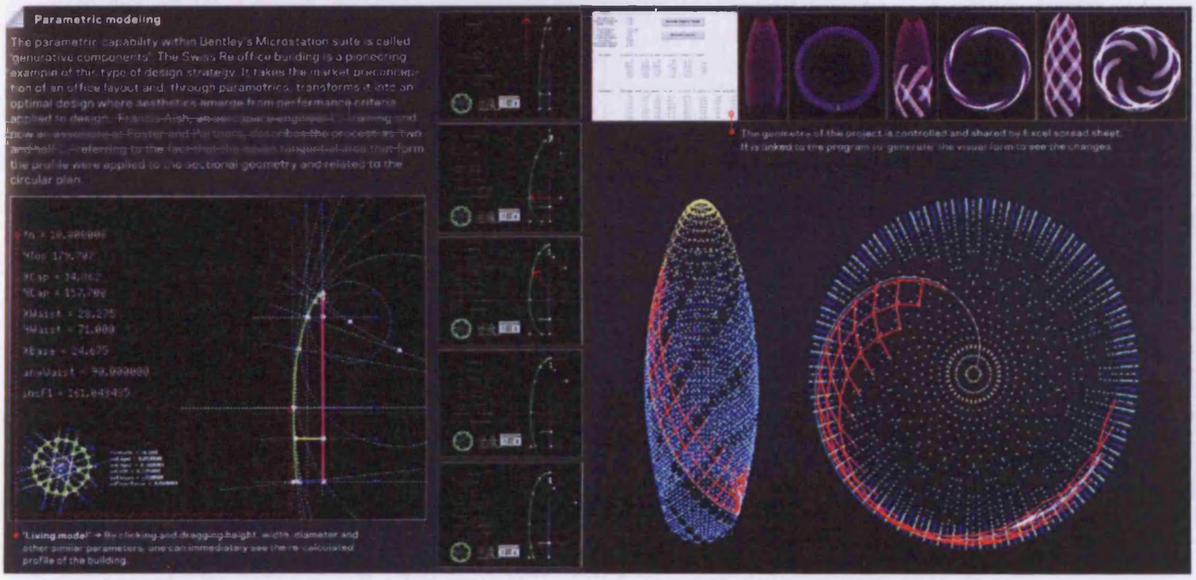


Figure 6.42 – Example of a computer tool that assist shape formation (Foster + Partners 2006)

Generative design tools

Generative design tools also assist in shape formation, but the designer interacts directly with the generative system and form will emerge from rules, relationships and principles, pre-formulated generative processes controlled and guided by the designer while selecting the desired solution (Figure 6.43). Examples of generative processes are the following:

(i) Shape grammar, in which a 3D a-periodical spatial tiling, mathematically described with regards to the tiling material and the basic generative grammar, is used as a basis for formal composition rules;

(ii) Evolutionary processes, in which form emerges from evolutionary processes derived from an internal genetic coding such as Genetic Algorithms or Cellular Automata, in which the main issue is to define the set of generative rules, evolution and development for a specific design context;

(iii) Morphogenesis, in which form emerges based on biological metaphors of generation, adaptation and evolution of living organisms.

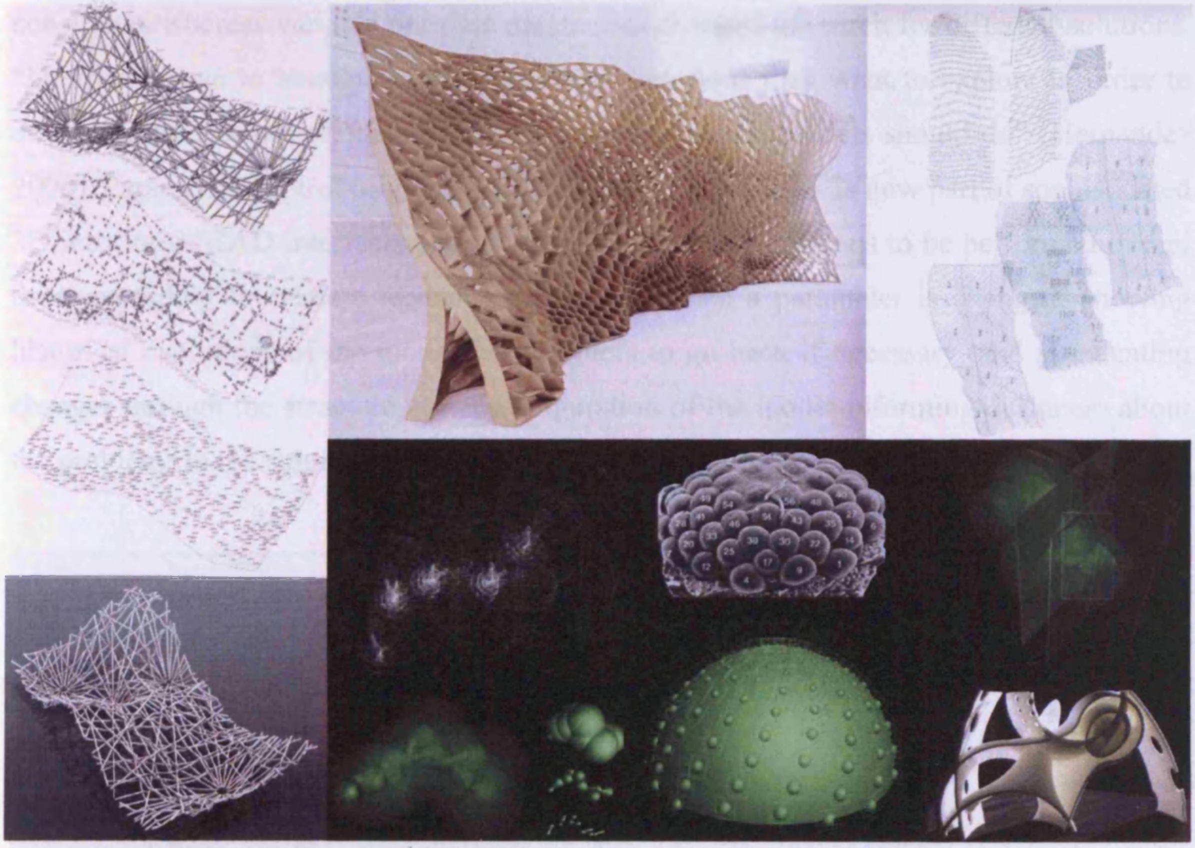


Figure 6.43 – Examples of generative models (Menges 2006 and Hensel and Menges 2006)

In generative design tools, designers are forced to approach design differently. They have to define performance criteria and generation criteria explicitly as the computer will output the results of these criteria in terms of form. Interfaces are not as interactive and visual as they are in shape formation tools and the user is forced to think about design in more abstract, mathematical terms.

<u>*Parametric design tools*</u>

Parametric design tools are one of the most powerful types of CAD tools to assist in the materialisation of the proposed artefact. "In parametric design, relationships between objects are explicitly described, establishing interdependencies between the various objects. Variations, once generated, can be easily transformed and manipulated by activating these attributes. Different value assignments can generate multiple variations while maintaining conditions of the topological relationships" (Oxman 2006).

Parametric models are then constructed keeping some attributes (properties) of geometrical entities fixed in order to explore variations in others. Fixed attributes are generally constraints whereas variable ones are parameters changed to search for different solutions. "Designers have to anticipate which kinds of variations they want to explore in order to determine what kinds of transformations their parametric models should do" (Hernandez 2006). Parametric control originally undertaken through scripts is now part of sophisticated 3D interactive CAD interfaces (Figure 6.44) that enable variations to be performed in real time, providing immediate feedback to the user when a parameter is changed, showing historical evolutions of the model for designers to go back if necessary, and propagating changes through the structure and reconfiguration of the model informing designers about the problems in the solution (Hernandez 2006).

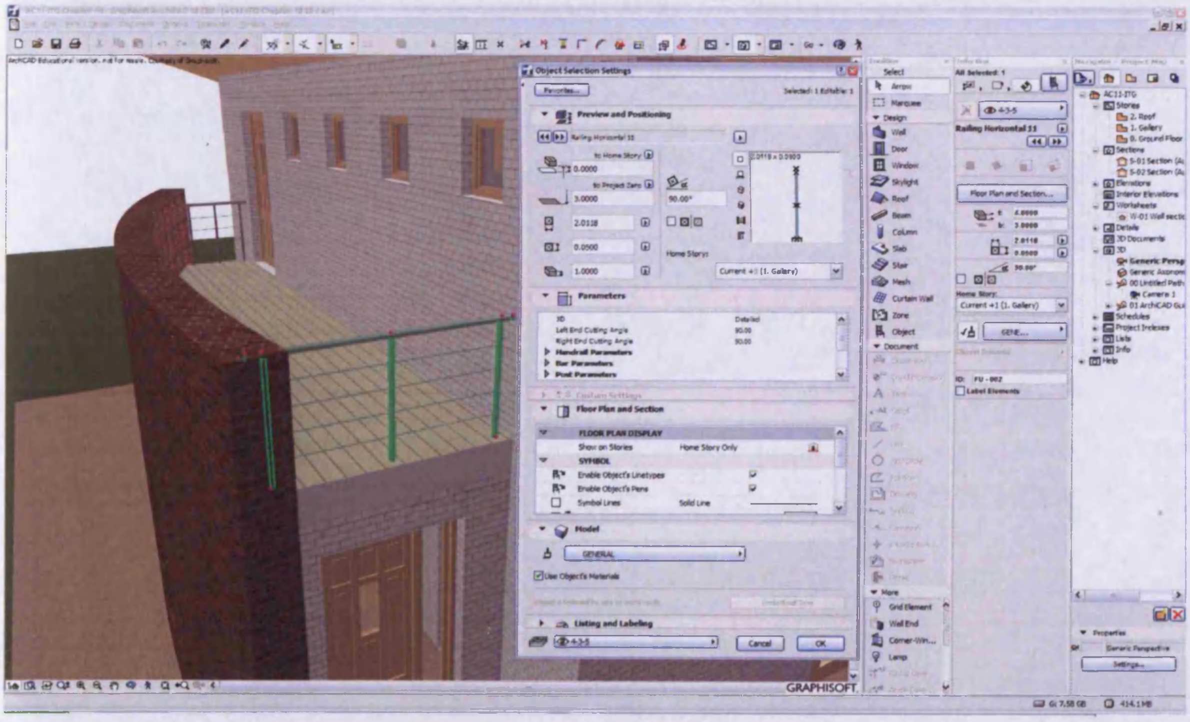


Figure 6.44 - Example of parametric interface (Graphisoft 2008)

Apart from that, parametric models are useful to explore changes in geometrical components without erasing and redrawing. They provide flexibility for exploration and refinement, re-usage of solutions by encapsulation, transformation of successful models into basic units that can be treated as primitive entities, rigour in design development and real time feedback about changes (Hernandez 2006). Designers can create a geometrical model and parameterized attributes based on a desired behaviour and/or combine different components in different ways achieving a large variety of solutions, setting up rules for combinations as well as for spatial relations among primitive components (Hernandez 2006). As a consequence interfaces are graphic/visual but elements are associated to databases containing innumerous properties that specify constructability and all other aspects related to the performance of each element.

Rationalism and objective performance

The fact that the representation systems used to manipulate concrete phenomena that develop in space are suitable to be mathematically represented, and consequently modelled, enabled information about form generation, manipulation and materialisation of the object being designed to be easily handled by computers. Shape formation, generation processes and parametric design are all part of performance based design tools. They are not analytical CAD tools but "software that can provide dynamic processes of formulation based on specific performance objectives" (Oxman 2006). They are software that uses performance as a formation technique, as a generative process parametrically defined by the problem conditions, site, program, etc. generating the object by simulating its performance.

Performance based design tools caused a real revolution in design in terms of expanding formal possibilities as well as in terms of design thinking, influencing the whole design process. However, they force designers to become much more rational about design conception, design manipulation and design decisions once the media used is the computer. Designers now need to combine representation systems used to manipulate phenomena that develop in space with abstract representation systems of rules and mathematical expressions in order to really take advantage of enhanced capabilities provided by computers. In parametric design, a wall for instance is not a 'plane' anymore it is an entity with all attributes that make it real. Even when interfaces are ontologically clear to designers and extremely visual, there are rules underlying form and function associations as well as rules controlling form generation, both based on hidden rational underlying principles.

As tools "neither consider nor generate facts, they manipulate symbolic representations that some person generated in the belief that they correspond to facts" (Winograd and Flores 1986), the computer acts as an advisor for rationalists once it enhances the number of operations to be undertaken in manipulating, storing and retrieving information along the design process because it converts representation systems used to manipulate phenomena that develop in space into mathematical representations.

This explains why tools are successful advisors when used to manipulate directly the object being designed instead of when they are tried to be used in the early design phases. Ambiguity, fluidity, imprecision, etc. are actually essential properties used to enhance creative thinking and explore new ideas and it is paramount that information being manipulated at this stage fits into that description so it becomes difficult to convert this type of information into a representation system that can be stored and interpreted in a computer.

6.4.2. Pragmatism and the engagement with the media

Although tools are essentially rational, interface development tends to follow a more pragmatic approach. There is a concern about the way users interact with the machine in very practical terms, i.e. the way the computer will be used (Coyne 1995), and an attempt to make the interaction between user/machine almost transparent, in order for thinking and doing to be inseparable. There is a strong orientation "towards an engagement with the material and technologies" (Coyne 1995) and the computer is understood as a medium to develop conversations with the materials of the situation, mainly to sculpt the object being designed and/or to simulate experiences provided by this object.

Sculpting the object being designed

When investigating ways of developing a conversation with computers in order to sculpt the object being designed, some studies focus on mirroring paper-based and other conventional representation schemes. They focus on using the computer to undertake 2D and 3D translations of paper-based sketches as well as to translate 3D CAD models into real models using rapid prototyping technologies.

Translations from analogue images to computer can be optical or manual. Optical digitizers such as scanners are generally used to produce digital pixel images of the analogue representation. Manual graphic tablets with pen-like pointing devices exhibit mechanical and ergonomic properties similar to the analogue media and can be used to produce digital vector information of analogue representations (Koutamanis 2006). However, contrarily to OCR techniques, in which each piece of handwriting can be decomposed into the different characters of the alphabet in order to be digitally re-constructed, vectorial representations simply transform drawing representations into mathematical representations. Further symbol recognition is still necessary to translate paper-based sketches into 2D or 3D CAD models, something extremely controversial to be done automatically.

"Interpretation of free hand drawing and extraction of embedded semantic content" (Gross and Do 2004) is facilitated when the use of inputs from pen, speech and text are connected to a library of previously framed templates. Once matching between what was drawn and what is in the library is achieved, the program returns a glyph that represents the digital version of the input information. The library contains the most common drawing elements that the designer intends to represent (for instance walls, columns, windows, etc.) and for "unintended figures formed by spatial relations among intentionally drawn components" (Gross and Do 2004) the system is programmed to generate a set of candidates for the user to choose and clearly specify. The effective move from a crude sketch to a precise drawing is achieved by preserving essential relationships of the design domain for instance geometrical relationships in architectural floor plans (Gross and Do 2004).

However, extracting the semantic concept of free hand drawings is still not enough to produce 2D and/or 3D models from sketching as going from sketching to technical drawings also involves moving forward in the design process, it involves evolution, commitment towards the materialisation of the artefact. Further information from assumptions made and decisions undertaken are necessary. Producing 2D and/or 3D models from sketching involves more than simply manipulating representations; it is a matter of dictating design directions through the specification of design details.

Ambiguities and multiple interpretations of sketches, essential properties used to enhance creative thinking and explore new ideas, provide the backgrounds for this to happen. As a consequence it is not uncommon to find studies which deal with interchangeability of digital and analogue versions of sketches instead of trying to convert everything directly into digital information (Koutamanis 2006).

An example of form creation from translating 3D CAD models into real models using stereo-lithography rapid prototyping technology is explored in Sass and Oxman 2006. They claim that rapid prototyping techniques are good to investigate construction systems, structures, shapes and aesthetics as they provide an environment appropriate to trials and redesign as well as for knowledge represented as parametric constraints and associative modelling.

Rapid prototype design models are generated as surfaces or objects, evaluated for shapes or assemblies, built based on parametric based components or combined with solid objects of fixed geometries. Once construction aspects are incorporated, the design of each component, assembly description, manufacturing descriptions and scaling that allows real size prototyping for assemblies and structure components are taken into account, i.e. all relationships between modelled geometry and material properties are established enabling structural, aesthetic and construction performance to be evaluated (Sass and Oxman 2006).

Although attempts are made in terms of facilitating the interaction between user's/computer to sculpt the object being designed, whenever information is made digital then ambiguity and imprecision involved in the conversation with the materials of the situation are reduced, as further specifications that force the designer to commit to the reality of materialising the artefact need to be provided. As digital drawings are more symbolic representations if compared to 3D rapid prototyping models they tend to be require less commitments. The comprehensive and clearly established relationships between modelled geometry and the material properties in 3D rapid prototyping in one hand enable designers to evaluate performance since the early stages but on the other hand, force the anticipation of commitments with regards to structural and construction aspects involved in form generation. It is up to the designer to decide if this is desirable or not during the conversation with the materials of the situation.

Simulating experiences provided by the object being designed

Computers are extremely powerful when simulating experiences provided by the object being designed. Tools are available to present "sensory information and feedback to give the convincing illusion that the technology user is immersed in an artificial world – a world that exists only inside the computer" (Coyne 1995). In these situations realism in representation is one of the keys for designers to experience their design. "Images generated by the technology and presented to the viewer are general, are invariant, capture the essence of the scene, and are independent of the viewer" (Coyne 1995) providing a "universal field of sensory input" (Coyne 1995).

When simulating experiences provided by the object being designed, information presented can be static or dynamic. In the first case, the result is photo-realistic rendered images that mirror paper-based perspective representation systems, which show the internal and external spaces of the proposed object. In the second case, the result is photo-realistic rendered movies which simulate walking-through, walking-around and flying around the object being designed. Movies can be displayed on screens or in virtual reality environments trying to simulate the experience as close as possible to a real one.

However, the most important point for the pragmatists is actually the way designers interact with the information presented. This can either be sequential or real time. In the first case, information takes time to be processed in order to return a digital representation whereas in the second case processing is extremely fast giving the impression the digital representation is returned instantaneously. Real time interaction is the first step for designers to get immersed in the technological environment and for human computer interfaces, hardware and software that aim to couple users and machine as naturally as possible, using from photo-realistic techniques up to devices to simulate immersion in virtual reality environments, to be developed.

Real time interactions are already very common in 2D and 3D CAD and they are becoming more and more common in formation and parametric CADs which now enable designers to develop dynamic and responsive design, using animation and morphing techniques as well as new theories of form generation (Oxman 2006). Designers not only interact with 3D real time form generation environments but also interactively explore parametric changes (Figure 6.45).

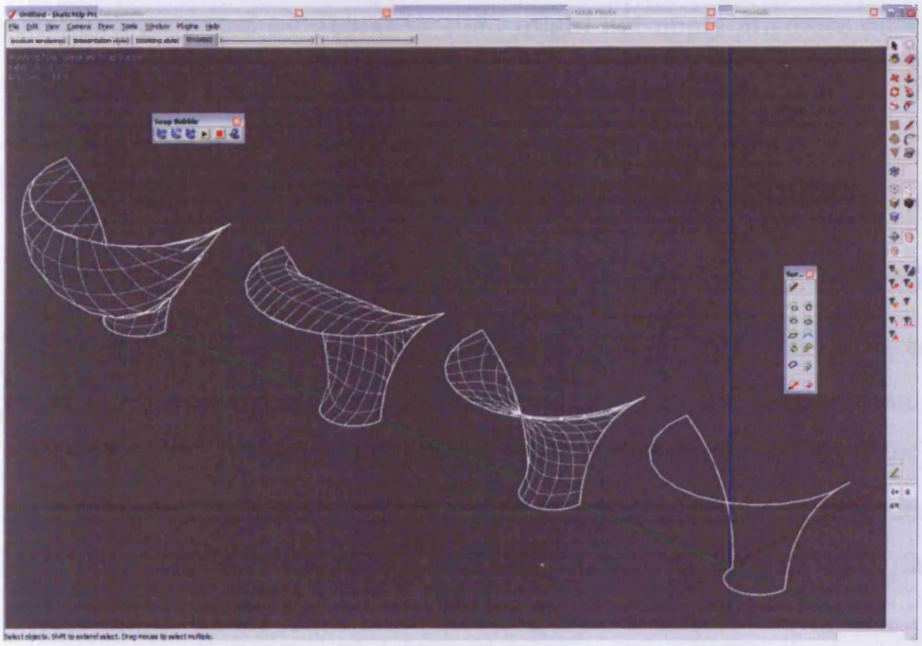


Figure 6.45 – Example of a 3D real time formation model (Sketchup.Google 2008 and Leibinger 2008)

3D formative and parametric interfaces with real time animation and morphing techniques to manipulate form and explore parametric changes mean a real digital revolution to the pragmatists. They provide the means to sculpt the object being designed as well as to simulate experiences that result from it. It is a different approach if compared to interchangeability of digital and analogue versions of sketches and perhaps a more efficient and less committed approach if compared to rapid prototyping technologies. It presents a totally new paradigm for experimentation, less ambiguous and less indeterminate if compared to sketches but still fluid, amorphous and imprecise if compared to rapid prototyping. It combines sculpting with experiencing its results moving "away from static abstractions that are implied in the concept of formal representations" (Oxman 2006) triggering real changes in design thinking.

Pragmatism and the engagement with the media

The belief of primacy of information in pragmatism allied with the strong enthusiasm for cyberspace (Coyne 1995) influenced the design of interfaces up to a point in which esoteric commands and formal logic are successively being replaced by familiar and recognizable design ontology. Strategies of representation systems are going further than simple compatibilities with paper based schemes. Questions about how to accommodate knowledge about types, references, spatial gestalt and archetypes in a computer as well as how to incorporate gestalt shifts and implications of these shifts in working units, rules and reasoning proposed by Schon in 1988 might not apply anymore once a whole change in design thinking is happening. Computers are moving beyond simple advisors and becoming an essential tool for reasoning.

6.4.3. Post-modernism: emergent forms or another way of domination?

The post-modern approach to computers is heterogeneous. On one side, there are worldviews which see it as an essential tool not only for thinking but also as a vehicle of self-expression enhancing possibilities of exploring new meanings. On the other side, there are worldviews which see it as a vehicle of oppression and reinforcement of relationships of power, mainly subordinating architecture to construction and manufacturing industries.

The computer as a vehicle of self-expression

Post-modern worldviews based on artistic and aesthetic discourses incorporated computers in their practices not only to sculpt the object being designed and to simulate experiences provided by this object using interactive interfaces. The role of computers is also to instigate, embed, diversify and multiply the effects of building performance in material and in time (Kolarevic 2005). Computers are used to inspire form generation and set to operate without employing a priori categories of form (Oxman 2006). A totally different concept for form definition in building design arises in which objects are part of a process of emergence (Spuybroek 2005). Discourses are not applied to appearance anymore but "to process of formation grounded in imagined performances, indeterminate patterns and dynamics of use and poetics of spatial temporal change" (Kolarevic 2005).

Computers started being integrated into design, materialisation, production and construction using a different approach by deconstructivists, which experimented with different technologies to develop new formal directions and new design methods (Oxman 2006). The paradigmatic work, the most iconic expression of which is the Frank Gehry Bilbao Guggenheim Museum (Figure 6.46) which illustrated a new geometric approach, free from traditional formalism of plan, structure and façade, and at the same time conveyed a different meaning for internal spaces resulting in an iconic urban intervention.

Form generation became a process of emergence in which the flexibility of action, structure and perception was consonant with the idea of breaking the distinction between plan, structure and façade. The non-standard behaviour, non-standard structure and non-standard architecture provoked a revolution in which formation processes were used mainly to generate building skins which resulted into new types of internal spaces and exceptional urban interventions. The initial postmodern aesthetic discourse of complexities and contradiction is replaced by digitally based generative techniques in which morphogenesis is applied in emerging form (Oxman 2006) shifting the idea of appearance to the idea of process formation.

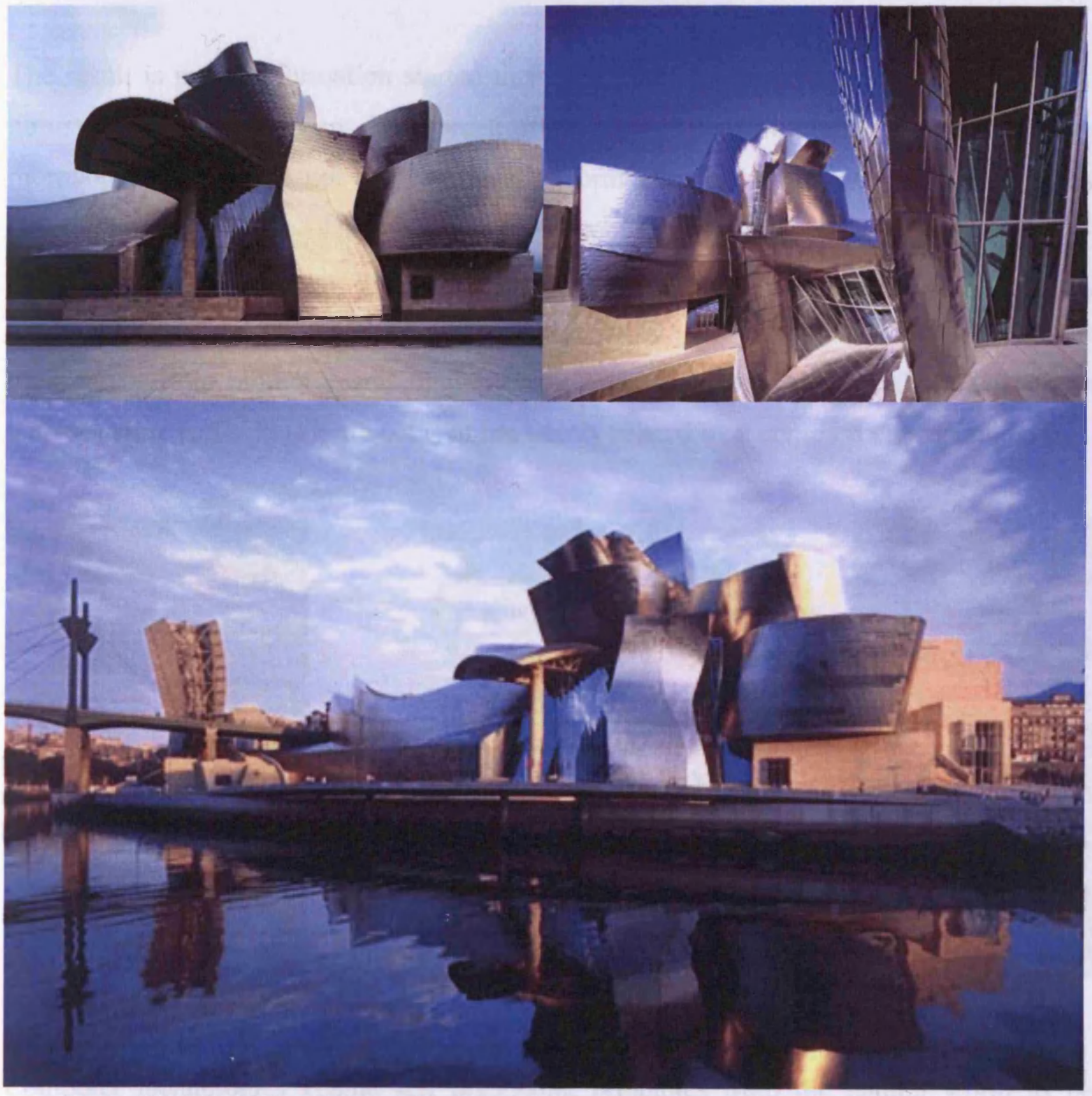


Figure 6.46 - Frank Gehry Bilbao Guggenheim Museum (Guggenheim-Bilbao 2008)

Process formation enables plan and elevation to become intertwined and to co-evolve into form (Spuybroek 2005). The tectonic paradigm is replaced by a more fluid and textile paradigm from which 'free form' can emerge. New technologies in material, construction and design resultant from the digital revolution 'freed' form from the straight extrusion of spatial organisation of plans and the paradigm of robustness and firmitas challenged by deconstructivists could effectively be put into practice. However, "although deconstructivism proved to be successful in breaking down most of the top-down ordering tools we were used to in architecture (proportion, axiality, etc.), it proved to be incapable of instrumentalizing complexity itself as a tool that was material and architectural" (Spuybroek 2005).

The result is process formation started inevitably moving design towards post-industrial, non-standard constructivism (Spuybroek 2005) as well as towards systemic thinking as morphogenesis is used not only to develop form but also to consider its evolutionary development over time. The new trends are to use the computer to explore complex geometries and textures in order to achieve formal differentiation with an underlying 'meta-narrative' about performance (Kolarevic 2005). Complex geometries most of the time derive from biomorphism, finding inspiration in nature. Building shells tend to be both structure and skin (Figure 6.47) or are tightly related by a common conceptual basis.

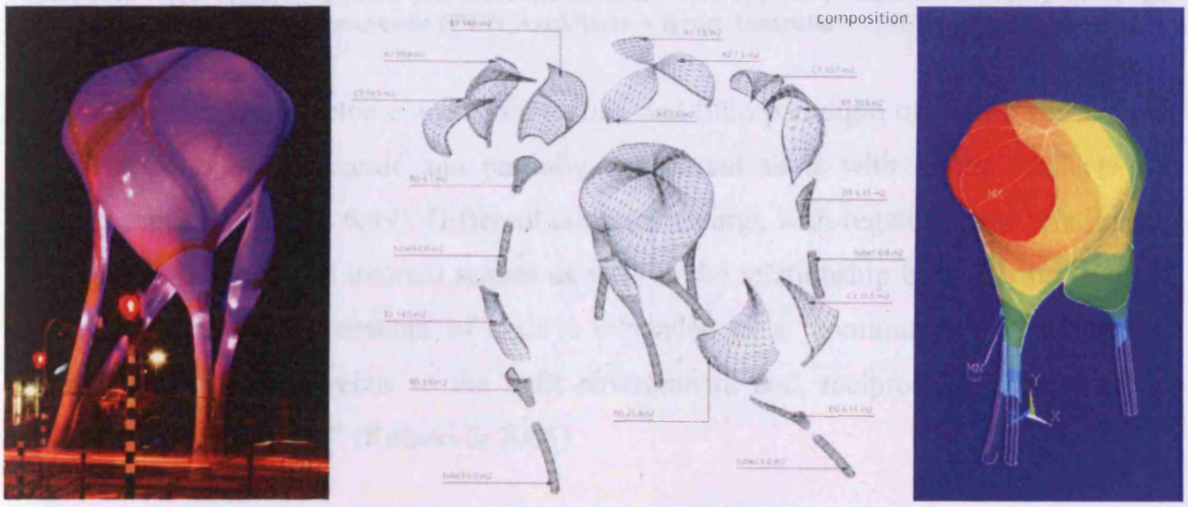


Figure 6.47 – Tectonic composition of the D-Tower shell (Kolarevic 2005)

Computer technologies enable self organising principles from the natural world to be applied to material sciences and structural engineering (Figure 6.48). Complex structures internal to the materials can be manufactured in various morphologies and topologies using strategies based on space-filling polyhedra and foam geometries enabling design and construction of bubble high-rise skins with entirely column-free interior spaces to be developed (Weinstock 2006).

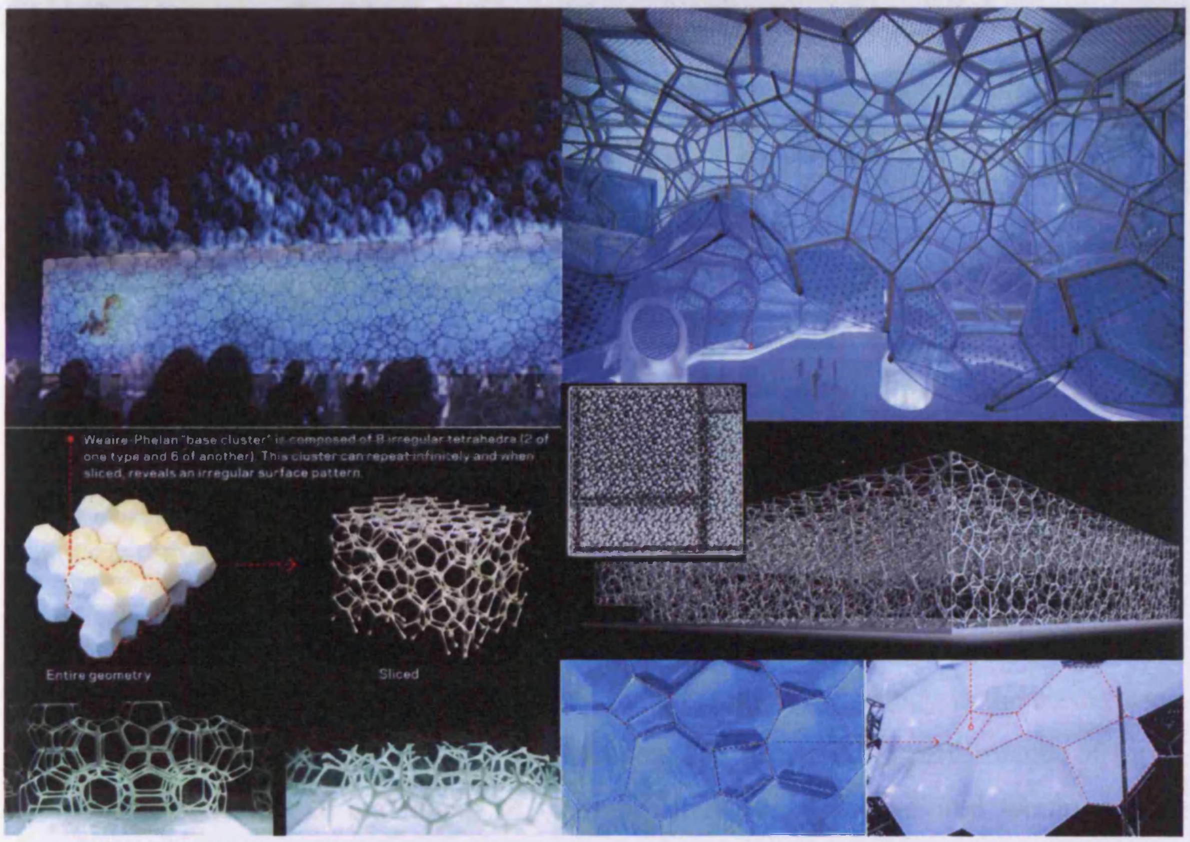


Figure 6.48 – Self-organising principles from the natural world applied to different levels of the design of the building skin in the Watercube (PTW Architects + Arup Australia + CSCEC 2006).

In addition to the less tectonic and more textual and fluid paradigm of 'free-form' enables designers to explore dynamic and partially transparent skins with multiple effects and different patterns (Figure 6.49). Different concepts emerge with regards to the relationship between the skin and the internal spaces as well as the relationship between the skin and the urban context. The concept of skin is expanded to a 'communicative membrane', "changing the way we relate to the built environment and, reciprocally, how the built environment relates to us" (Kolarevic 2005).

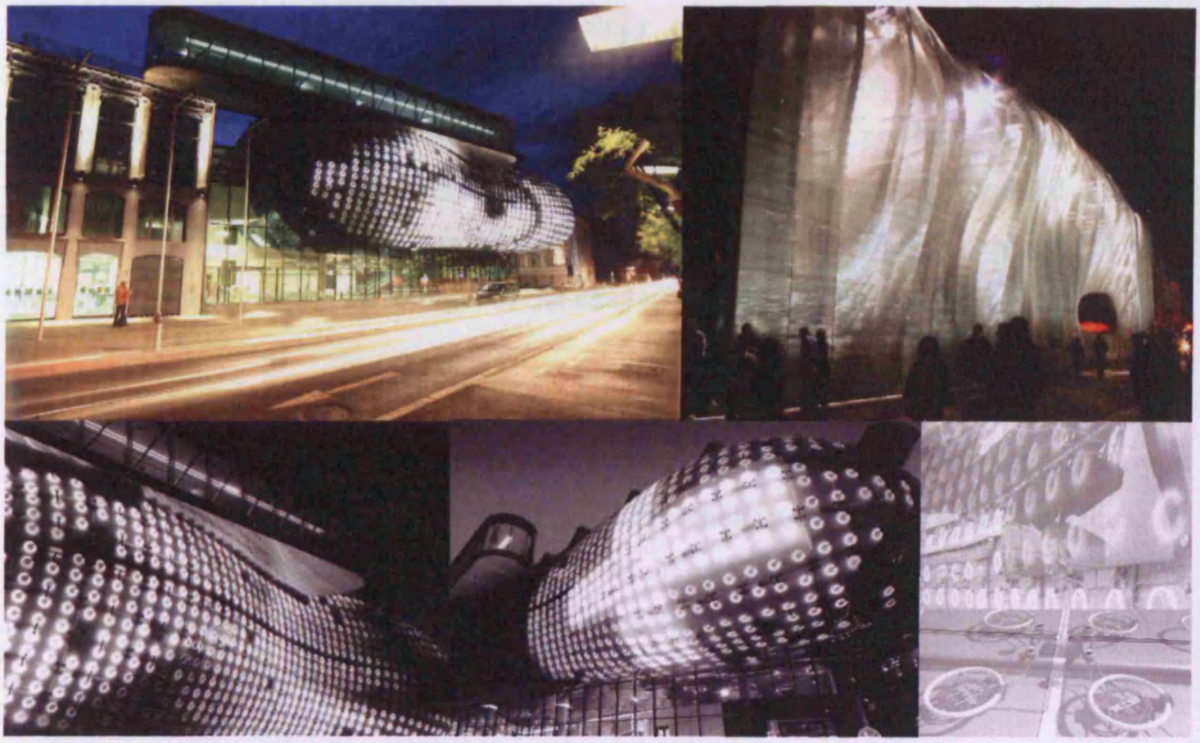


Figure 6.49 – Examples of textual and fluid skins (Kolarevic 2005).

As a result, postmodern designers when using the computer to experiment and sculpt form end up surrendering themselves to science and technology. Technology is the media used to move architecture closer to the fine arts. Meaning is translated into performance of form, into artistic performance and many of the innovative concepts explored would not be possible without the use of the computer. Under this worldview "the technological context is not at war with focal practices, they are mutually enhancing" (Coyne 1995). Performance of form, mainly of structure and skin are central. "Performative architecture is a 'meta-narrative' with aims that depend on particular performance-related aspects of each project" (Kolarevic 2005). And the use of computers in post-modern architecture is "associated with the representation and manipulation of complex form and space" (Sass and Oxman 2006). Characteristics of this style encompass topological form, transformational or differentiated evolution of spatial structure, non-hierarchical organisation, complex and hyper-connective spatial conditions (Oxman 2006).

<u>*The computer as a vehicle of oppression and control*</u>

As already mentioned, the extreme emphasis in form generation and self-expression of artistic post-modern designers is accused of being supported by wicked discourses. Radical theories once criticising structures also criticise the use of technologies. "Critical theory identifies the choices presented by technology as illusionary" (Coyne 1995) we are persuaded to believe we have choices and to choose among alternatives when in fact "the choices are already made" (Coyne 1995). Tools are a product resultant from "predetermined choices of objects, properties and relations and are limited in their descriptions of a domain" (Winograd and Flores 1986). Tools are reductionist and have embedded in them the frame of mind of the ones who conceived them.

The over valorisation of information, the idea that "the more information we have the better, even though there is a scarce space to store and to process this information" (Coyne 1995) does not increase the universe of available choices, it simply puts everything in terms of decision making. The idea that "lots of options are available and the ethical dimension resides in our choosing, not in the technologies themselves" (Coyne 1995) is actually considered false.

The fake illusion that designers are free to create form and to express themselves more and more by integrating the computer and technologies into their praxis is actually supported by control mechanisms of "technologically oriented professional groups, corporations and government and institutional bureaucracies" (Coyne 1995) to bring architecture into line with construction and manufacturing (Coyne 1995), to "universalise and homogenise human practice" (Coyne 1995). "Buildings are increasingly conceived not as unique events marking the once-in-a-lifetime coalescence of site, prevailing culture and design team, but as collections of mass-produced components assembled by firms with specialised techniques that may be located far from the geographical locations they are designed for" (Tweed and Carabine 1999).

Computers enabled information to be easily exchanged between partners and consultants and this together with software interoperability enabled integration of different programs, consequently putting together the different agents involved in the process. The different systems and subsystems that need to be conceived for the design object to function and for the design and its functioning to be materialised can be worked out separately and coordinated appropriately. Designers become heavily dependant on consultants and specialists from the manipulation computer tools to the materialisation of formal ideas. They lose control over the process and are forced to conform to standards of construction industry and manufacturing.

Under this circumstance "designers are either perpetrators or victims of domination" (Coyne 1995) if they are not aware of the fact that, once technology is seen beyond the ethical, the implications of technologies to frame needs are ignored. Critical theory criticises technology heavily accusing it of putting technical issues on top of human factors, marginalising ethics, de-contextualising human experiences, amplifying and promoting domination. It claims designers should be aware of underlying control mechanisms and at the same time should develop a strong ethical code.

6.4.4. Building design and the computer

The aim of this section is not to conclude what computers still can't do, but actually to outline that computers affect the way designers think, generate and interact with the object being designed depending on the worldview they subscribe to when designing. How far the computer can assist in the design process will depend on:

(i) The type and nature of information being manipulated, specifically on how much it is possible to clearly define and classify this information for it to be stored, manipulated and retrieved digitally;

(ii) The ontology of the user's interface, specifically on how well it corresponds to the "language that creates the world in which the user operates" (Winograd and Flores 1986).

An analysis of the rationalist viewpoint outlines the basis for reasoning about tools. It starts by showing how difficult it is to develop tools comprehensive enough to be used in early design stages when information is abstract and difficult to be classified and represented mathematically, as many models for problem-solving structure are available to rationalise about requirements and conceptual solutions. The success of paper-based systems in the early design stages due to its flexibility and affordances in terms of representing the problem is overcome by computer tools when form starts being generated and explored. Information is then concrete/visual, it can be mathematically represented making it suitable to be stored, manipulated and retrieved by computer systems.

A real 'digital revolution' happens when tools start to be used to assist in shape formation, in form generation, and design starts to be conceived and manipulated parametrically. New formal possibilities emerge together with new ways of designing and new ways of approaching design. CAD systems are transformed into real computer aided design systems, instead of simply being computer aided drawing systems, becoming effective assistants in functional issues. The real problem becomes the fact that the conversation with the materials of the situation "has to be on the computer terms rather than on the human design terms" (Lawson 1997).

An analysis of the pragmatic viewpoint shows how interaction between user/machine needs to be as transparent and as ontologically clear as possible for interface development to be successful. The idea of using the computer to mirror paper-based representation systems is questioned. Interchangeability between analogue, pen and paper, representation schemes and digital, computer, representation schemes is seen as a way forward to preserve sketch capabilities. And new ways of manipulating form are introduced once 3D, dynamic, real time form generation environments with photorealistic renderings provide means to virtually sculpt the object being designed as well as to simulate experiences that result from it. The new formal possibilities and the new ways of designing and approaching design become accessible.

An analysis of the post-modern viewpoint finally outlines how computers start being effectively incorporated in the design process, inaugurating a new way of thinking. Computers and technology are used to inspire design and become part of a process of emergence. New forms, new spaces, new paradigms are proposed taking advantage of virtual sculpting capabilities, instantaneous feedback about changes, dynamic representation systems and parametric control possibilities. A new world of visual and formal possibilities arises in which performance of form, mainly of structure and skin is central. In post-modern worldviews based on artistic and aesthetic discourses the hermeneutics idea about language can be transferred to the use of computers, and it is clear that "the individual is changed through the use of (the computer), and that (the computer) changes through its use by individuals" (Winograd and Flores 1986).

Overall, computers are mainly used for building designers to reason on, to converse with and to artistically experiment with form (Figure 6.50), i.e. to deal with aspects involved in modelling the spatial phenomena concretely/visually. The idea that designers "make use of technological objects as they ought to be used" (Coyne 1995) or let them alone when convenient does not apply anymore. Buildings are conceived, designed, documented, fabricated and assembled with assistance of digital means as digital models connect design and materialisation, supporting new depths of contextualisation and 'performative' design (Oxman 2006).

Rationalism	Pragmatism	Post-Modernism
Reasoning / Configuration	Interaction / Conversation	Experimentation / Incorporation

Figure 6.50 – The emphasis each worldview gives to the use of computers in building design.

However, although sculpting and artistic experimentations with form are possible through pragmatic and intuitive interfaces, the structure and configuration underlying this manipulation will still be rationalist. Computers are rational which means all the information being stored, manipulated and retrieved is limited by a rational structure even if the users interact with it in a non-rational, intuitive way. Everything will be tied to choices previously made when the tool was conceived. There is always a predetermined selection of objects, properties and relations that will structure, limit and direct possibilities.

As structure is heavily connected to choices and the more transparent and user friendly interfaces become, the more difficult it is to see the underlying structure, technology can only be used for choosing instead of decision making once designers are aware of the underlying structures they are manipulating. This does not mean they will be able to interfere in this structure directly but it certainly helps them to evaluate what the computer will be necessary for when designing. After all, technology will always tend to push design towards rationalism even if artistic experimentations are undertaken using an intuitive interface.

6.5. Practice in building design problem-solving

Design is a continuous learning process and one cannot understand design without actually doing it (Lawson 1997).

Although design praxis is most of the time contingent and idiosyncratic, thinking tends not to be separated from doing and the process generally starts with a brief and ends with a set of contract documents. In any case, it is important not to confuse the descriptions of the products of the process with the description of the process itself.

The products of the process, generally mapped in architectural practice handbooks such as the RIBA 1965 for instance, tend to roughly decompose the design activity into: information gathering (in which accumulation and ordering of information is undertaken), general study (when the problem is investigated and a solution is proposed for it), design development (when the piece of design is refined) and construction documentation (when solutions are communicated to materialise the designed object). Maps are useful for management purposes as well as to control and set up budgets and deliverables to clients.

However, they are also widely used as a basis for cognitive sciences to carry on studies about the cognitive processes involved in design, to improve collaboration among specialists, to improve tools that support design, to improve design education and to better manage complexities involved in design. This is highly controversial as the process itself might not necessarily be sequential and the "development of solutions rarely goes smoothly to one inevitable conclusion" (Lawson 1997). Unpredictable jumps happen quite often and a lot of the process itself tends to be influenced by the worldview designers subscribe to when undertaking problem-solving activity. Besides that, problem-solving activity is heavily incorporating computer tools used to reason on, to converse with and to artistically experiment with form, inaugurating new approaches to design.

The aim of this section is then to outline descriptions of building design processes, not descriptions of the products of the process but descriptions of the process itself, based on the review of the literature together with what has been previously discussed in this chapter with regards to the role of computers in rationalist, pragmatic and post-modern problem-solving paradigms.

6.5.1. Rationalism in practice: Structuring and framing

For rationalists the design process should be explicit, transparent and self-conscious in order for it to be properly scrutinised (Eastman 1999) enabling results to be objectively evaluated. Many of the rationalist models are goal-directed (Coyne 1995) and believe that design synthesis as a consequence should follow logical procedures that can be assisted by logical deductions constructed with the help of computer tools.

Rationalists focused on prescribed procedures and the setting of clearly defined problem-solving structures, when dealing with the 'object of design'. They shifted the focus of research to empirical studies about creative strategies used to approach problem-solving, when dealing with 'subjects undertaking design activities'.

In any case, rationalists describe the process itself roughly as comprised of the following stages:

(i) Problem-structuring, the most important stage to attempt to transform design into something more scientific, in which problems at hand are mapped into an existing or proposed structure and requirements are put together with conceptual solutions;

(ii) Preliminary design, a stage in which one or more formal responses to the problem are proposed;

(iii) Design development, a stage in which one of the specific solutions from the preliminary design stage is developed further;

(iv) Refinement or detailing, a stage in which the developed solution is crystallized into construction and contract documents.

Prescriptive procedures

Prescriptive procedures to deal with each stage were proposed by design methodologies which listed possible strategies to put the methods into action. Originally based on design methods from the 1970s, prescriptive procedures to deal with the problem-solving activity were grouped into a sequence of actions comprising analysis – synthesis – evaluation. Analysis would encompass the exploration of relationships and patterns, classification of objectives, ordering and structuring of the problem, i.e. problems structure. Synthesis would encompass the creation of a response to the problem, a solution, i.e. preliminary design. And evaluation would consist of a critical appraisal of the proposed solution against the objectives defined in the analysis phase, i.e. design development, refinement and detailing.

A classic list of strategies to put analysis, synthesis and evaluation methods in action is extensively explored in Jones 1981, who proposes a non-domain specific approach and deals with the whole process in a theoretical level. Although design methods were very clear in terms of providing strategies to be used in the analysis and evaluation stages, strategies to be used in synthesis, mainly referring to form generation were still very loose and open. Most of rationalist research that derived from design methods then emphasised aspects related to problem-solving structures, proposing a mixture of structure and procedures that would enable form to emerge from abstract matching between requirements and solutions.

Templates for design problem-solving

Propositions based on models that deal with the 'object of design', focused on hierarchical structures to be used as templates for design problems at hand to be re-written accordingly. They generally focused on how the problem should be analysed and how conceptual solutions would be derived from it in order to guarantee that form would naturally emerge from the matching problem/solution so that refinement could follow logical procedures towards the materialisation of a useful artefact. Hierarchical structures were developed further into language structures, in order to enhance flexibility by combining procedures with the definition of very basic entity structures. The basic idea underlying rationalist studies about the object being designed was still centred in the fact that problems need to be discovered and identified, not invented (Rapoport 2005). Design was considered a "process of choosing among alternatives" (Rapoport 2005) and what would vary in all different kinds of design would be "the alternatives considered, who makes choices, over how long a period of time, the criteria used in eliminating alternatives, the ideal model one is trying to reach, and the rules using in applying the criteria" (Rapoport 2005).

The whole focus in problem-solving structure was an attempt to somehow make design more scientific, to provide general structures for problems at hand to be mapped accordingly. Describing the design process using scientific based techniques aims at relating requirements to solutions to enable an objective judgement of design decisions.

Based on the idea that "the development and information of the problem and its structure is by nature iterative and cyclical" (Kokotovich 2008); that designers "draw on personal accumulated knowledge and information, subsequently representing that knowledge" (Kokotovich 2008) in order to understand it; and that "problem structuring requires the designer to draw on knowledge and information flows an diagrammatically map the information/issues in order to move forward and develop a solution" (Kokotovich 2008), design researchers continue proposing digital environments that allow users to construct case-based libraries or to link ideas and requirements using topological relationships to explore new design possibilities. The use of computers for this specific purpose is still uncertain as problem structuring can be approached from many ways. It is hard to find a tool comprehensive enough to be able to cope with ambiguities and fluidity needed of this stage, which can be comparable to the freedom allowed in paper-based schemes.

However, the emergence of form from an abstract matching between requirements and solutions either using structures, language structures or even formal languages, was still not obvious. Creative solutions, the heart of architecture design, tend to be product driven and emerge in preliminary design mainly from creative strategies which are more comprehensive than simply resultants from the problem-structuring phase.

Creative problem-solving strategies

Once rationalist design research changed the focus towards analysing 'subjects undertaking design activities', there was also a change of focus from problem-structure to preliminary design. When focusing on preliminary design, cognitive scientists used empirical studies to analyse cognitive processes involved in synthesising the 'object of design', examining creative strategies specifically used to develop form. Empirical studies vary from very rationalist based analysis of creative processes inherited from design methods, to analysis that reinterpret concepts and ideas from pragmatic studies. In the first case, creative strategies are generally analysed based on brainstorming and problem/solution decomposition whereas in the second case, creative strategies are analysed based on problem framing and co-evolution of problem-solution.

Creative problem-solving strategies - Brainstorming

Reports from cognitive scientists about creative problem-solving strategies show that in the very beginning of the design process, designers instantiate a large number of ideas to explore a full range of possibilities prior to taking any commitment about solving the problem (Goel 2001). Searches tend to be first in breath, when major alternatives are developed in order to structure the problem domain, then in depth, when one of the principal alternatives is chosen to be developed further (Akin 2001). Designers might either commit to a single conceptual solution and develop it further or explore multiple alternatives a bit longer prior to establishing any commitment.

Although theories recommend developing more than one solution because it would promote a "more comprehensive assessment and understanding of the problem" (Cross 2001), studies show that either few alternatives or a lot of them are not desirable. Whether few alternatives may lead to fixation, many alternatives are time consuming in terms of generation, organisation and evaluation. Success is said to be based on a balanced search for alternatives, the number of which depends on the nature of the problem at hand as well as on personal preferences.

Heylighen et al 2007 analysed architects who work with single design solutions and compared their methods with architects who work with multiple alternatives before selecting a single one to refine. Some architects tend to develop simultaneously more than one alternative until they fail whereas others only develop a single idea and successively refine it through criticising, rejecting it completely and starting a brand new one when it fails. Controversies arise from both strategies. Multiple alternatives might be easier to be used in discussing issues with the client as well as trying to make him commit to "the supposing principles underlying design" (Heylighen et al 2007). On the other hand, they might be understood as a sign of weakness and poor team performance, taking time and resources from the refinement stage. Single solutions, although apparently not promoting comprehensive assessment and understanding of the problem (Cross 2001), allow for more time to be spent on combining and restructuring elements within a solution increasing the potential for originality (Heylighen et al 2007).

Creative problem-solving strategies – Problem-solution decomposition

However, to explore several early solution concepts does not necessarily mean to generate several independent fragments and choose between them. It can mean a progressive exploration of possibilities and commitments that will be used to structure and constrain the refinement of an idea will be undertaken. When this is the case, cognitive scientists suggest designers either explore the problem space by recognising partial structures in it (Cross 2001 and Akin 2001) or develop the problem as a whole using lateral and vertical transformations.

In the first case, partial structures are used to generate partial solutions in the solution space and organising initial ideas to form a design concept (Cross 2001). Strategies used to generate and integrate partial solutions are not standard, not based on known procedures (Figure 6.51). Sub-problems are idiosyncratic rather than following a global schema and strategies used to recompose partial solutions are said to be based on knowledge and skills. "The interactions of the parts in an architectural design are not theoretically determined. The architect devises ad hoc strategies for accomplishing pair-wise integration" (Akin 2001).

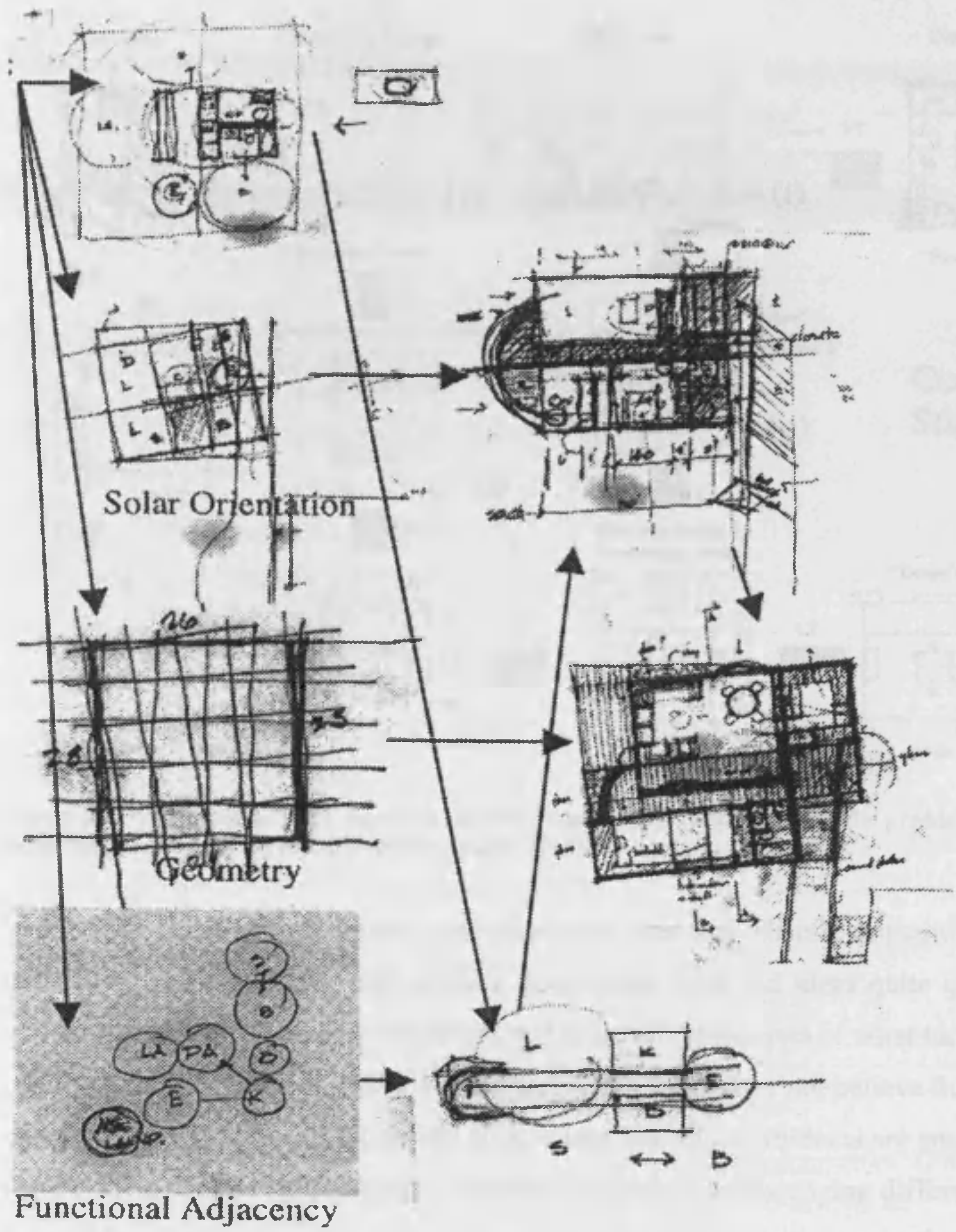


Figure 6.51 – Example of what cognitive scientists understand for partial solutions as well as a possible way used to integrate them (Akin 2001).

In the second case, designers use successive lateral transformations (LT), movements from one idea to a different one, to assist and explore alternatives with a low degree of commitment followed by vertical transformations (VT), movements from one idea to a more detailed version of the same idea, propagating commitments to particular solutions throughout the whole design process (Figure 6.52).

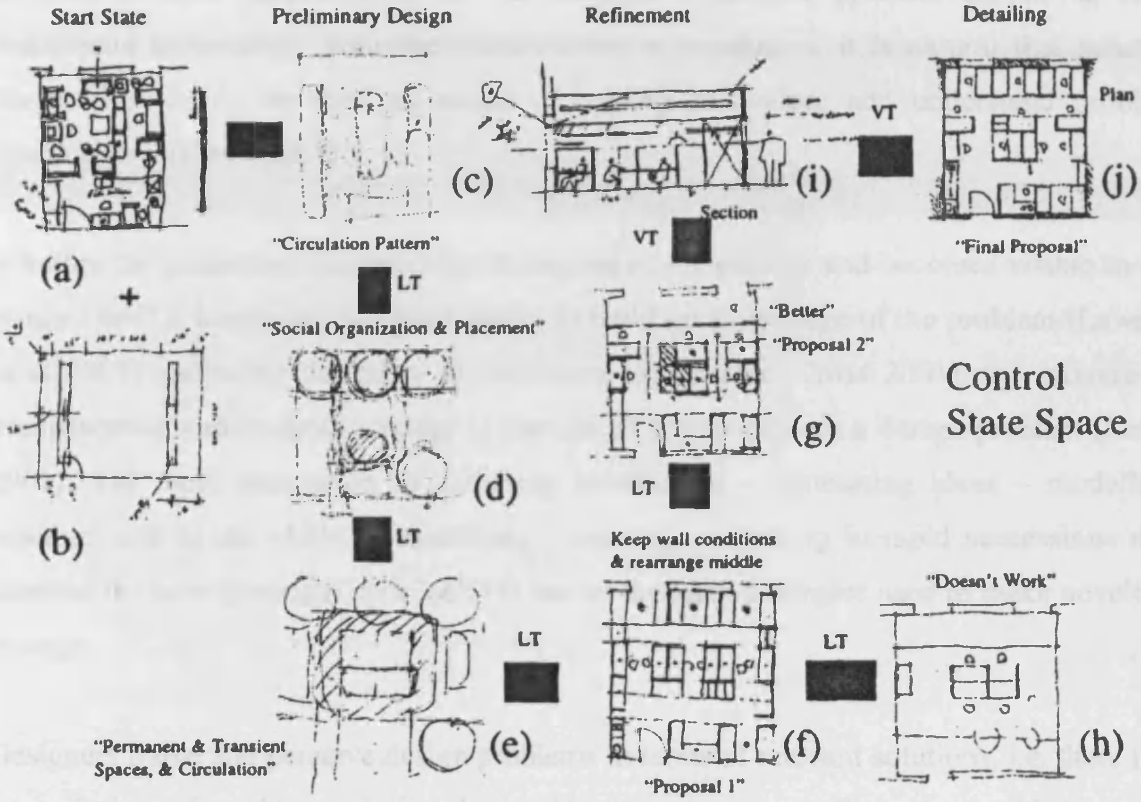


Figure 6.52 – Example of what cognitive scientists understand for developing the problem as a whole using lateral and vertical transformations (Goel 2001).

In either case, non-design domain specific reports state that one of the qualities of creative individuals is the ability to differentiate good ideas from bad ideas quite quickly not to waste too much time in the development and evaluation processes of what turns out to be a bad idea (Csiksentmihalyi 1996). The author of this thesis does not believe that this simply means to reject a bad proposition and adopt a new one when problems are encountered, but the ability to adequately judge early solution concepts acknowledging different aspects of the problem that need to be addressed in order to be able to persevere in the development of a conceptually satisfactory solution even when problems are faced.

<u>*Creative problem-solving strategies – framing and co-evolution of problem and solution*</u>

Empirical studies that analyse creative strategies, reinterpreting concepts and ideas from pragmatic studies will show that designers generally formulate an hypothesis about what they think might be the important aspects of the problem, then develop crude alternatives based on it in order to examine them further to try and discover further aspects to be addressed (Lawson et al 2003). They "tend to use solution conjectures as the means of developing their understanding of the problem. Since the problem cannot be fully understood in isolation from the consideration of a solution, it is natural that solution conjectures should be used as means of helping to explore and understand problem formulation" (Cross 2001).

Whether the generative idea goes up to the end of the process and becomes visible in the product or if it is rejected and used purely to build up knowledge of the problem (Lawson et al 2003) reminding designers of the issues to consider (Cross 2001), the mixture of brainstorming and in-depth strategy is used to creatively explore a design problem (Cross 2001). The rapid alternation of gathering information – generating ideas – modelling together with modal shifts of examining – drawing – thinking in rapid successions that happens in the beginning (Cross 2001) is one of the main strategies used to make novelties emerge.

Designers frame and perceive design problems in terms of relevant solutions, i.e. there is a co-evolution of problem-solution happening that does not allow the problem to be understood in isolation from the consideration of a solution (Cross 2001). There is a "period of exploration in which problem and solution spaces are evolving and unstable until fixed by an emergent bridge which identifies a problem-solution pairing" (Harfield 2007).

Problem framing involves the selection of features of the problem space designers choose to attend and the identification of areas of the solution space to explore (Cross 2001). It is a process of searching and transformation (Kvan and Gao 2006) in which "the ends to be sought and the means to be employed" (Schon 1983 in Gao and Kvan 2004) are identified. In problem framing the designer determines "the features to be attended, the order imposed on the situation and the directions of change" (Schon 1983 in Kvan and Gao 2006).

The co-evolution of problem and solution can either mean working first on the solution space or first on the problem space. "Designers formulate a partial structuring of the problem space and then transfer that partial structure into the solution space, and so develop both problem and solution in parallel" (Kruger and Cross 2006). Or alternatively, "designers first identify a partial structure in the solution space, such as a preferred shape or form, and then uses that to structure the problem space" (Kruger and Cross 2006).

When focusing at first in formulating the design problem as best understood from the information gathered, and evaluating the solution based on the problems requirements, designers can apply direct knowledge of problem-structure in which former structures can be used as references. When focusing at first in generating a solution for the design problem, the information gathered as well as the evaluation of the piece of design produced is solution specific and the applied knowledge involves reframing the problem. Kruger and Cross 2006 believe that designers will prefer using either one strategy or the other, the author believes the preference is related to the problem at hand, the context into which it is inserted, and the overall characteristics of the situation being faced.

In any case, "efforts to solve a problem must be preceded by efforts to understand it" (Simon 1996). Problem-setting is part of problem understanding and it involves:

(i) Selecting the entities of the situation,

(ii) Setting the boundaries of attention,

(iii) Imposing coherence to say what is wrong and in what directions the situation needs to be changed.

Problem understanding involves translating the problem statement to such entities so that action can be undertaken (Simon 1996). It basically involves problem structuring.

The ability to manipulate frames is also an extremely important design skill. In order to generate creative alternatives many times it is important to break the frame of reference the designer is in (Cross 2001). Whenever stuck in a situation, designers construct a new way of setting the problem, a new frame to impose on the situation (Zimring and Craig 2001). "Appropriate problem reformulation can prevent designers from being trapped into default assumptions about the constraints of the problem and thus assist designers to identify new criteria and constraints that enable different approaches to design" (Gao and Kvan 2004). Reframing means accessing different knowledge and "a mental insight exists when the subject perceives its own fixation within a standard frame of reference and simultaneously perceives a new frame of reference" (Cross 2001).

Insights

Insights are seen by Cross 2001 as bridges between problem space and solution space. It is when partial models of problem space and creative space are bridged by a concept, and the models can be mapped onto each other (Cross 2001). A model for mental insight is provided by Akin and Akin 1996 in which they demystify the creative process by stating that "what arises suddenly does not arise from nothing but from the cognitive preparation that anticipates and evokes the idea in the first place" (Akin and Akin 1996). "The creative process is a whole in which the conception of the idea influences and is influenced by the anticipation of subsequent developments" (Akin and Akin 1996).

Breaking out of the frame of reference is necessary to solve the problem but it is not the only thing needed. Further operations are also necessary and only when a new frame of reference together with these further operations are realised, that the problem can be solved (Akin and Akin 1996). "Breaking the frame of reference is not sufficient to reach a sudden mental insight. A new frame of reference must be, simultaneously, established" (Akin and Akin 1996). "Realizing a creative solution, by breaking out a frame of reference, depends on simultaneously specifying a new set of frame of reference that restructure the problem in such a way that the creative process is enhanced" (Akin and Akin 1996).

Rationalist practice and the computer

Although computers are not a very suitable medium to be used in problem-structuring they can be very powerful tools to assist in generating solutions for the problem with regards to form. Performance based design tools provide powerful means to deal with problem framing and co-evolution of problem and solution especially if designers are rational about design conception, design manipulation and design decisions. "If a synthesis of a design follows some variations of logic, then computers can help construct logical deductions" (Coyne 1995). Expert systems can be used to set constraints, operations, and overlays, formulate axioms, prove theorems are consistent with axioms, deduce new theorems, etc.

Rational design manipulation and decisions are all facilitated by the computer as they depend on setting up the following control mechanisms:

(i) Relating different states of design development with desired states,

(ii) Providing mechanisms that simply enable cross-referencing proposed solutions with requirements,

(iii) Enabling the creation and manipulation of rules that test the fitness of the proposed solution to a desired state,

(iv) Providing a series of decision support mechanisms to guide the design development based on clear and objective criteria, listing alternatives, determining, comparing and evaluating consequences.

Objective means to evaluate the results and compare the alternatives, as well as rules to describe behaviour, can be applied arming designers with powerful analytical tools. Different types of ideas can be tested with regards to all sorts of performance criteria, from aesthetic, to economic and environmental. This analysis can happen in a numeric, graphic and visual 3D format, either providing static and printable outputs or dynamic and almost instantaneous feedback.

Besides that, ideas can be brainstormed or developed within controlled environments taking advantage of computers generative capabilities. Auxiliary tools to help designers generate patterns, solutions or specific types of interventions along the design process based on specific algorithms, scripts, rule-based generative systems or genetic algorithms are constantly under development.

Rationalist practice: constructing frames and structures

As a whole, rationalists, either when dealing with problem-structuring or when dealing with preliminary design, are structuralist. Constructing a frame implies choosing a decomposition system for the problem, a structure, (Zimring and Craig 2001) to bridge the problem space and the solution space. "Decomposition involves dependencies that work in many directions at once" (Zimring and Craig 2001). Decompositions many times influence the whole. Changing a part can frequently imply reconsidering the whole, including how parts themselves should be organised. "Knowing the situation you are in illuminates opportunities to change this situation" (Zimring and Craig 2001). "Mediating concepts may recast the relationships between different modules as a design solution is being worked out" (Zimring and Craig 2001).

It is part of a designer's knowledge to develop a repertoire of problem-solving structures. "Experts have a greater range of data structures with which to examine new situations and hence identify fruitful stereotypes with which to frame the new" (Gao and Kvan 2004). Frames are a central activity in design, they depend on knowledge and they are essential to formulate new knowledge (Gao and Kvan 2004).

In this context, "structures might be created midway through a design, changing the direction of the decomposition at that point" (Zimring and Craig 2001). "Designers construct novel situations by reflecting on compositions that they have never thought about before. They assemble concepts triggered by the statement of a problem and look for novel structures within that assembly" (Zimring and Craig 2001). Architects are then mainly trained to deal with creative problem-solving strategies. They can "restructure problems and launch new searches even beyond the point of finding a satisfactory solution" (Akin 2001). "Expert designers are conditioned to use creative-design strategies under all conditions, even when problems do not warrant it" (Akin 2001).

In the end, structuring, framing and reframing are the main recurrent strategies used from preliminary design up to development and refinement or detailing. As the designer proceeds the choices become more committing and the moves more nearly irreversible. The whole process becomes then about moving towards deepening the commitment to a chosen frame, which results in a deeper and broader coherence of the idea of the artefact.

6.5.2. Pragmatism in practice: A sequence of moves directed by reflection in action

For the pragmatists, the design process is a conversation with the materials of the situation in which a sequence of moves is directed by reflection in action. Pragmatists believe designers can only gain understanding of what information is actually necessary by engaging in the activity (Coyne and Snodgrass 1991). Designers are constantly engaged in testing and developing ideas (Coyne and Snodgrass 1991) either using paper-based sketches or by manipulating form and exploring parametric changes using 3D real time digital models.

Framing in pragmatism

Pragmatists believe the design process itself is based on a sequence of moves that go from conception to refinement in which problem-setting and problem-solving co-evolve continuously starting with problem framing and finishing with a coherent idea for the materialisation of the artefact.

However, for the pragmatists "framing is seldom done in one burst at the beginning of a design process" (Schon 1988). Framing is a continuous process that is embedded in the moves designers undertake while designing. The reasoning behind framing goes from premises to conclusions, in which premises take the form of rules, either implicit or explicit, and "conclusions take the form of judgements about desirable or undesirable directions of designing or decision about design moves" (Schon 1988). Rules involved in premises are always idiosyncratic to the situation which explains how "practiced designers come to see things in new ways as they respond to the perceived uniqueness of a design situation" (Schon 1988) whereas judgements can be generalised in terms of how moves are evaluated which explains "how designers build up repertoires of broadly usable design knowledge" (Schon 1988).

A "practitioner approaches a practice problem as a unique case" (Schon 1991) attending to the peculiarities of the situation at hand without having any cues about standard solutions. Particular features of a problematic situation are discovered and an intervention is designed from this gradual discovery (Schon 1991). The problem is not given, "the situation is complex and uncertain" (Schon 1991), the brief may be highly specified but the "design situation is always partly indeterminate" (Schon 1988). "There is a problem in finding the problem" (Schon 1991). "Creatively uncovering the range of the problem is one of the designer's most important skills" (Lawson 1997).

"In order to formulate a design problem to be solved, the designer must frame a problematic design situation: set its boundaries, select particular things and relations for attention and impose on the situation a coherence that guides subsequent moves" (Schon 1988). "To frame a problem you have to begin with a 'what if' situation to be evaluated" (Schon 1991), i.e. the practitioner needs to set a problem he can solve, frame the problem for which he feels he can find a solution for. This frame imposed on the situation lends the practitioner to a method of inquiry in which he has confidence as "when trying to solve the problem he has set, the practitioner seeks both to understand the situation and to change it" (Schon 1991). The "situation is understood through the attempts to change it and changed through the attempts to be understood" (Schon 1991) and problem framing triggers a process of reflection in action.

The web of 'moves'

Understanding and changing happens throughout a continuous cycle of seeing – moving - seeing in which the designer "shapes the situation in accordance with his/her initial appreciation of it, the situation 'talks back' and he responds to the situation's 'back talk'. In answering the situation's 'back talk', the designer reflects in action on the construction of the problem, the strategies of action, or the model of the phenomena, which have been implicit in his/her moves" (Schon 1991).

Through a web of moves, designers discover the consequences, implications, appreciations and further moves. Within these moves, phenomena are understood, problems are solved and opportunities are exploited. "Through the unintended effects of action, the situation 'talks back'. The practitioner, reflecting on this 'back talk' may find new meanings in the situation which lead him to a new reframing" (Schon 1991). The practitioner examines the situation further to see whether he likes the unintended changes and what he can make out of them. "He judges a problem-setting by the directions of the reflective conversation to which it leads" (Schon 1991).

Once coherence is achieved enquiry does not end. New questions arrive to keep the enquiry moving and reflection in action continues after successful reframing. There is no attempt to fit the current problem into a standard solution. The aim is to set in motion an inquiry into the peculiar features of certain familiar things which respond in very special ways to the imposition of a certain problem frame, creating particular set of problems and a particular coherence (Schon 1991). "Designers discover or construct many different variables. They interact in multiple ways, never wholly predictable ahead of time" (Schon 1988). Each move satisfies a variety of requirements and each move has not only the consequences intended for it (Schon 1988). "Designing triggers awareness of new criteria for design: problem-solving triggers problem-setting" (Schon 1988), as a consequence whenever trying to solve a problem designers rewrite the problem statement in terms of the constructs they are able to deal with.

Although competing views of the nature of practice arise as well as controversies about the way of solving specific problems, "there is a fundamental structure of professional enquiry" (Schon 1991) and there is a selective management of large amounts of information in which long lines of invention and inference are spun out and "several ways of looking at things at once without disturbing the flow of enquiry" (Schon 1991) are assured.

The design process tends to begin with a diagrammatic phase in which there is a placement of the building into the contours of the land, together with a simultaneous and cyclical exploration of the layout. In this stage organisation of spaces (mainly locations of main elements), building elements (not functions), programme and use (access, circulation and clarity of movement from one unit to another), form, scale and proportions as well as inside and outside relationships are analysed and explored. "Coherence must be given to the site in terms of a geometry – a 'discipline' – which can be imposed upon it" (Schon 1991). This discipline is important even if arbitrary as it can always be opened later. It will be the starting point for designers to work simultaneously in the units and the whole, the global and the local, in cycles back and forth. As this is the case, the focus changes between global geometry, site, properties and potential materials, construction modules, building character, precedence influence, etc. depending on the emphasis of the 'conversation' being undertaken.

All the moves are spatial, and design elements are acted upon in order to create form and organise spaces. Each move has consequences described and evaluated in terms of different domains. "Each move has implications binding on later moves. Each move creates new problems to be described and solved. Each move is a local experiment that contributes to the global experiment of reframing the problem" (Schon 1991). Some moves are restricted, constrained, while others generate new phenomena. The "designer reflects on unexpected consequences and implications of the move and forms new appreciations that guide his/her further moves" (Schon 1991). The problem is constantly being reframed through a continued 'conversation with the situation'.

"In the designer's conversation with the materials of his/her design, he can never make a move which has only the effects intended for it. These materials are continually talking back to him, causing him to apprehend unanticipated problems and potentials" (Schon 1991). "When a move is found to be 'unusually difficult' on the basis of reasoning that appeals to considerations of workability, that move sometimes triggers a new round of designing in which a different kind of language and a different sort of designing begins to appear" (Schon 1988).

Experiments in practice

As a consequence, "reflection in action necessarily involves experiment" (Schon 1991), local and global experiments that happen in practice and therefore are not controlled, do not allow phenomena to be isolated and variables to be separated. In practice several kinds of experiments, exploratory experiments, move-testing experiments as well as hypothesis-testing experiments are all mixed together. Exploratory experiments are those in which action is undertaken only to see what follows, without accompanying predictions or expectations. Move-testing experiments are used to affirm or negate moves depending on the type of changes they produce. Moves that get intended consequences are affirmed whereas moves that do not get intended consequences are negated. At the same time the practitioner appreciates the value of the situation, judging if he likes what he gets from the action undertaken in terms of local and global consequences. Hypothesis-testing experiments are used to discriminate among competing alternatives. The best alternative is defined based on confirmations of the consequences of a given hypothesis together with predictions derived from alternative hypothesis that conflicted with observations. Experiments in practice have a very specific aim: The "practitioner has an interest in transforming the situation from what it is to something he likes better" (Schon 1991). That means the practitioner needs to solve the problem at hand and at the same time he has to like what he can make out of what he gets.

When outlining the design in the site the practitioner undertakes a global sequence of moves whose intent is to transform the situation into one that fits the way he framed the problem. He is trying to affirm a global move through:

(i) An exploratory experiment because he discovers new things in the 'back-talk',

(ii) A move-testing experiment because he affirms or negates global sequences of moves and

(iii) It is a hypothesis-testing experiment because he is constantly reframing the problem through a new hypothesis to be tested.

Moves are evaluated in terms of how desirable their consequences are in relation to intentions, how desirable the moves are in terms of their conformity to or violation of implications set up by earlier moves and how desirable the moves are in terms the designer's appreciations of the new problem or potentials they have created.

Figure 6.53 exemplifies how moves are evaluated. It relates consequences in relation to intentions together with overall consequences perceived and the designer's appreciation of the problem being evaluated, showing that "the perceived changes produced by earlier moves determine the need for and the direction appropriate to reflection in action" (Schon 1991). The aim behind experiments is to 'get a feeling' for the elements being manipulated in order to develop an intuitive understanding of the problem.

Consequences in relation to intentions	Desirability of all perceived consequences intended or unintended	Designer's appreciation of the problem
Surprise	Undesirable	Reflection in action Move negated Theory refuted
...learning sequence takes place and only terminates when a new theory leads to new moves that are affirmed		
Surprise	Desirable / Neutral	Reflection on theory Theory refuted Move affirmed
No surprise	Desirable / Neutral	No need to reflect Theory confirmed Move confirmed
No surprise	Undesirable	Reflection on theory Relevance or not on theory Truth

Figure 6.53 – Table of sequences of affirmation and exploration procedures (based in Schon 1991)

In any case, practitioners "seek to exert influence in such a way as to confirm not refute their hypothesis" (Schon 1991). They try to make the situation conform to their hypothesis but they remain open to the possibility that it will not. The "practitioner shapes the situation in conversation with it, so that his own models and appreciations are also shaped by the situation" (Schon 1991). The practitioner tends to be always inside the situation he seeks to understand and "he understands the situation by trying to change it and considers the resulting changes … the essence of its success" (Schon 1991).

The practitioner has to learn by reflection on the situation's resistance if his/her hypothesis and framing are inadequate and in what way. Whether he ought to reflect in action and how he ought to experiment will depend on the changes produced by his earlier moves" (Schon 1991). In general, the criteria of fit are set in a way that 'slightly' is enough. The process is stopped when changes in the whole are satisfactory or when new features which give the situation new meanings and affect the nature of questions to be explored are discovered. Overall hypothesis are only worth being tested if they can be immediately translated into design.

Pragmatism in practice

To sum up, "architectural designing can be understood as a kind of experimentation" (Schon 1984) in which 'what ifs' have consequences and implications evaluated virtually through drawings and 3D models. The conversation can happen either on a paper-based scheme in which sketches are used to represent ambiguous and undifferentiated properties that play an important role in human creativity or in computer-based schemes in which 3D, real-time graphic interfaces provide the means to converse with the 'object of design' being sculpted and experienced. In either case, the process assumes an engagement with a media suitable to keep the 'conversation' going so that a hypothesis can be tested (to explore the phenomena), moves affirmed or negated and the situation can 'talk back' to the designer and from its new meanings and intentions it can be constructed. That is the way the designer becomes aware of his own prejudices, assumptions and also understands the scope, latitude and nature of the design problem. They learn about the problem while attempting to create a solution for it (Lawson 1997). "Design problems generally take on meaning as they are being worked upon" (Craig 2001). "Practitioner approaches practice problem solving as a unique case" (Schon 1991). He "frames a situation, tries to adapt the situation to the frame, through a web of moves, discover the consequences, implications, appreciations and further moves" (Schon 1991). Within these moves, phenomena are understood, problems solved and opportunities exploited (Schon 1991). "It is rather through the non-technical process of framing the problematic situation that we may organise and clarify both the ends to be achieved and the possible means of achieving them" (Schon 1991).

As a result, practice and skills are about not having to reason much "from features of the situation to the appropriate types" (Schon 1988) but to see upfront what is relevant. It is about "short-cutting the design thinking by seeing a design situation as one they have encountered and dealt with before" (Schon 1988). "As a practitioner experiences many variations of a small number of cases ... he develops a repertoire of expectations, images and techniques. He learns what to look for and how to respond to what he finds" (Schon 1991). Knowing in practice becomes increasingly tacit, spontaneous and automatic. "Reflection in action is bounded by the action present, the zone of time in which action can still make a difference to the situation" (Schon 1991). Pace and duration of reflection depends on pace and duration of the situation in practice. Reflection can happen in tacit norms that underlie a judgement, strategies and theories implicit in a pattern of behaviour, feeling for a situation, way the problem was framed and designer's own role.

Practitioners reflect on the phenomena and on their understanding implicit in their behaviour and carry out "an experiment which serves to generate a new understanding of the phenomena and a change in the situation" (Schon 1991). Practitioners then become researchers in the context of practice. However, there is no dependence on established theory or technique but a construction of a theory of the unique case. Means and ends are not separated; they are interactively defined while framing a problematic situation which makes thinking not separated from doing.

6.5.3. Post-modernism in practice: The arguments as a central theme

For the post-moderns design action is about practical reasoning and argumentation which reflects "the deliberations of designers and their efforts to integrate knowledge in new ways, suited to specific circumstances and needs" (Buchanan 1995). Every step in the process is an example of such argumentation (Buchanan 1995) and either based on artistic premises or on critical action, arguments are a central theme used to define, undertake and evaluate design 'moves' within or without a computer environment.

When based on artistic premises, the central argument is underpinned by the idea that the artist is 'free' to develop his/her own personality, style and taste (Stolterman 1994). Methods are negated and theoretical knowledge is undervalued contrasting with any form of deterministic scientific approach. "The desire to build 'art' to the exclusion of other, more important variables" (Ward 1990) is corroborated by artistic autonomy through formal image (Dovey 1990) in which drawings are considered things in themselves (Ward 1989) and within a computer environment, shape formation technologies move architecture closer to the fine arts by rejecting tectonics in favour of artistic performance.

However, under this frame of mind, the role of architecture is said to be buried beneath the myths of the arts together with the design process itself as when separating itself from the act of building and getting closer to the fine arts, architecture got into a territory of logic mystification in terms of process (Ward 1989). The hyper valorisation of the designer as an artist together with the fact that technology allowed the detailing of construction to be partially automated indeed placed a stronger emphasis in conceptual design. Nevertheless, designers actually have their possibilities in terms of choices reduced. As tool capabilities are very specific and will always conform to the frame of mind of the ones who conceived them, what are increased are the possibilities in terms of decision making.

As a result, when based on critical action, the design process comprises a constant criticism of social, cultural, economic and political values embedded in the arguments used to set up design propositions (Ward 1990). Critical action is about a constant questioning of the traditions and values predominant in the specific design area allied with a strong technological literacy, in order for designers not to become heavily dependant on consultants and specialists to manipulate tools and materialise ideas.

The whole idea behind critical action is that there is a fundamental difference about knowledge in design and knowledge about design work (Stolterman 1994). Design "should strive towards designers constantly reflecting upon and critically examining their design practice" (Stolterman 1994). The lack of critical practice will lead to a stagnation of design practice long term (Stolterman 1994) and together with technological illiteracy it is likely to put designers completely in conformity with standards of construction industry and manufacturing, placing them as the creative agents in a chain of mass production externally controlled.

Critical design action wants "a designer with an open and reflective mind who has a chance of breaking with old ways of doing design and may thereby be more able to handle a complex and challenging reality" (Stolterman 1994). The design practice itself should be regarded as a result of a design process, which is therefore possible to change and redesign based on a continuous "process of reflection on the nature and preconceptions of design work in general" (Stolterman 1994). Critical design action goes beyond reflection in action, it focuses on reflection about action in which a meta-narrative involved in the conversation with the materials of the situation is to be identified and worked upon.

6.5.4. Practice: is there a paradigm for the design process itself?

The aim of this section was to explore the hypothesis that problem-solving paradigms and the acts involved in solving a problem cannot be separated nor considered independently of the role of computers in building design. As this has been shown to be the case, the last part of this chapter discussed how design problems are worked upon under rationalist, pragmatic and post-modern worldviews, showing there is not only one paradigm for the design process itself but different ways to prescribe and describe this process.

For rationalists the process itself should be transparent and explicit with a clear method which well-defines the ill-defined and stages the problem to be solved so that form can 'naturally' emerge from requirements. Analysis and evaluation techniques are widely explored whereas synthesis, form generation, still remains unexplained in studies that deal with the 'object of design'. Once describing the 'object of design', rationalists, heavily reliant on scientific premises, transform problem-solving into something technical and based on specialised scientific knowledge (Schon 1991). According to these theories, practitioners act in practice and should be concerned with problem-solving using applied science whereas researchers are specialists in identifying problems and develop the technical and scientific means to be employed in solving these problems.

If "sufficient uniformities in problems and in devices for solving" (Schon 1991) are found and it is up to science to provide the basis for these problems to be solved, then there is no space for problem-setting in design. "The process by which we define the decision to be made, the ends to be achieved, the means which may be chosen" (Schon 1991) is previously defined in the form of a 'scientific problem structure' which should be used by designers as a template to map problems at hand accordingly. The result is theories that state that science would provide the basis for problems to be solved, with a scientific base technique to select means appropriate to ends to be used as instrumental practice models, in fact set up a separation between theory and practice in which the latter is only about "technical problem solving based on specialized scientific knowledge" (Schon 1991).

However, when studying the design activity rather than the 'object of design', rationalists acknowledged that "problem-setting is a necessary condition for problem-solving" (Schon 1991) and "problem-solving triggers problem setting" (Schon 1988) because whenever solving a problem designers rewrite the problem statement in terms of the constructs that they are able to deal with, that is they set up the problem-solving paradigm. As a consequence rationalism could finally provide better explanations for the process of form generation once shifting the focus of study to 'designers undertaking activities'. Problem-setting and problem-solving are understood as inseparable. Whether studies approach form generation using brainstorming and problem-solution decomposition explanations, having their support on paper based scheme representation systems, or if studies reinterpret pragmatic concepts of problem framing and co-evolution of problem and solution, having their support in computer-based schemes, they will always comprehend structuring and formulating not only accepting a problem as given (Cross 2001). Solution conjectures are part of understanding the problem, they are like scientific hypothesis, they are part of strategies used to make novelties to emerge.

By studying 'subjects undertaking design activities', rationalists realised there is no single procedure to optimize single factors and construct a whole by putting its parts together, i.e. there is no single procedure to structure a design problem. It is not a type of problem that can be solved through the use of a deductive logic in which design possibilities are eliminated until a 'what an artefact should be' as a final option is reached. It is up to the practitioner to construct a structure that will guide him to generate the artefact.

An analysis of the pragmatic viewpoint will show that practitioners will construct the reality they use to deal with the problematic situation by framing the problem, determining the features to which they will attend, determining the order they will attempt to impose on the situation as well as the directions in which they will try to change it (Schon 1991). They will identify ends to be sought and means to be employed making action integrated with deciding. Framing means shaping a situation not fitting the problem into a standard structure to then solve it. There is no attempt to well-define the ill-defined as problems are rewritten in terms of the constructs designers are able to deal with through a constant process of questions and answers.

As pragmatists acknowledge the uniqueness of each problem and the fact that the designer's "knowledge is personal, bounded by his commitments to appreciative systems and overarching theory" (Schon 1991), the process cannot be different than a constant conversation with the situation. Problem solving is part of a larger experiment in problem setting in which the practitioner reflects on his/her intuitive understanding of the phenomena and constructs new problems and models derived from his/her own repertoire of familiar examples and themes, not from an application of research based theories (Schon 1991). Problems-solving includes 'getting a feeling for the problem' therefore action involves experimenting in practice with two very specific aims: solving the problem and at the same time liking the solution proposed.

As a result the process itself consists of making and testing new models of the situation and the formulation of a hypothesis depends on "the situation's potential for transformation" (Schon 1991). The process itself is based on a sequence of moves directed by reflection in action. All the moves are spatial. Elements are acted upon to create form and organise spaces and actions are judged based on local and global consequences. Action is about organising ends to be achieved and means of achieving them, it is about researching in the context of practice, about constructing a theory of the unique case. Design is a continuous learning process which cannot be understood without being practised (Lawson 1997).

For the pragmatists, design is essentially about learning by doing as "designers are not philosophers for whom the thought process itself is the centre of study" (Lawson 1997). "Skills are remarkably dependent on our own experience to interpret and makes sense of more systematically acquired data" (Lawson 1997). This is part of a spontaneous behaviour involved in skilful practice in which actions are not thought about, recognitions and judgements are carried out spontaneously, there is unawareness about when things were learnt as they are just done and it is not possible to describe the knowing which actions reveal (Schon 1991).

This description of the process goes very well with a postmodern worldview in which practical reasoning and argumentation involved in each step of the process is based on an artistic underpinning. When this is the case the process itself is buried beneath the myths of the arts because designers are seen as artists with a specific personality, style, taste and methods.

The fact that design is treated as a 'universe of one' makes it difficult to explain reasoning (Schon 1988) however, most of the worldviews understand designers are not objective experts distant from life and culture they are dealing with, nor the creative genius (Coyne and Snodgrass 1991). They are practitioners with expertise in problem setting and problem solving who construct concepts on the fly (Zimring and Craig 2001). Concepts are within specific perspectives which influence interpretation of information and treatment of design problems in general. Perspectives are used "to help in direct action and organising sets of information into coherent goals" (Zimring and Craig 2001).

"On the whole it is more important to be skilful in thinking than to be stuffed with facts" (Lawson 1997). Thinking is a skill that can be analysed, developed and practised even when done without thinking. Therefore, arguments when based on critical action believe the process itself should be focused on constant questioning allied to technological literacy so that not only knowledge in design is developed but also knowledge about design work in which wickedness can be consciously acknowledged. As a result, the process can be understood as some sort of 'soft constructivism' based in learning about the problem while trying to solve it once solving the problem of how to solve the problem at hand. It is 'soft' because the knowledge about the problem of solving the problem as well as the knowledge about the problem itself are constructed without a specific method, not necessarily following a structure.

6.6. Design problem-solving in architecture: The ill-defined or the wicked?

Having now demonstrated how the building design community is structured to deal with problem solving it is possible to see that there is not a single paradigm to set and solve building design problems. The absence of a single paradigm results in a lack of a standard representation format to develop design ideas as well as the absence of a single procedure to be used in problem-solving.

In building design designers not only solve the problem itself but also the problem of solving the design problem at hand. That means pure deductive logic is not applicable as possibilities cannot be eliminated until a 'what an artefact should be' is the final option, because solving a problem does not only comprehend structuring the ends to be achieved but also the means to achieve them. As this is the case, building design always comprehend structuring and formulating not only accepting a problem as a given. This situation is visible in all problem-solving paradigms presented.

Even the rationalist paradigm highlighted the fact that problem-solving in building design is not a straightforward proposition. The lack of agreement about a single structure and a single group of rules, rigid or not, generic or specific resulting in different frameworks to map requirements in attempts to well-define the ill-defined objectively illustrate how difficult it is to understand building design. It also illustrates that the idea that form and function can be separated (although a powerful way to organise thoughts specifically in designing for performance allowing different formal responses to be explored), not only assumes the existence of clear aims without acknowledging the fact that the best means to achieve them are actually elusive but also that aims are context independent and therefore narrow in scope. That is not to say that structures should be negated but that the nature of building design problems implies models cannot be more important than the data and therefore cannot be understood as templates to be used to map problems at hand into known structures prior to solve them.

What can be concluded is that in building design practice the data about the actual problem are more important than any problem-solving structure or model, therefore building design problem-solving is actually about constructing a theory of the unique case. This idea is corroborated by the shift of focus in rationalist studies from the 'object of design' to 'subjects undertaking design activities', as well as by the observations from pragmatic studies that focus on designers solving design problems. When this is the case, problem-solving structuring is replaced by the idea that problem and solution co-evolve either through rational framing or through conversations with the materials of the situation.

Studies about the 'objects of design' are however important because problem-solving structures can be powerful tools to work upon design problems if constructed by designers while designing as under such circumstances they will be inserted into a specific context and will acknowledge the peculiarities and idiosyncrasies of the situation, even if aims cannot be made clear. They can be used as sources of inspiration to work upon problems at hand even if constantly changing and adapted to move from one purpose to another and they can also be useful analytical tools to interpret precedence and references. As a consequence, radical post-modern paradigms although criticising rationalism do not negate problem-solving structures but subvert their basis in order to understand the meaning behind them. Either using a method or by constantly questioning, post-modern radical theories such as deconstruction or critical design theory aim to unfold meta-narratives behind structures to consciously work with the wickedness.

On the other hand, studies about designers undertaking design activities are also important because the co-evolution of problem and solution illustrates how in practice the process can well be interpreted as similar to the ones used in the arts in which discussions centred in meaning conveyed by form are undertaken throughout a constant refining of a proto-solution. This opens a route to post-modern discourses that explore the complexities of architecture theory, mainly theories centred in 'architecture in itself' to replace mechanistic and deterministic paradigms putting everything in terms of the architect self-expression.

As the ultimate product of building design is form, representation systems used by designers while designing tend to be highly visual, most of the time static with dynamic effects acknowledged manly in connection with perception. In paper-based schemes, diagrams and textual material tend to be used to represent functional requirements and abstract ideas; sketches tend to be used to manipulate form mainly in the conceptual stages but also throughout the whole design process itself enabling designers to communicate with the design world they are inhabiting; and technical drawings simulate the materialisation of the proposed artefact in a clear and unambiguous way allowing it to be transformed into a real object.

However, representation systems as well as the design process as a whole are starting to become more and more affected by the use of computers once computers are used mainly to reason on, to converse with and to artistically experiment with form, allowing spatial phenomena to be modelled visually/concretely. As computers and computer software are always 'rational' the choices are made when tools are conceived, i.e. object properties and relations are pre-selected limiting and directing possibilities. Once designers understand the underlying rational proposition involved in the conception of the tools then, as well as being able to reason about the design process they undertake while solving design problems, they can attempt to influence the questions they can ask, the problems they can solve either by choosing the appropriate tool or by influencing somehow in their design. On the other hand, if designers simply undertake artistic experiments using intuitive interfaces they become merely decision makers in the context of hidden rational discourses. They then control their design superficially through form.

As a result, in building design independently of which worldviews designers subscribe to while designing, "wickedness is the norm. It is tame formulations of professional analysis that stand out as deviation" (Coyne 2005). Building "design begins with what should be called a quasi-subject matter. A quasi-subject matter is not an undetermined subject waiting to be made specific and concrete" (Buchanan 1995), quite the opposite a quasi-subject matter is a by-product of a worldview that tends to come from humanities, mainly history and theory based on continental philosophy, according to, and attested by, anthologies, monographs and writings of prominent practitioners (Coyne 2005). These worldviews influence not only the objects being designed but also the way designers undertake design activities and that is why it is important not only to know *in* design but to know *about* design.

Thinking *about* design, i.e. reflecting on worldviews involved in problem-solving paradigms as well as on how these paradigms relate to representation systems, practices and computer tools used by practitioners, is a useful resource to outline the main contrasts existing within the architecture design profession (Figure 6.54).

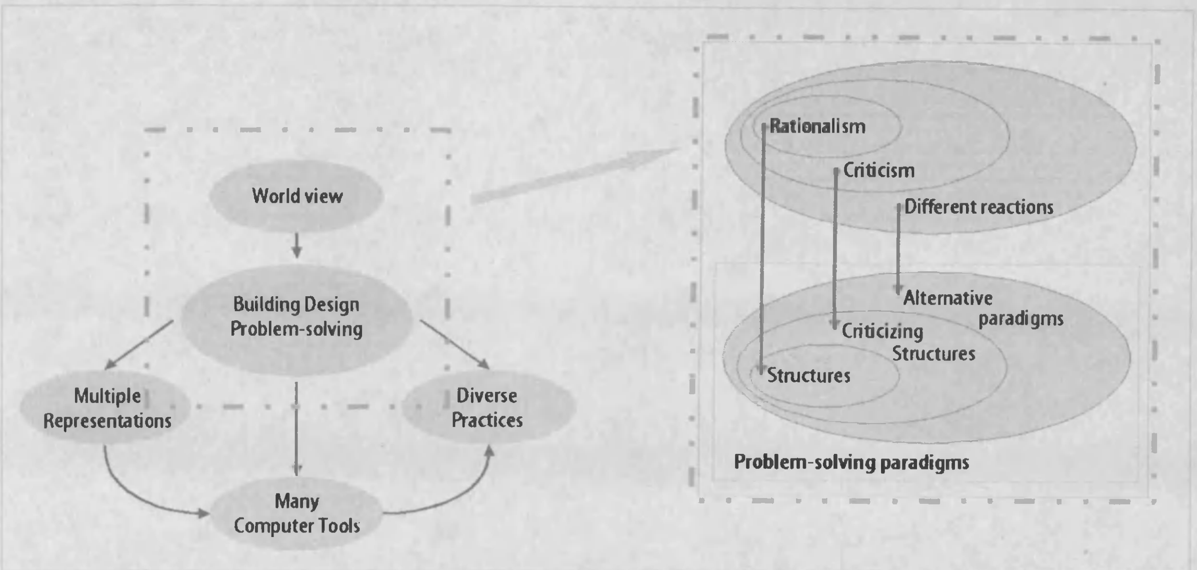


Figure 6.54 – Design problem solving in architecture

Thinking *about* design is also useful to outline differences between thermal building physics and the architecture design domain. Thinking *about* design becomes as important as thinking *in* design especially if the aim is to construct scenarios to critically reflect upon integration. After all, the creation of scenarios to critically reflect upon integration can well be seen as a matter of design problem-solving.

7. DESIGN PROBLEM-SOLVING: A NEW BASIS TO DISCUSS HOW BUILDING THERMAL SIMULATION TOOLS MIGHT BE INTEGRATED THROUGHOUT THE WHOLE BUILDING DESIGN PROCESS

"The problem of flexibility is not so much to open up space to more possibilities, but the concept of possible itself." (Spuybroek 2005)

The aim of this chapter is to construct scenarios to discuss and reflect on the problem of integrating thermal simulation tools throughout the whole building design process. Two scenarios are designed after a discussion that outlines the contrasts between design problem-solving in building thermal physics and design problem-solving in architecture.

Initially a pragmatic scenario based on expertise and specialisation is proposed. This scenario is constructed based on current propositions of studies of sociology of scientific knowledge that discusses interdisciplinary work. A criticism of this scenario together with the outcomes of the critical debate in design problem-solving undertaken in this research is used as a basis to propose a critical constructivist scenario based on general knowledge and mutual understanding.

The same analysis structure used in chapters 5 and 6 underlies the discussion that happens in this chapter, as the issue of integration is also understood as an issue of design problem-solving.

7.1. Contrasting paradigms of building physics and building design problem-solving

Although the two design domains are part of a larger culture, i.e. the design community – which has specific inherent characteristics in terms of problem-solving, the individual debates show that design problem-solving in thermal building physics and design problem-solving in architecture differ quite drastically.

In the case of thermal building physics, there is a single worldview to apply science to solve design problems in which general system theory is used to structure problem-setting and problem-solving. There is also a very clear ontology in which energy is the 'currency' and problems are structured and articulated to express heat flow in terms of variations in temperature differences over periods of time.

The complexity of interactions between the whole and the parts as well as among the parts is enhanced by the fact that phenomena develop in time. Phenomena that develop in time are very difficult if not impossible to be visually represented which compromises intuition about quantitative results. Recourse to mathematics is necessary to account for the simultaneity of phenomena together with the system responses to past and present situations. As a result, building thermal physics concentrates in dealing with mathematically represented phenomena that happen in a time/frequency domain.

A mathematical representation system enables physicists to make extensive use of computer tools, and plenty of algorithms to solve thermodynamic problems are developed and refined. The type of representation systems used to deal with the phenomena and the media used to assist in problem-solving, together with the complexity of relationships between variables and the fact that phenomena develop in time, justifies the use of very clear search strategies to approach problem-solving.

As a result, there is a single paradigm to apply science to building thermal physics design problem-solving. Existing problems are mapped into known structures and cause/effect relationships are established between parameters and resultant behaviour, either manually or automatically, in order to meet a set of predefined criteria about what would define the best solution to be achieved. Once paradigms are taken for granted, there is no need anymore to start from first principles and justify them using new concepts (Kuhn 1996). As a result, practice can be summarised as a number of prediction/evaluation cycles in which different technologies not different approaches to problem-solving are applied.

In the case of building design, there is *not* only one worldview underlying problem-solving. Architectural design is far more than a matter of simply applying science to solve design problems. Debates involving philosophical worldviews although mostly connected with architecture theory, as they can be directly related to the object of design, became common place at the level of problem-solving since a design science was proposed in the 1970s. These debates, either when connected to architecture theory or when connected to architecture design problem-solving directly, define the ontology of architecture.

The fundamental entities that compose the universe of architectural design, the way these entities interact with each other and the questions more significant to be solved are all dependent on the worldview the designer subscribes to either consciously or unconsciously when solving the problem at hand. Once an analysis of how different problem-solving paradigms originated from different worldviews is undertaken it is possible to see how wide the architecture ontology can be. However, as the ultimate product of architecture design is form, phenomena related to form in space are central in all types of problem-solving paradigms even when controversies with regards to function, meaning and form itself are the locus of debate among different philosophical discourses.

As the ultimate product of architecture is form, representation systems are mainly visual, most of the time static with dynamic effects acknowledged mainly in connection with perception. The complexity of interactions between the whole and the parts as well as among the parts can be grasped quantitatively because phenomena develop mainly in space. Form, dimensions, proportions, usage, visual effects, scale, disposition of elements, organisation of activities, accesses, circulations, etc. - mainly geometrical and material data - comprise the majority of the entities architects deal with which can be all visually represented. However, because the complexity of interactions that happen in space is huge, a great variety of visual representation systems are used along the process and commonalities can only be identified when the object being designed is close to materialisation.

The controversies that arise with regards to function, meaning and form itself; the wide ontology and the complexity of interactions that happen in space, manifested through a myriad of different visual representation systems do not justify a procedural approach in design problem-solving. There is not a standard format to be used along the process of developing a design idea - which initially collides with the extreme rational structure of computers.

On one side, the debate about the use of computers in building design can then well be seen as a debate about control. Information stored, manipulated and retrieved by computers is bounded by a rational structure which means, in essence, that how far the computer can assist in the design process will depend on the type and nature of information computers allow designers to manipulate. As "the range of questions one gets is determined by the domain of questions one can ask" (Wiezenbaum 1976), computers will transform a problem of choices into a problem of decisions. The type and nature of information designers manipulate are more comprehensive than what is possible to be handled by computers, but the structures on which computer tools are based will determine the types of questions that can be asked.

On the other side, computers are powerful in dealing with aspects involved in modelling the spatial phenomena concretely / visually because shapes used to compose form can be easily mathematically represented and therefore simulated on the screen. If on top of that new ways of manipulating form are introduced such as 3D, dynamic, real time form generation environments with photorealistic rendering, means to virtually sculpt the object being designed as well as to simulate experiences that result from it, it becomes easier to converse with and to artistically experiment with form even if in computer terms.

As a result, the role of computers in building design is ambiguous. It collides with the freedom designers want to express and develop their ideas but at the same time it opens a whole new set of possibilities to experiment, converse with and reason with architectural ideas.

Controversies about the use of computers, the lack of a single representation system as well as divergences in worldviews and problem-solving paradigms within the architecture design community, result in a lack of a standard format to be used along the process of developing a design idea, a lack of a single praxis of design problem-solving. Although there are maps for the products of the process used for management, control, budget and deliverable purposes, the process itself is far from being a consensus. Different schools, different practices, different individuals will have different ways of acting upon the problem of solving the problem at hand.

The starting point might be a conscious debate about problem-solving itself. It might be a debate at a more philosophical level, either referring to the object to be designed or about the problem of solving the problem at hand. It might be a discussion about architecture theory with a discussion about architecture ontology embedded in it. It might be simply dealing with the problem at hand directly without thinking about it, which means unconsciously subscribing to a specific paradigm of problem-solving.

Overall practice tends to be constructed in a case-by-case basis. It might be seen as constructivist in a 'soft' way, i.e. lacking a specific unified method or structure. As paradigms are not taken for granted, every time a new problem is to be solved, architects start from first principles. Practice end up being summarised as a complex interrelation between product and process in which the main task is to solve the problem of solving the problem at hand.

7.2. Proposing scenarios to reflect on how building thermal physics simulation tools might be integrated throughout the whole building design process

Once problem-solving is discussed in its essence, it is possible to see both communities share some inherent characteristics with regards to problem-solving as a whole (Chapter 4), the ones referring to designing and conceiving different aspects of a same new artefact. However, they speak completely different 'languages' as they have different worldviews to approach design problem-solving, different representation systems, different practices and a different use for the computer throughout their design processes.

As a result, whenever a potential way forward to integrate the two design professions does not take into account those differences, any proposition will end up being biased by whichever community is setting it up and the results are likely to be unsuccessful.

If the debate about integration starts on the premise of differences to show how impossible it is to compare the two design cultures in value or excellence, the whole discussion about integration is shifted towards how these two different cultures could potentially interact. The discussion about integration is set on the basis of a critical reflection on the matter rather than on the basis of prescribing solutions straight away for it to happen. This type of approach is commonly used in studies of sociology of scientific knowledge to discuss interdisciplinary work.

Although it is beyond the scope of this study to review the literature on this matter a quick overview of the literature referring to interdisciplinary work from sociology of scientific knowledge suggests that the basis of interaction is communication (Collins, Evans and Gorman 2008, Galison 1997, Star and Griesemer 1989, Collins and Evans 2002, Gorman 2002, Chrisman 1999 and Kuhn 1996).

However, a critical analysis of the literature together with the outcomes of the critical debates about design problem-solving undertaken in this research, suggests two conflicting approaches when discussing interaction and integration with its basis in communication.

The approach supported by most of the literature is highly pragmatic, based on specialisation and expertise focused in communication among different cultures through translation metaphors.

The approach supported by the author of this thesis is an opposition to the approach suggested in the literature. It is a critical constructivist approach in which communication between two cultures is mainly based on general knowledge and mutual understanding as translation metaphors are not comprehensive enough to capture all the different meanings involved in each of the two different languages.

Each approach is used to construct a scenario to reflect on the matter of integration. They show how integration can be viewed in the light of design problem-solving, and highlight the importance of a conscious choice to resolve the problem of integration. A pragmatic scenario is proposed first, followed by a critical constructivist scenario created in opposition to the pragmatic one as the discussion progresses. The same structure of analysis used in chapters 5 and 6 is repeated here to organise a discussion on how building thermal physics simulation tools might be integrated throughout the whole building design process.

7.2.1. Scenarios and design problem-solving paradigms

In this sub-section the two different worldviews used to set up scenarios to reflect on integration are discussed. The validity of the pragmatic scenario based on specialised knowledge and expertise is questioned with regards to its efficacy to improve communication between the parts when points of agreements in terms of design problem-solving paradigms are trying to be reached. A critical constructivist scenario based on general knowledge and mutual understanding is proposed as an alternative in which a more effective communication between the parts would suggest potentials for the construction of joint paradigms of design problem-solving.

7.2.1.1. The pragmatic scenario: Using translation metaphors to resolve differences in design problem-solving paradigms

The pragmatic scenario is centred in reinforcing specialisation and expertise, it is centred on reinforcing specific languages and cultures within their own domains as communication among the different cultures can be established through translation metaphors. It is a scenario that focuses on the "notion of cooperation through heterogeneity" (Galison 1997) in which cultures are "distinct but living near enough to trade" (Galison 1997) and therefore they can "share some activities while diverging in many others" (Galison 1997). It is a scenario in which the aim in communication is to "establish a consensus about the procedure of exchange" (Galison 1997). The locus of communication resides in "a localized zone of activity in which a restricted set of actions and beliefs is deployed" (Galison 1997). Translation mechanisms such as trading zones and boundary objects are created to make professionals from different specialties able to communicate.

Trading zone means "any kind of interdisciplinary partnership in which two or more perspectives are combined and a new shared language develops" (Collins, Evans and Gorman 2008). In trading zones there is room for translation to occur because "there is no universal notion of neutral currency but partial sharing of meanings which allow things to be coordinated without reference to some external gauge" (Galison 1997). In trading zones communities with a deep problem of communication manage to communicate (Collins, Evans and Gorman 2008) either through translation or by developing an in-between vocabulary through which communication can be accomplished (Collins, Evans and Gorman 2008).

Boundary objects are objects that "have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, as means of translation" (Star and Griesemer 1989). Boundary objects maintain a common identity across sites "but inhabit several intersecting social worlds and satisfy the informational requirements of each of them" (Star and Griesemer 1989).

As in pragmatism everything is about practice, interdisciplinary partnership happens at the level of practice using the suggested translation mechanisms as the basis of communication among practitioners. Partial sharing of beliefs and vocabulary together with specific points of exchange are seen as more than enough to set up collaboration between two different cultures. In case simple translations do not suffice, the creation of a third profession to bridge the two existent distinct domains is proposed as many times communication can only be reached by people with a special ability to take on "the position of the 'other' and to alternate between different social worlds and translate between them" (Collins and Evans 2002).

Most of the examples of the literature review (Chapter 2) when referring to integration unconsciously work within pragmatic worldviews. They refer to improving the role of tools in practice by establishing points of communication between participants. These points of communication either happen in computer interfaces, in which building physics requirements and results are attempted to be translated into information building designers understand, and/or in specific points along the design process when consultants should be expected to joint the design team.

7.2.1.2. A critical reflection about the pragmatic scenario

A critical reflection about the pragmatic scenario suggests that if two cultures have different aims, translation might be a resource "to establish a consensus about the procedure of exchange" (Galison 1997) because the significance of what is being exchanged is different in each culture and what matters is the process of exchange itself. However, if two cultures have the same ultimate aim, the significance of what is being exchanged as well as the process of exchange cannot be reached through simple translation metaphors.

Translation will always imply on interpreting the meaning of the terms used in a specific language under the lights of the other language. "Translation never conveys meaning flawlessly, either in regular usage or in specialised analysis" (Chrisman 1999). Besides that, translations necessarily imply loosing information in terms of meaning as the terms used in a specific language make sense only within the context of that language itself, especially if cultural differences are evident. The concept of trading zone becomes harder to find (Chrisman 1999) and any kind of translation metaphors are seen as an empirical artifice far from being comprehensive enough to address all the complexities involved in interdisciplinary collaborations (Chrisman 1999).

As "professional expertise and disciplinary training plays a significant role in rendering results useful to others" (Chrisman 1999), any form of translation will be wicked. If integration means sharing information from different sources to construct something new, it cannot happen at the simple level of tacit knowledge nor be simply achieved through extensions of a translation metaphor. Theoretical understanding and criticism in this case are also fundamental. "We must understand a lot more than traditional metadata to be able to understand how to integrate sources from radically different origins" (Chrisman 1999). It is essential to understand design problem-solving paradigms and the worldviews behind them and it is also essential to establish a critical debate about how interdisciplinary partnership is to be achieved.

However, this does not seem to be the case in most examples of the literature about integration (Chapter 2). The majority of the propositions are top-down and highly prescriptive either when referring to improving the role of tools in practice or when referring to improving data interpretation. It is quite common to see points of communication between the two design communities biased by the building physics community which does not understand paradigms of architecture design problem-solving and set up propositions of collaboration unconsciously enforcing its own paradigms.

7.2.1.3. The constructivist scenario: Using general knowledge and mutual understanding to resolve differences in design problem-solving paradigms

A critical constructivist scenario suggests differences in design problem-solving should be resolved through mutual understanding of design problem-solving paradigms rather than simply using translation metaphors to make participants communicate. When the two cultures have the same ultimate aim and the problem is to establish a consensus about the means to achieve this aim "we are left with a constructivist alternative" (Chrisman 1999).

A constructivist alternative does not deny the importance of specialisation but believes interdisciplinary partnership is constructed based on awareness from both design professions about the following aspects:

(i) It is impossible to dissociate political and ethical commitments from design because all design problems are wicked;

(ii) As a consequence, the designer's role as a problem-solver is the one of a creator as well as the one of a manager of different sources of information. Therefore he/she needs knowledge about the different types of information he/she manipulates and is responsible for the outcomes of his/her propositions;

(iii) In this context, it is highly important for designers to have quite a lot of general knowledge, not only to be specialists in a very narrow subject matter. General knowledge is useful to contextualise specialised knowledge, to question and propose different paradigms, to enhance the quality, quantity and complexity of ideas, to achieve something new. General knowledge is paramount if designers want to be really creative and effectively propose new solutions coherent and congruent with the challenges and complexities they face nowadays. General knowledge is important to manage different sources of information and essential to deal with the wicked.

The basis for this awareness comes from a mutual understanding of worldviews and design problem-solving paradigms that building physicists and architects manipulate. In both cases it is important to understand not only the concepts being manipulated but also the context they are within, i.e. the problem-solving paradigm and the worldview underlying it. Once disconnected from the context they are within, concepts become meaningless and there is no possibility of mutual understanding.

As this is the case, building designers need to understand the fundamentals of building physics in the context of building physics problem-solving structure within the worldview of general system theory. They need to understand phenomena develop in time and are mathematically represented, and that it is very difficult, if not impossible, to be intuitive about quantitative results. They need to understand that as a result practice ends up being procedural and based on series of prediction/evaluation cycles with very clear search strategies.

At the same time, building physicists need to understand there is not only one worldview underlying building design problem-solving and that as a consequence the ontology of architecture is wide. They need to understand that in architecture phenomena develop in space and that highly visual representation systems are used to work with design problem-solving making it quite easily to grasp results quantitatively. They need to understand that as a result there is no need for practice to be procedural, in fact quite the opposite, as architecture design practice is about solving the problem of solving the problem at hand.

Understanding involves not only learning the theory but also having skills in manipulating concepts as "it is impossible to make a creative contribution without internalizing the fundamental knowledge of a domain" (Czikszentmihalyi 1996). That means understanding only at a theoretical level does not suffice, designers from both sides also need to work upon the concepts and structures they are learning in order to get a real 'feeling' for them, i.e. concepts being manipulated need to become 'tangible'. Theoretical understanding cannot be neglected but effective understanding can only be fully accomplished through practice and manipulation of a specific ontology, i.e. through experience. If concepts are not part of a repertoire of the practitioner they cannot be transformed or used, they cannot make sense in new situations.

Under these circumstances, the author believes that if one culture understands the problem-solving paradigms of the other and how these paradigms are dependent on specific worldviews, it is likely that the two following phenomena unfold:

(i) The culture becomes conscious about the problem-solving paradigms it currently uses and at the same time

(ii) It understands its own paradigm(s) is not the only one(s) to be used to deal with the specific design problem-solving situation.

Problem-solving paradigms start being perceived in relative terms in both cultures opening space for critical appreciations and deeper discussions to happen, potentially setting up a locus for real innovation.

As result, once there is mutual understanding between different design cultures involved in a task, design would involve not only applying scientific knowledge to solve a specific problem, nor unconsciously solving the problem of solving the design problem at hand. It would involve understanding, criticising and thinking about how the problem of solving the design problem at hand is being resolved. It would involve going deep into scrutinising the wickedness involved in each type of problem-solving activity. It would involve recognising structures and meta-narratives acknowledging the worldviews behind them which would enable designers from both domains to construct every time a new solution to deal with the problem at hand enriching practitioner's repertoire in both domains.

7.2.2. *Scenarios influencing representation systems, the role of computers and practices*

In this sub-section the two different worldviews used to set up scenarios to reflect on integration are discussed with regards to their implications in representation systems and practices. The pragmatic scenario is criticized and a constructivist scenario is proposed in response to the criticisms. The intention is to show how much the worldviews underlying the scenarios used to reflect on integration can generate totally different practical results and therefore need to be considered whenever integration is to be debated.

7.2.2.1. *Criticizing the pragmatic scenario influence in representation systems, the role of computers and practice*

A pragmatic scenario would suggest points of communication could be 'identified' in representation systems and practices for professionals to work in collaboration, it suggests that points could be identified for professionals to 'trade'. This can be interpreted as either points in which professionals give feedback to each other or points in which the two professions interact through the use of building physics thermal simulation tools.

A review of the literature about integration (Chapter 2) shows many approaches used to integrate building thermal simulation tools throughout the whole design process could well fit into a pragmatic scenario. Propositions are considered pragmatic for two different reasons:

(i) They happen on a practical and empirical basis as there seems to be no theoretical study on the matter of integration.

(ii) They acknowledge and reinforce the role of specialization and expertise.

Most of the propositions from the literature that address integration are based on points of communication that either happen at the level of computer interfaces, in which building physics requirements and results are supposed to be 'translated' into information building designers understand, and/or in specific points along the design process when specific tools would be expected to be used and/or consultants should be expected to join the design team.

When points of communication happen at the level of computer interfaces, visual display representation systems provide results referring to behaviour in time together with clear and structured systems to facilitate the use of search strategies to approach design problem-solving.

When communication happen at specific points along the design process then specific interfaces or even tools to be used at each different design stage are developed according to the type of data that is believed to be manipulated at each stage. If the ultimate aims are for instance referring to refining the object being designed, visual display representation systems with search strategies oriented towards refinement are provided and most of the time consultants are expected to join the design process. If the ultimate aims are for instance referring to conceiving, creating and developing the object of design then either design-like input interfaces or tools aimed at generating formal ideas with appropriate performance responses are provided and mainly architects are expected to take part in the design process.

As has already been mentioned, propositions from the literature about integration (Chapter 2) are mainly developed by building physicists who know little about architecture design and deal with it using a very empirical basis. Once paradigms of building physics and building design problem-solving are contrasted (section 7.1) it is possible to see that propositions from the literature about integration (Chapter 2) are actually unsuccessful because of the following reasons:

(i) Propositions that attempt to improve the role of tools in practice and deal with the design process as a whole misinterpret the products of the building design process as the process itself, and as a consequence the design problem-solving activity is misunderstood as procedural with clear stages.

(ii) Propositions also assume everything is actually a matter of using visual representation systems without acknowledging any representation system is actually related to worldviews and design problem-solving paradigms which in this specific case differ quite drastically.

The result is that tools end up being of little use to designers because of the following reasons:

(i) Visual representation systems rarely acknowledge the fact that architects deal with phenomena that develop in space. Tools are not prepared to deal with the complexities of phenomena that develop in space and although visual representation systems are provided, results referring to behaviour in time do not relate to results referring to form in space.

(ii) Output interfaces provide very clear and structured display systems to facilitate the use of search strategies to approach design problem-solving, strategies that architects rarely use when designing.

On the other hand, in an environment of specialists, building thermal physicists are not the only ones to be blamed for unsuccessful attempts to communicate with building designers. The contrasts in design problem-solving paradigms outlined in section 7.1 also show designers do not understand the paradigms and worldviews involved in building thermal physics.

As a consequence, they end up not using the tools also because of the following reasons:

(i) They do not understand that it is very difficult if not impossible to develop intuition about quantitative results for phenomena that develop in the time/frequency domain. These types of phenomena cannot be visually represented with regards to the interaction between the whole and the parts but need to be mathematically represented so that simultaneity of interactions together with responses to past and present situations can be taken into account.

(ii) They do not understand that mathematical representation system together with difficulties in developing intuition about these types of phenomena call for the use of very clear search strategies due to the lack of a visual representation system that enables insights about quantitative results.

Approaches to propose integration using a pragmatic scenario illustrate how translation mechanisms and metaphors are insufficient to set up a proper communication between the two parts. As there is no 'merging' but maintaining distinctness (Galison 1997), "both sides impose constraints on the nature of the exchange" (Galison 1997) and the outcomes of any attempts to integrate the two cultures will be bounded by these constraints. The result is propositions although attempting to reach a consensus about the processes of exchange fail to be effective with regards to integrating the two design professions. As a consequence the pragmatic scenario generates fragmented and unarticulated results in practice.

7.2.2.2. Outlining a critical constructivist scenario to deal with representation systems, the role of computers and practice

A constructivist scenario based on general knowledge and mutual understanding would imply professionals in both cultures would have enough mutual understanding of the paradigms involved in design problem-solving to be able to effectively collaborate at the level of representation systems and practice. Effective collaboration could happen either through the use of building physics thermal simulation tools that address the complexities involved in each of the two design profession and/or through constructions of concerted actions between participants in practice.

The whole idea underlying a constructivist scenario is that there is no 'trading', there is achieving the ultimate aims together. This does not mean the two professions would merge and general knowledge would replace specialization, it would simply mean communication and interaction between the two design professions would not happen only at specific points. Interaction and communication would be comprehensive enough to cover paradigms of design problem-solving as well as the worldviews behind them together with the influences of these paradigms in representation systems, the use of computers and practices. A constructivist environment would be created with its basis in constant debates in design problem-solving between the two design professions.

It is believed that from a constructivist environment, the following challenges with regards to how building physics thermal simulation tools might be more effectively integrated throughout the whole design process would be addressed:

(i) Representation systems that develop in time could be effectively related to representation systems referring to phenomena that develop in space;

(ii) Differences in practice of design problem-solving could be seen as an opportunity to explore different processes to deal with the problem of solving the problem at hand.

Integration could be creatively addressed and critically constructed in a case-by-case basis and the challenges would consider not only ultimate aims referring to refining the object being designed but also ultimate aims in conceiving, creating, manipulating and developing the object of design.

In a constructivist scenario effective collaboration through constructive concerted actions between participants in practice suggests learning environments in which knowledge about the different design domains involved in the task would be constantly enhanced improving the repertoires of the practitioners, putting together experienced and creative individuals to construct something new.

In this environment there would be an understanding that in building thermal physics design problem-solving needs to be made well-defined because the representation system used to deal with the phenomena cannot afford non well-defined design problems. There would be also an understanding that there is first an acknowledgement of the wickedness involved in design problem-solving which makes it extremely complex, contextual and able to be approached from multiple philosophical viewpoints.

As a result, practice could be a debate about when and how design problem-solving paradigms are going to be structured. If structures are to be set 'on the fly' or the problem is to be conformed to a single or many predefined structures are always open to debate. The idea would be to have a practice which would consist of a debate about choices, choices comprehending everything that would be involved in the task, from worldviews up to practical aspects about the problem of solving the problem at hand.

In a constructivist scenario effective collaboration through the use of building physics thermal simulation tools would involve discussion about how these tools could be used to promote joint reasoning with regards to design problem-solving. It is believed that a starting point to propose tools that address joint reasoning would be to consider the role of computers in architecture design problem-solving as well as the role of computers in building thermal physics design problem-solving. This consideration should examine the following aspects:

(i) Aim at demystifying the dialectics of what should be analyzed quantitatively versus what should be analyzed qualitatively.

(ii) Understand computers are fundamentally rational and therefore require parts of the design problem-solving to be structured in order for data to be stored, manipulated and retrieved digitally.

A decision about which parts should be rationalized and at which stage this should happen will have an impact on the design of the tool interfaces. If this decision is to be made every time a new problem arises or on the basis of the idiosyncrasies of each practice, interfaces would need to be somehow customizable to account for it. The level of customization could determine an important role for consultants.

In a constructivist scenario the computer is understood as the media that will facilitate the dialogue and joint reasoning between the two different cultures because of the following reasons:

(i) Computers and technology are now used in building design from the conceptual stages. New forms, new spaces, new paradigms are proposed taking advantage of virtual sculpting capabilities, instantaneous feedback about changes, dynamic representation systems and parametric control possibilities.

(ii) At the same time computers are the main instrument of building physicists to simulate building performance.

Both cultures already use the computer as an important media for reasoning and an effective point of connection would be to construct interfaces in which a mixture of interactions between understanding the behaviour of the building while conceiving, creating, manipulating and developing could be the key. This is important to enable both professionals to use computer tools to ask significant questions about the design problem at hand and the most important features to enable this to happen are the following:

(i) Visual real time performance feedback

(ii) A strong relation between representation systems that refer to behaviour in time with representation systems that refer to form in space.

Building designers need to be able to get visual performance feedback about the design parameters they are manipulating, and building physicists need to understand the implications of thermal properties and performance results in design parameters. Besides that, heavily procedural prediction/evaluation cycles need to be 'diluted' within 'softer' ways of exploring ideas. How these features are to be put together to enable constructivist environments to be developed appropriately are still to be explored either when ultimate aims refer to refinement of the object being designed or when they refer to conceiving, creating and developing the object being designed.

It is the intention that a constructivist scenario could be comprehensive enough to propose that computers should bridge the gap between the artistic and the scientific by equipping both types of designers to deal with the rational structures underlying the tools they use. Otherwise, computers are simply tools used to 'play' within externally constrained and controlled formal or performative environments.

Aims to propose integration under the approach of a constructivist scenario illustrate the need for a theoretical understanding with regards to design problem-solving if proper communication is to be set between the two parts involved. Specialization is not denied but contextualized once general knowledge and mutual understanding of design problem-solving paradigms are proposed. As a result, there is a possibility for both sides to participate in the construction of a less fragmented and more articulated practice.

7.3. Setting up new premises to debate how building thermal simulation tools might be better integrated throughout the whole design process

This chapter discussed integration of thermal simulation tools throughout the whole design process under the lights of design problem-solving considering two different scenarios for reflection on the matter: a pragmatic scenario and a critical constructivist one (Figure 7.1).

Worldview	Pragmatism	Critical Constructivism
Emphasis	Expertise / Specialisation	General and conetxtualised knowledge
Problem-solving paradigm	Translation metaphors	Speaking more than one 'design language'
Representation systems and Practices	Punctual collaboration	Collaboration throughout whole process
Role of computers	Reinforce prediction/evaluation cycles	Joint reasoning

Figure 7.1 - Scenarios for reflection in the matter of integration

The validity of the pragmatic scenario based on specialised knowledge and expertise was questioned with regards to its efficacy to improve communication between the two design cultures. When criticized with regards to its influence in representation systems, the role of computers and practice, the points of communication suggested for professionals to interact proved to be ineffective. Translation mechanisms and metaphors either for professionals to provide feedback to each other or for building physics thermal simulation tools to be used throughout the design process generated fragmented and unarticulated results in practice.

The criticism, originated from contrasts between the two different cultures when examined under the lights of design problem-solving, suggested a critical constructivist scenario based on general knowledge and mutual understanding as an alternative. The alternative critical constructivist scenario used design problem-solving as a theme to promote a more effective communication between the parts either through the use of building physics thermal simulation tools or through constructive concerted actions between participants in practice.

A critical approach to the pragmatic scenario highlighted the fact that a reinforcement of specialization neglecting general and contextualized knowledge could potentially produce environments in which professionals are extremely limited in their capacity to work in collaboration (Figure 7.1). An emphasis in specialization promotes less flexible professionals which result in the following two pitfalls:

(i) There is a need to set up top-down approaches to deal with the different design problems at hand in order for participants to be positioned wherever they are most needed, either through the use of mediators/translators to act as coordinators/managers, or by making one of the cultures subordinate to the other every time decisions need to be made.

(ii) The role of building thermal simulation tools in assisting the design process reinforces the paradigms of the ones conceiving the tools.

A critical constructivist scenario, by not denying specialization but by contextualizing it through an enhancement in the levels of general knowledge among practitioners, could potentially produce environments in which professionals could effectively work in collaboration (Figure 7.1). An emphasis on general knowledge and mutual understanding rather than in pure specialization could result in the following positive outcomes:

(i) Professionals would be assumed to be better prepared to work in teams due to their enriched individual repertoires, an important quality to set up the grounds for creative contributions and real innovative solutions to be designed

(ii) The role of building thermal simulation tools in assisting the design process could effectively be improved as tool developers and users could understand each other's languages

An emphasis in specialization and expertise without a reasonable amount of general knowledge would call for a debate on the matter of control. A pragmatic and highly specialised orientation can result in a process driven practice with hidden rational intentions. These hidden rational intentions gradually reduce the control of designers over conception and development of their object of design.

Critical constructivist scenarios which promote integration through professionals understanding each other's languages enhance potentials for designers to restore control over the design process once there is no need for translations to occur. The approach to design problem-solving can be designed based on a critical appreciation of the situation which could happen either every time a new problem arises or in the basis of the idiosyncrasies of each practice. These scenarios have the potential to resolve integration through concerted actions among professionals who have enough general knowledge to reach a joint solution as well as specialised knowledge to enrich this solution and transform it into something unique, far beyond a simple discourse of 'form following performance'.

The author believes architects and building physicists have paradigms and worldviews underlying design problem-solving that need to be mutually understood in order for them to be questioned and manipulated so that new and creative artefacts can be produced. Mutual understanding about how each design community thinks, together with critical appreciations of these ways of thinking, enable the construction of a theory of the unique to creatively deal with the design problem-solving every time a new situation arises.

Understanding different design problem-solving paradigms is part of the challenge to expand the scope of professional thinking still present, and the best way to achieve that is to look at theories, to keep a constant critical attitude and to explore different practical approaches to it. Under this frame of mind, the final chapter of this thesis outlines the outcomes of a critical appreciation about the proposed scenarios for reflection discussed in this chapter as well as the outcomes of the structured debates in design problem-solving proposed in chapters 5 and 6, thus concluding the discussion set up in this thesis and outlining potential themes for future work.

8. CLOSURE

"The world is many things, and no single framework is large enough to contain them all, neither that of man's science nor that of his poetry, neither that of calculating reason nor that of pure intuition" (Wiezenbaum 1976)

This thesis aimed to theoretically and critically examine how building thermal simulation tools might be integrated throughout the whole design process. In order to meet this aim, the author of this thesis used a critical constructivist position to propose a structured methodology to discuss and debate the problem of integration on a theoretical basis.

Design problem-solving was the central theme chosen for reflection and debates in design problem-solving were undertaken for thermal building physics as well as architecture design. These debates followed a very clear structure of analysis in which design problem-solving paradigms were understood within specific worldviews and related to representation systems, practices and computer tools used by each group of practitioner in their everyday activities. Contrasts between these two debates were outlined and potential scenarios to critically reflect on integration were proposed using the same structure of analysis.

The outcomes of this critical theoretical reflection are listed and discussed in this last chapter, setting up the final conclusions of this thesis as well as outlining possible themes for future work.

8.1. Outcomes of the critical theoretical reflection in design problem-solving

The structured debates in design problem-solving as well as the critical appreciations about the proposed scenarios for reflection leads to the conclusion that *there is not a global solution for building thermal simulation tools to be better integrated throughout the whole design process. The best solution is to be tailored; the best solution is to be critically constructed based on the idiosyncrasies of each practice together with the peculiarities involved in dealing with a specific problem at hand.*

In order for that to happen two important points need to be addressed:

(i) Building physicists and building designers education needs to be improved for the two professionals to be able to properly communicate and effectively construct a joint practice;

(ii) Simulation software needs to be designed with configurable interfaces that can be tailored to address the idiosyncrasies of each practice together with the peculiarities involved in dealing with each specific problem at hand.

These two important points involve the following considerations:

(i) Improving general knowledge involved in design problem-solving;

(ii) Developing critical thinking *about* design problem-solving and

(iii) Understanding, creating, manipulating and criticising design problem-solving structures.

There is a need for professionals not only to be specialists in their own fields of study but also to have a reasonable amount of general knowledge about the other fields of study involved in the overall activity of designing buildings. Improving general knowledge is useful to contextualise specialised knowledge, to question and propose different paradigms, to enhance the quality, quantity and complexity of ideas, to equip professionals to work in teams and merge the tasks of managing and creating, restoring control over the work back to designers. This is important because all design professions have the same ultimate aim of conceiving and materialising *a* building with qualities and values. As a result, if general knowledge of practitioners is improved, a basis for concerted actions to happen can be set enabling the different specialities to better communicate with each other while interacting and overlapping throughout the whole design process.

A reasonable amount of general knowledge would comprehend the ontology each design domain deals with as well as the implications of this ontology in the types of phenomena being manipulated by each design domain. In this context, it is expected that architects would understand thermal building physics has a clear ontology in which problems are structured and articulated to express energy flows in terms of variations in temperature differences over periods of time with cause/effect relationships referring to phenomena that happen in a time/frequency domain. It is also expected for thermal building physicists to understand that although architecture has a wide ontology the ultimate product of architecture design is form, which therefore makes phenomena related to form in space central to architecture design problem-solving.

It is the idea that an improvement in general knowledge involved in design problem-solving enables designers from both communities to understand the basic difference between the two design domains, which are:

(i) In building physics because phenomena develop in time it is very difficult, if not impossible, to develop intuition about quantitative results. It is very difficult to visually represent interactions between the whole and the parts as well as interactions among the parts over time which justifies e procedural approach to design problem-solving based on mapping problems into known structures together with the use of very clear search strategies.

(ii) In building design because phenomena develop in space it is much easier to develop intuition about quantitative results. There is a space for a general approach to design problem-solving in which structures are broken for creative ideas to arise. It is easy to visually represent interactions between the whole and the parts, as well as among the parts, which makes procedural approaches to problem-solving unjustifiable in terms of time and resources.

An improvement in general knowledge involved in design problem-solving is also important to develop critical thinking *about* design problem-solving. Learning about different ontologies, about the different types of phenomena being manipulated as well as about the basic difference between the two design cultures opens space to question and critically reflect on paradigms of problem-solving generally used. It enables practitioners to become conscious about the way they solve their own problems and it makes them understand there is not only one viewpoint involved in this task. Problem-solving paradigms are likely to start being perceived in relative terms as opening space for designers to critically reflect on the problem of solving the problems they face in their everyday activities.

In this context, it is also expected that practitioners can reflect about how these paradigms and worldviews articulate representation systems and practices as well as how they articulate the use of current technologies available (computer tools). These critical reflections would comprehend not only the domain the practitioner is specialised in but also the other domains involved in the overall activity of designing buildings. These reflections would aim to expand the scope of professional thinking which is still at present which encompasses only thinking *in* design rather than also critically thinking *about* design.

In this sense, expanding the scope of professional thinking for building physicists would involve making them aware of the fact that they follow a single and prescriptive design problem-solving paradigm whereas architects are free to choose, even if unconsciously, the design problem-solving paradigm they want to follow. Expanding the scope of professional thinking for architects would involve making them aware of the fact that they choose the design problem-solving paradigm they use in their everyday activities, even if this choice is unconscious, whereas the scientific community has prescribed the design problem-solving paradigm building physicists should use.

As building physics design problem-solving basically consists of applying science to solve the problem at hand, the building physics community is structured to handle well-defined problems. Under the worldview of general system theory, in which a pre-defined structures to handle problems of thermodynamics are constructed, the activity of design problem-solving involves mapping the problem at hand into this known structure and then solving it by searching through a solution space with clearly defined boundaries. As it is very difficult to intuit which problems are the most significant ones to be solved, further strategies and tools are developed to work within these clearly defined boundaries, guiding design actions. The approach to design problem-solving is procedural and scientific. Results are quantified and compared against references to judge the value of the building response to the natural laws. A single paradigm of problem-solving is taken for granted and design actions become very much deterministic within it.

On the other hand, different worldviews underlie design problem-solving in architecture and the community, even if attempting to handle ill-defined problems through rational design problem-solving structured propositions, actually always ends up dealing directly with the wicked. The lack of agreement about a single specific structure of design problem-solving shows that there is not a single paradigm to set and solve architecture design problems. In building design data are more important then pre-defined problem-solving structures and design problem-solving is generally based on a 'science of the unique'. Architects tend to design specific approaches to deal with the problem at hand on a case-by-case basis. Building design comprehends structuring and formulating not only mapping the problem at hand into a known structure. As a consequence worldviews underlying problem-solving paradigms are chosen upfront whenever a new problem arises. Debates on worldviews involved in conceiving the object of design tend to happen more commonly than debates on worldviews underlying design problem-solving in itself. This is the case because designers are used to thinking *in* design rather than to thinking *about* design.

However, as the object of design cannot be separated from the design problem-solving activity, if professionals only think *in* design rather than also critically think *about* design, they are actually taking for granted an important part of their professional activities. They are taking for granted paradigms of design problem-solving.

By taking for granted paradigms of design problem-solving they cannot fully understand their practices and as a consequence it becomes difficult to communicate with and among specialists, to expand the scope of representation systems available to evaluate the qualities and values of the proposed object as well as to expand and use more effectively the myriad of existing computer tools. It becomes difficult to undertake concerted actions among professionals, to reach a joint solution when proposing the object of design, to enrich this solution by transforming it into something unique. It becomes difficult to exert joint control over the process as well as to decide, based on a critical appreciation of each situation, how to best approach the design problem-solving every time a new problem arises.

Critical thinking *about* design problem-solving is important for professionals to understand, create, manipulate and criticise design problem-solving structures. Understanding, creating, manipulating and criticising design problem-solving structures is expected to be important for two different reasons:

(i) To create and coordinate relationships among the different practitioners involved in the design task every time a new problem comes in;

(ii) To effectively use and propose computer tools to be used throughout almost the whole design process.

In the first case, knowledge about structures would enable professionals to coordinate multiple specialities and practices in a case-by-case basis avoiding top-down and process driven practices, in which mediators and managers dictate the design orientation and control the overall outcomes of the product and its materialisation by positioning specialists wherever they are most needed. Understanding creating, manipulating and criticising design problem-solving structures would enable integration among professionals of multiple specialities to happen through concerted actions enhancing the potential for solutions to be something unique. The involved design communities would exert joint control over the process and could decide based on a critical appreciation of each situation how to best approach design problem-solving every time a new problem arises.

In this context, it is expected that building physicists need to understand, create, manipulate and criticise structures of design problem-solving beyond the single pre-defined paradigm they use in their everyday activities if they want to build new tools and establish better dialogues with building designers. It is expected that they need to understand structures as actually a construct which can be based on several principles that vary from scientific theories up to a collection of subjective axioms. It is expected that they understand structures are not deterministic and that the approach their whole community uses in design problem-solving is basically focused on an analytical way of applying science to solve design problems.

Building designers do not like determinism and want to be free to set up their own propositions. Although, the negation of structures in favour of a 'narrative of the contingent' seems seductive to building designers as it produces effects that cannot be predicted as they are circumstantial, directed and determined by the designers main concern while acting. However, the negation of structures makes it difficult to consider all the technical requirements involved in architecture as well as to consciously place the computer within the design process.

Building designers need to understand, create, manipulate and criticise structures even if they are not using rationalist design problem-solving paradigms. Structures are powerful instruments of analysis as well as also powerful tools to work upon design problems. Especially if constructed by designers while designing, structures will be inserted into a specific context and will acknowledge the peculiarities and idiosyncrasies of the situation, even if aims are not yet perfectly clear.

If building designers do not understand create, manipulate and criticise design problem-solving structures, they are probably not going to be able to reason using the more and more sophisticated computer tools that have been made available such as the parametric and environmental simulation ones. They are also probably not going to be able to communicate properly with the other professionals involved in the overall building design activity who use applied sciences to solve specialised design problems. This severely compromises the architect's hope of achieving joint control over the process.

As the computer is predominantly becoming the media used to reason on design problem-solving in both design professions, knowledge about structures also becomes important to create and manipulate computer tools involved in the whole design process. Once information can be rationally structured, it can be stored, manipulated and retrieved digitally allowing computers to become powerful assistants in reasoning. For information to be manipulated using computers, designers need to discuss and decide when and how design problem-solving paradigms are going to be structured. A decision about which parts should be rationalised and at which stage this should happen will have an impact in the design of the tool interface. If this decision is to be made every time a new problem arises or on the basis of the idiosyncrasies of each practice, interfaces would need to be somehow customizable to account for it. The level of customization could determine an important role for consultants.

Besides that, if visual real time thermal performance feedback is provided within 3D parametric environments, heavily structured prediction/evaluation cycles can actually be diluted within 'softer' ways of exploring ideas. Once this is the case, structures of the natural world used mainly for analytical purposes when refining the object being designed can also start being used according to the way they can best solve design problems, and finally the starting point to enable cause/effect relationships of phenomena developing in time to be associated with cause/effect relationships of phenomena developing in space is established.

8.2. Possible themes for future work

A critical appreciation of the outcomes of this work suggests the following questions are still to be answered if building thermal simulation tools are to be better integrated throughout the whole design process:

(i) How to improve general knowledge involved in design problem-solving? Specifically how to make architects understand the ontology and types of phenomena building physics manipulate as well as how to make building physicists understand the ontology and types of phenomena architects manipulate, considering understanding not only involves learning the theory but also having skills in manipulating concepts? How to make professionals clearly understand the main basic difference involved in the two design professions?

(ii) How to develop critical thinking *about* design problem-solving? How to make practitioners critically reflect on or even acknowledge the actual design problem-solving paradigms they use in their everyday activities, considering that in modern society they are allowed less and less time for thinking?

(iii) How to make professionals understand, create, manipulate and criticise structures? How to make knowledge about structures useful in enabling professionals to construct a more solid basis for concerted actions to happen? How to make knowledge about structures of the natural world, used mainly for analytical purposes when refining the object being designed, able to be used according to the way they can best solve design problems? How to make knowledge about structures useful for computers able to become powerful assistants in reasoning about design?

These questions still to be answered are mainly connected to the education of building physicists and building designers. They are important to improve communication between the two types of professionals and consequently to improve the design of building thermal simulation tools.

8.3. Closing remarks

The author of this thesis believes the use of building thermal simulation tools throughout the whole building design process should be designed as opposed to being left to chance. This use should be critically constructed based on the idiosyncrasies of each practice.

As there is no global solution comprehensive enough to cope with the rich universe of possibilities involved in building design, simulation tools need to be designed with configurable interfaces that can be tailored to address the idiosyncrasies of each practice together with the peculiarities involved in dealing with a specific problem at hand.

In order for that to happen, empirical appreciations of the problem and practical attempts alone will not suffice. There is a need for theoretical understanding together with a great deal of critical reflection for building designers and building physicists to be able to properly communicate and effectively construct a joint practice; a need that should be addressed throughout both professional's education.

9. REFERENCES

Aazam, Z. 2007. Seminar of Space Syntax, Welsh School of Architecture. Cardiff, UK. Feb 2007.

Adjaye, D., 2006. *Making public buildings: Specificity, customization, imbrications.* London: Thames and Hudson.

Adnot J et al., 2007. *AUDITAC - Field benchmarking and Market development for Audit methods in Air Conditioning. Final Report to European Commission.* Grant Agreement EIE/04/104/S07.38632. February 2007.

Akin, O., 1986. *Psychology of architectural design.* London: Pion Ltd.

Akin, O. and Akin, C., 1996. Frames of reference in architecture design: analysing the hyper-acclamation (A-ha!). *Design Studies*, 17 (4), 341-361.

Akin, O., 2001. Variants in design cognition. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education.* Atlanta: Elsevier, 105-124.

Alexander, C., 1971. *Notes on the synthesis of form.* 2nd ed. Cambridge: Harvard University Press (1st edition 1964).

Alexander, C., 1977. *Pattern language.* New York: Oxford University Press.

Alexander, C., 1979. *The timeless way of buildings.* New York: Oxford University Press.

Approved Document L2, 2002. *Conservation of fuel and power in buildings other than dwellings.* 2002 ed. Department of transport, Local Government and the Regions. UK, April 2002.

ASHRAE, 2004. *ASHRAE Standard: Energy standard for buildings except Low-rise residential buildings*. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc. (ANSI/ASHRAE/IESNA Standard 90.1-2004).

ASHRAE, 2005. *Handbooks of Fundamentals*. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Atman, C. J., Turns, J., 2001. Studying engineering design learning: Four verbal protocol studies. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education*. Atlanta: Elsevier, 37-60.

Augenbroe, G., Wilde, P., Moon, H. J., Malkawi, A., 2003. The design analysis integration (DAI) initiative. *In*: Schellen and van der Spoel, ed. *Building Simulation '03, 8th International IBPSA Conference,* Eindhoven, Netherlands, September 18-21, 2003, 79-86.

Bachman, L., 2003. *Integrated Buildings: The Systems Basis of Architecture*. New Jersey: John Wiley & Sons Inc.

Benedikt, M., 1991. *Deconstructing the Kimbell: An essay on meaning and architecture*. New York: Sites/Lumen Books.

Bielefeld, B., Skiba, I., 2006. *Basics technical drawing*. Munich: Birkhauser Verlag.

Bilda, Z., Gero, J., Purcell, T., 2006. To sketch or not to sketch? That is the question. *Design Studies*, 27 (5), 587-613.

Bleil de Souza, C., Knight, I. P., Dunn, G. N. and Marsh, A. J., 2006. Modelling buildings for energy use: A study of the effects of using multiple simulation tools and varying levels of input detail. *In*: Luxembourg: Office for Official Publications of the European Communities. *International Conference on Electricity Efficiency in Commercial Buildings (IEECB 2006)*, Frankfurt, Germany, April 26-27, 2006.

Bleil de Souza, C., Knight, I., 2007. Interpreting building simulation modelling data for building designers, with specific reference to the cooling demand. *In*: Santamouris, M. and Wouters, P. *Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century. Proceedings 2nd PALENC Conference and 28th AIVC Conference*. Crete, Greece, September 27-29 2007, 126-131.

Bleil de Souza, C., Knight, I., 2007. Thermal Performance Simulation from an Architectural Design Viewpoint. *In*: Jiang, Zhu, Yang and Li. *Building Simulation '07, 10th International IBPSA Conference,* Beijing, China, September 3-6, 2007, 87-94.

Braham, W., 2005. Biotechniques: Remarks on the intensity of conditioning. *In*: Kolarevic and Malkawi ed. *Performative Architecture: Beyond instrumentality*. New York: Spon Press, 55-70.

Broadbent, G., 1988. *Design in architecture*. 2nd ed. London: David Fulton Publishers. (1st Edition 1975).

Bucciarelli, L. L., 2001. Design knowing and learning: A socially mediated activity. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education*. Atlanta: Elsevier, 297-314.

Buchanan, P., 2000. *Renzo Piano Buildings workshop (3)*. London: Phaidon Press Inc.

Buchanan, R., 1995. Wicked problems in design thinking. *In*: Margolin, V. and Buchanan, R. ed. *The idea of Design: A design Issue reader*. Cambridge: The MIT Press, 3-20.

Buckminster Fuller, R., 1976. *Operating manual for spaceship earth*. New York: Aeonian Press, Inc.

Building Research Establishment (BRE 2008). *National Calculation Method. SBEM software* [online]. Watford, UK. Available from: http://www.ncm.bre.co.uk/ [Accessed: Nov 2008].

Caldas, L. G., Norford, L. A., Rocha, J., 2003. An evolutionary model for sustainable design. *Management of Environmental Quality: An international Journal,* 14 (3), 383-397.

Caldas, L. G., Norford, L. K., 2002. A design optimization tool based on a genetic algorithm. *Automation in construction,* 11 (2), 173-184.

Capon, D. S., 1983. Categories in architectural theory and design: derivation and precedent. *Design Studies*, 4 (4), 215-226.

Carroll, J. M., 2001. Scenario-based design: A brief history and rationale. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education.* Atlanta: Elsevier, 241-268.

Ching, F., 1993. *Architectura: Forma, espacio y orden.* 8th ed. Mexico: Ediciones G. Gili S.A. (1st edition 1979).

Chrisman, N., 1999. Trading zones or boundary objects: Understanding incomplete translations of technical expertise. *Social Studies of Science Annual Meeting. San Diego, California, USA. Oct 1999.*
Available from: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.24.6239 [Accessed: 29th October 2008].

Clarke, J. A., 2001. *Energy Simulation in Building Design.* 2nd ed. Oxford: Butterworth-Heinemann (1st edition 1985).

Clarke, J. A., Hand, J. W., Strachan, P. A., Mac Randal, D. F., 1995. The development of an intelligent, integrated building design system within the European COMBINE project. *In*: Mitchell and Beckman, ed. *Building Simulation '95, 4th International IBPSA Conference*, Madison, Wisconsin, USA, August 14-16, 1995, 444-453.

Collins, H. M., Evans, R. J. and Gorman, M., 2008. Trading zones and interactional expertise. *In* Collins, H. ed. Case Studies of Expertise and Experience, special issue of *Studies in History and Philosophy of Science,* 38 (4), 657-666.

Collins, H., Evans, R., 2002. The third wave of science studies: studies of expertise and experience. *Social Studies of Science,* 32 (2), 235-296.

Coyne, R. and Snodgrass, A., 1991. Is designing mysterious? Challenging the dual knowledge thesis. *Design Studies*, 12 (3), 124-131.

Coyne, R., 1995. *Designing information technology in the postmodern age: From method to metaphor*. London: The MIT Press.

Coyne, R., 2005. Wicked problem revisited. *Design Studies*, 26 (1), 5-17.

Craig, D., 2001. Stalking Homo Faber: A comparison of research strategies for studying design behaviour. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education.* Atlanta: Elsevier, 13-36.

Cross, N., 2001. Design cognition: Results from protocol and other empirical studies of design activity. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education.* Atlanta: Elsevier, 79-103.

Cross, N., 2004. Expertise in design: An overview. *Design Studies*, 25 (5), 427-441.

Csikszentmihalyi, M., 1996. *Creativity: Flow and the psychology of discovery and invention.* New York: Harper Collins Publishers.

Csikszentmihalyi, M., 1992. *Flow: The classic work on how to achieve happiness.* London: Rider Editor.

Demirbas, O. O., Demirkan, H., 2003. Focus on architectural design process through learning styles. *Design Studies,* 24 (5), 437-456.

Design Builder Software (2008). *Design Builder* [online]. Stroud, UK. Available from: http://www.designbuilder.co.uk/ [Accessed: Nov 2008].

DOE, 2007. *Energy Plus Engineering Reference*. The reference to Energy Plus calculation. Washington DC: US Department of Energy.

Donn, M. R., 1999. Quality assurance: Simulation and the real world. *In*: Kakahara, Yoshida, Udagawa and Hensen, ed. *Building Simulation '99, 6th International IBPSA Conference*, Kyoto, Japan, September 13-15, 1999, 1139-1146.

Donn, M. R., 2004. *Simulation of imagined realities: Environmental decision support tools in architecture*. Thesis (PhD). Victoria University of Wellington, New Zealand.

Dovey, K., 1990. The pattern language and its enemies. *Design Studies,* 11 (1), 3-9.

Eastman, C. M., 1999. Representations of design processes. *Proceedings of the 4th Design Thinking Research Symposium,* MIT, Boston, USA, April 23-25, 1999.

Eastman, C. M., 2001. New directions in design cognition: studies of representation and recall. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education*. Atlanta: Elsevier, 147-198.

Eastman, C. M., McCracken, M., Newstetter, W., 2001. Bringing design knowing and learning together. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education*. Atlanta: Elsevier, 1-11.

Eisenman, P., 2002a. Blurred zones. *In*: Benjamin et al. ed. *Blurred Zones: Investigations of the interstitial: Eisenman Architects 1988-1998*. New York: The Monacelli Press Inc.

Eisenman, P., 2002b. Processes of the interstitial. *In*: Benjamin et al. ed. *Blurred Zones: Investigations of the interstitial: Eisenman Architects 1988-1998*. New York: The Monacelli Press Inc.

Eisenman, P., 2002c. Folding in time: The singularity of Rebstock. *In*: Benjamin et al. ed. *Blurred Zones: Investigations of the interstitial: Eisenman Architects 1988-1998*. New York: The Monacelli Press Inc.

Eisenman, P., 2002d. Zones of undecidability I. *In*: Benjamin et al. ed. *Blurred Zones: Investigations of the interstitial: Eisenman Architects 1988-1998*. New York: The Monacelli Press Inc.

Eisenman, P., 2002e. Zones of undecidability II. *In*: Benjamin et al. ed. *Blurred Zones: Investigations of the interstitial: Eisenman Architects 1988-1998*. New York: The Monacelli Press Inc.

Energy System Research Unit (2008). *ESP-r* [online]. Glasgow, UK. Available from: http://www.esru.strath.ac.uk/ [Accessed Nov 2008].

Foster + Partners, 2006. 30 St. Mary Axe, Swiss Headquarters. *In*: Hwang, I. et al. ed. *Verb Natures*, 5, Barcelona, Spain, 50-54.

Galison, P., 1997. *Image and Logic: A material culture of microphysics*. Chicago: The University of Chicago Press.

Gao, S. and Kvan, T., 2004. An analysis of problem framing in multiple settings. *In*: Gero, J. S. ed. *Design Computing and Cognition '04*. Dordrecht: Kluwer Academic Publishers, 117-134.

Gero, J., Kannengiesser, U., 2004. The situated function-behaviour-structure framework. *Design Studies,* 25 (4), 373-391.

Ghiaus, C. Allard, F., 2003. Statistical interpretation of the results of building simulation and its use in design decisions. *In*: Schellen and van der Spoel, ed. *Building Simulation '03, 8th International IBPSA Conference,* Eindhoven, Netherlands, September 18-21, 2003, 387-390.

Givoni, B., 1994. *Passive and low energy cooling of buildings*. New York: John Wiley and Sons Inc.

Goel, V., 1995. *Sketches of thought*. Cambridge: The MIT Press.

Goel, V., 2001. Dissociation of design knowledge. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education.* Atlanta: Elsevier, 221-240.

Goldschmidt, G., 2001. Visual analogy: A strategy for design reasoning and learning." *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education.* Atlanta: Elsevier, 199-219.

Gorman, M. E., 2002. Levels of expertise and trading zones: A framework for multidisciplinary collaboration. *Social Studies of Science*, 32(5-6), 933-938.

Graphisoft (2008). *ArchiCAD homepage* [online]. USA. Available from: http://www.graphisoftus.com/external.php?url=https://trialregistration.graphisoft.com/&return=/products_archicad.php [Accessed: 4 August 2008].

Gross, M. D., Do, E. Y., 2004. Three R's of drawing and design computation. *In*: Gero, J. S. ed. *Design Computing and Cognition '04.* Dordrecht: Kluwer Academic Publishers, 613-632.

Guggenheim-Bilbao (2008). *Guggenheim-Bilbao homepage* [online]. Bilbao, Spain. Available from: http://www.guggenheim-bilbao.es/secciones/el_museo/el_edificio.php?idioma=en [Accessed: 09 August 2008].

Hacking, I., 1983. *Representing and Intervening: Introductory topics in the philosophy of natural science.* Cambridge: Cambridge University Press.

Hamby, D. M., 1994. A review of techniques for parameters sensitivity analysis of environmental models. *Environmental Monitoring and Assessment,* 32 (2), 136-154.

Hand, J., Clarke, J. A., Strachan, P., 1999. Deployment of simulation within design practice. *In*: Kakahara, Yoshida, Udagawa and Hensen, ed. *Building Simulation '99; 6th International IBPSA Conference*, Kyoto, Japan, September 13-15, 1999, 241-247.

Hand, W. J., 1998. *Removing barriers to the use of simulation in the building design professions*. Thesis (PhD). University of Strathclyde, Department of Mechanical Engineering, UK.

Harfield, S., 2007. On design `problematization': theorizing differences in designed outcomes. *Design Studies*, 28 (2), 159-173.

Harris, H. and Lipman, A., 1989. Form and content in contemporary architecture: issues of style and power. *Design Studies,* 10 (1), 67-74.

Hensel, M. and Menges, A., 2006. Material and digital design synthesis. *In*: Hensel, Mengues and Weinstock, ed. Techniques and technologies in morphogenetic design. *Architectural design*, 76 (2), 88-96.

Hernandez, C. R. B., 2006. Thinking parametric design: Introducing parametric Gaudi. *Design Studies,* 27 (3), 309-324.

Heylighen, A. and Neuckermans, H., 2000. DYNAMO—a dynamic architectural memory on-line. *Educational Technology and Society*, 3 (2), 86-95.

Heylighen, A., Verstijnen, I. M., 2003. Close encounters of the architectural kind. *Design Studies,* 24 (4), 313-326.

Heylighen, A., Deisz, P. and Verstijnen. I. M., 2007. Less is more original? *Design Studies,* 28 (5), 499-512.

Hillier, B. and Hanson, J., 1984. *The social logic of space*. Cambridge: Cambrdige University Press.

Huang, Y., 2008. Investigating the cognitive behaviour of generating idea sketches through neural network systems. *Design Studies,* 29 (1), 70-92.

Incropera, F., DeWitt, D., Bergman, T.L., Lavine, A., 2006. *Fundamentals of heat and mass transfer*. 6th ed. USA: John Willey and sons.

Jonas, W., 1993. Design as problem-solving? Or: here is the solution – what was the problem? *Design Studies,* 14 (2), 157-170.

Jones, J.C., 1981. *Design methods: seeds of human futures.* 2nd ed. Bath: John Wiley & Sons. (1st edition 1970).

Kan, J. W. T and Gero, J. S., 2008. Acquiring information from linkography in protocol studies of designing. *Design Studies,* 29 (4), 315-337.

Kees, D., 2008. Design research: a revolution waiting to happen. *Design Studies,* 29 (1), 4-11.

Kim, M. H., Kim, Y. S., Lee, H. S., Park, J. A., 2007. An underlying cognitive aspect of design creativity: Limited Commitment Mode control strategy. *Design Studies,* 28 (6), 585-604.

Knight, I., Marsh, A., Bleil de Souza. C., 2006. *The AUDITAC Customer Advising Tool (CAT) Website and stand-alone software* [online]. Available at: http://www.cardiff.ac.uk/archi/research/auditac/advice_tool.html.
European Commission Grant Agreement EIE/04/104/S07.38632. [Accessed: December 2006].

Knight, I. P., Marsh, A. J., Dunn, G. N. and Bleil de Souza, C., 2006. The components of heating and cooling energy loads in UK offices, with a detailed study of the solar component. *In*: Luxembourg: Office for Official Publications of the European Communities. *International Conference on Electricity Efficiency in Commercial Buildings (IEECB 2006)*, Frankfurt, Germany, April 26-27, 2006.

Knight, I., Bleil de Souza, C., Alexandre, J.L., Marsh, A., 2007. The AUDITAC Customer Advising Tool (CAT) to assist the inspection and audit of air conditioning systems in buildings. *In*: Seppanen and Sateri ed. *Proceedings Clima 2007 WellBeing Indoors Conference*, Helsinki, Finland, June 10-14, 2007, 1251-1348.

Kokotovich, V., 2008. Problem analysis and thinking tools: an empirical study of non-hierarchical mind mapping. *Design Studies,* 29 (1), 49-69.

Kolarevic, B., 2005. Computing the performative. *In*: Kolarevic and Malkawi ed. *Performative Architecture: Beyond instrumentality*. New York: Spon Press, 193-202.

Koutamanis, A., 2006. Digital sketching in a multi-actor environment. *In*: Gero, J. S. ed. *Design Computing and Cognition '06*. Dordrecht: Kluwer Academic Publishers, 103-121.

Kruger, C. and Cross, N., 2006. Solution driven versus problem driven: design strategies and outcomes. *Design Studies,* 27 (5), 527-548.

Kuhn, T. S., 1996. The structure of scientific revolutions. 3rd ed. Chicago: The University of Chicago Press. (1st edition 1962).

Kvan, T. and Gao, S., 2006. A comparative study of problem framing in multiple settings. *In*: Gero, J. S. Eds. *Design Computing and Cognition '06*. Dordrecht: Kluwer Academic Publishers, 245-263.

Kwinter, S., 1995. "The Eisenman wave". *In*: Dobney, S., W. ed. *Eisenman architects: selected and current works*. Victoria: The Images Publishing Group Pty.

Lai, I. C., Chang, T. W., 2006. A distributed linking system for supporting idea association during the conceptual design stage. *Design Studies,* 27 (6), 685-710.

Lawrence Berkeley National Laboratory (LBNL). (2008a). *DOE-2 homepage* [online]. Berkeley, USA. Available from: http://gundog.lbl.gov/dirsoft/d2whatis.html [Accessed: 14 April 2008].

Lawrence Berkeley National Laboratory. (2008b). *GenOpt Summary homepage* [online]. Berkeley, USA. Available from: http://gundog.lbl.gov/GO/summary.html [Accessed: 14 April 2008].

Lawson, B., 1997. *How designers think: the design process demystified.* 4th ed. Burlington: Architectural Press. (1st edition 1980).

Lawson, B., 2004. Schemata, gambits and precedence: Some factors in design expertise. *Design Studies,* 25 (5), 443-457.

Lawson, B., Bassanino, M., Phiri, M., Worthington, J., 2003. Intentions, practices and aspirations: understanding learning in design. *Design Studies,* 24 (4), 327-339.

Leatherbarrow, D., 2005. Architecture's unscripted performance. *In*: Kolarevic and Malkawi ed. *Performative Architecture: Beyond instrumentality*. New York: Spon Press, 5-19.

Leibinger, J., (2008). *Soap, skin & Bubble. Tensile Structures* Leichte Flächentragwerke homepage [online]. Allensbach, Germany. Available from: http://www.tensile-structures.de/ [Accessed: 09 August 2008].

Liddament, T., 1994. Technological literacy: The construction of meaning. *Design Studies,* 15 (2), 198-213.

Lomas, K.J., Eppel, H., 1992. Sensitivity analysis techniques for building thermal simulation programs. *Energy and Buildings,* 19 (1), 21-44.

MacDonald, I., 2002. Quantifying the effects of uncertainty in building simulation. Thesis (PhD). University of Strathclyde, Department of Mechanical Engineering, UK.

MacDonalds, I., McElroy, L., Hand, J., Clarke, J., 2005. Transferring simulation from specialists into design practice. *In*: Beausoleil-Morrison and Bernier ed. *Building Simulation '05, 9th International IBPSA Conference*, Montreal, Canada, August 15-18, 2005, 657-662.

Mahdavi, A., 1999. A comprehensive computational environment for performance based reasoning in building design and evaluation. *Automation in construction*, 8 (4), 427-435.

Mahdavi, A., Bachinger, J. Suter, G., 2005. Towards a unified information space for the specification of building performance simulation results. *In*: Beausoleil-Morrison and Bernier ed. *Building Simulation '05, 9th International IBPSA Conference*, Montreal, Canada, August 15-18, 2005, 671- 676.

Marcuse, H., 1991. *One-dimensional man: Studies in the ideology of advanced industrial society.* 2nd ed. New York: Routledge Classics (1st edition 1964).

Marsh, A. Haghparast, F., 2004. The Application of Computer-Optimised Solutions to Tightly Defined Design Problems. *Proceedings of the 21st Passive and Low Energy Architecture Conference (PLEA 2004)*, Eindhoven, Netherlands, September 19-22, 2004.

Marsh, A., 1996a. Integrating performance modelling into the initial stages of design. *Proceedings of the 30th Australia and New Zealand Architectural Science Association (ANZAScA) Conference*, Chinese University of Hong Kong, Hong Kong, China, July, 17-19, 1996.

Marsh, A., 1996b: Performance modelling and conceptual design. International IBPSA Conference, University of New South Wales, Sydney, Australia, 1996.

Menges, A., 2006. Polymorphism. *In*: Hensel, Mengues Weinstock, ed. Techniques and technologies in morphogenetic design. *Architectural design*, 76 (2), 78-87.

Mitchell, W. J., 1990. *The logic of architecture: design, computation and cognition.* Cambridge: The MIT press.

Morbitzer, C. A., 2003. *Towards the integration of simulation into the building design process.* Thesis (PhD). University of Strathclyde, Energy System Research Unit ESRU, UK.

Morbitzer, C., Stratchan, P. Simpson, C., 2003. Application of data mining techniques for building simulation performance prediction analysis. *In*: Schellen and van der Spoel, ed. *Building Simulation '03, 8th International IBPSA Conference,* Eindhoven, Netherlands, September 18-21, 2003, 911-918.

Mourshed, M. M., Kelliher, D., Keane, M., 2003: Integrating simulation in design - integrating building energy simulation in the design process. *IBPSA News: The Journal of International Building Performance Simulation Association,* 13 (1), 911-918.

Oxman, R., 2001. The mind in design: A conceptual framework for cognition in design education. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education.* Atlanta: Elsevier, 269-295.

Oxman, R., 2006. Theory and design in the first digital age. *Design Studies,* 27 (3), 229-265.

Ozkaya, I. and Akin, O., 2006. Requirement-driven design: assistance for information traceability in design computing. *Design Studies,* 27 (3), 381-398.

Papamichael, K., La Porta, J. and Chauvet, H., 1997. Decision making through use of interoperable simulation software. *In*: Spitler and Hensen ed. *Building Simulation '97, 5th International IBPSA Conference*, Prague, Czech Republic, September 8-10, 1997.

Papamichael, K., 1999a. Application of information technologies in building design decisions. *Building research and information,* 27, 20-34.

Papamichael, K., 1999b. Product modeling for computer-aided decision-making. *Automation in construction,* 8 (3), 339-350.

Portillo, M., Dohr, J. H. 1994. Bridging process and structure through criteria. *Design Studies,* 15 (4), 403-416.

Prazeres, L. and Clarke, J., 2003 Communicating building simulation outputs to users. *In*: Schellen and van der Spoel, ed. *Building Simulation '03, 8th International IBPSA Conference,* Eindhoven, Netherlands, September 18-21, 2003, 1053-1060.

Prazeres, L. and Clarke, J., 2005. Qualitative analysis on the usefulness of perceptualization techniques in communicating building simulation outputs. *In*: Beausoleil-

Morrison and Bernier ed. *Building Simulation '05, 9th International IBPSA Conference*, Montreal, Canada, August 15-18, 2005, 961-968.

PTW Architects + Arup Australia + CSCEC, 2006. Watercube. *In*: Hwang, I. et al. ed. *Verb Natures*, 5, Barcelona, Spain, 66-87.

Purini, F., 2002. Classicism Lost. *In*: Benjamin et al. ed. *Blurred Zones: Investigations of the interstitial: Eisenman Architects 1988-1998*. New York: The Monacelli Press Inc.

Radford, A. D. and Gero, J. S., 1980. Tradeoff diagrams for the integrated design of the physical environment in buildings. *In*: Conwan, H. J. ed. *Solar Energy Applications in the Design of Buildings*. London: Applied Science Publisher Ltd.

Rapoport, A. 2005. *Culture, architecture and design*. Chicago: Locke Science Publishing Company.

Rees, S.J., Spitler, J.D., Davies, M.G., Haves, P., 2000. Qualitative Comparison of North American and UK Cooling Load Calculation Methods. *HVAC & Research,* 6 (1), 75-99.

Rith, C. Dobberly, H., 2007. Why Horst W. J. Rittel matters. *Design Issues*, 23 (1), 72-91.

Rittel, H. W. J. and Webber, M. V., 1974. Wicked problems. *In*: Cross, Elliot and Roy ed. *Man-made futures, Readings in society, technology and design*. London: Hutchinson Educational.

Rowe, P., 1987. *Design thinking*. London: The MIT Press.

Sass, L. and Oxman, R., 2006. Materializing design: the implications of rapid prototyping in digital design. *Design Studies,* 27 (3), 325-355.

Schittich, C., 2003. Building in existing fabric: Refurbishment, extensions, new design. *Edition Detail*. Munchen: Institut fur Internationale Architektur-Dokumentation GmbH & Co.

Schon, D. A., 1984. Problems, frames and perspectives on designing. *Design Studies,* 5 (3), 132-136.

Schon, D. A., 1988. Designing: Rules, types and worlds. *Design Studies*, 9 (3), 181-190.

Schon, D. A., 1991. *The reflective practitioner: How professionals think in action.* UK: Ashgate Publishing Limited. (1st edition 1983).

Schon, D. A., 1992. Kinds of seeing and their functions in designing. *Design Studies,* 13 (2), 135-156.

Shearer, J. L., Murphy, A. T., Richardson, H. H., 1971. *Introduction to system dynamics.* Reading: Addison-Wesley Publishing Company.

Simon, H. A., 1973. The structure of ill-structured problems. *Artificial Intelligence,* 4 (3-4), 181-201.

Simon, H. A., 1996. *The sciences of the artificial.* 3rd ed. Cambridge: The MIT Press. (1st edition 1972).

Sketchup Google (2008). *Google sketchup home page* [online]. USA. Available from: http://sketchup.google.com/download/ [Accessed: 4 August 2008].

Stolterman, E., 1994. Guidelines or aesthetics: design learning strategies. *Design Studies,* 15 (4), 448-458.

Soebarto, V. 2005. Teaching simulation programs in architecture schools: Lessons learned. *In*: Beausoleil-Morrison and Bernier ed. *Building Simulation '05, 9th International IBPSA Conference*, Montreal, Canada, August 15-18, 2005, 1147-1154.

Soebarto, V. and Williamson, T., 1999. Designer orientated performance evaluation of buildings. *In*: Kakahara, Yoshida, Udagawa and Hensen, ed. *Building Simulation '99, 6th International IBPSA Conference*, Kyoto, Japan, September 13-15, 1999, 225-232.

Soebarto, V. e Degelman, L. O., 1995. An interactive energy design and simulation tool for building designers. *In*: Mitchell and Beckman, ed. *Building Simulation '95, 4th International IBPSA Conference,* Madison, Wisconsin, USA, August 14-16, 1995, 431-436.

Solar Energy Research Institute (SERI), 1985. *The design of energy-responsive commercial buildings*. USA: John Wiley and Sons Publication.

Spuybroek, L., 2005. The structure of vagueness. *In*: Kolarevic and Malkawi ed. *Performative Architecture: Beyond instrumentality.* New York: Spon Press, 161-176.

Square One Research (2008). *Ecotect Homepage* [online]. Square One Research, UK. Available from: http://www.squ1.com/products/ecotect/features/thermal [Accessed: 14 April 2008].

Star, S. L., Griesemer, J. R., 1989. Institutional ecology, 'translations' and boundary objects: Amateurs and professionals in Berkeley Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science*, 19 (3), 387-420.

Stravoravdis, S. Marsh, A., 2005. A proposed method for generating, storing and managing large amounts of modelling data using scripts and on-line databases. *In*: Beausoleil-Morrison and Bernier ed. *Building Simulation '05, 9th International IBPSA Conference*, Montreal, Canada, August 15-18, 2005, 1185 - 1190.

Szokolay, S. V., 1980. *Environmental Science Handbook, for architects and builders*. Lancaster: The construction Press Ltd.

Tomovic, R., 1963. *Sensitivity Analysis of Dynamic Systems*. London: McGraw-Hill Book Company Inc.

Tufte, E. R., 1991a. *Envisioning information.* 2nd ed. USA: Graphic Press.

Tufte, E. R., 1991b. *The visual display of quantitative information*. USA: Graphic Press.

Tweed, C. and Carabine, B., 1999. CAAD in the future perfect. *In*: Brown, Knight and Berridge ed. *Architectural Computing from Turing to 2000: Proceedings of the 17th Conference on Education in Computer Aided Architectural Design in Europe, e CAADe and The University of Liverpool*, Liverpool, UK, 18-24.

Tweed, C., Bijl, A., 1989. MOLE: E reasonable logic for design? *In*: Akman, tenHagen and Veerkamp ed. *Intelligent CAD systems II: Implementational issues.* New York: Springer-Verlag.

US Department of Energy. (2007). *Energy Plus* [Online]. Washington, USA. Available from: http://www.eere.energy.gov/buildings/energy_tools/energyplus/ [Accessed 04 October 2007].

Venturi, R., 1977. *Complexities and contradictions in architecture*. 2nd ed. The New York: Museum of Modern Art, New York. (1st edition 1966).

Von Bertalanffy, L., 1969. *General System Theory: Foundations, Development, Applications*. New York: George Braziller Inc.

Waltz, J. P., 2000. *Computerized Building Energy Simulation Handbook.* Lilburn: The Fairmont press Inc.

Ward, A., (2008). *The emergence of design as a social category homepage* [online]. Whakatane, New Zealand. Available from:
http://www.tonywardedu.com/content/view/283/96/ [Accessed: 18th July 2008].

Ward, A., 1989. Phenomenological analysis in the design process. *Design Studies,* 10 (1), 53-66.

Ward, A., 1990. Ideology, culture and the design studio. *Design Studies,* 11 (1), 10-16.

Weinstock, M., 2006. Self-Organisation and material constructions *In*: Hensel, Mengues and Weinstock, ed. Techniques and technologies in morphogenetic design. *Architectural design*, 76 (2), 34-41.

Wendy, C., Newstetter, W., and McCracken, M., 2001. Novice conceptions of design: Implications for the design of learning environments. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education.* Atlanta: Elsevier, 63-77.

Wiezenbaum, J., 1976. *Computer power and human reason: from judgement to calculation.* San Francisco: The MIT Press.

de Wilde, P., 2004. *Computational support for the selection of energy saving building components.* Delft: Delft University Press.

de Wilde, P. and Voorden, M. van der., 2003. Computational support for the selection of energy saving building components. *In*: Schellen and van der Spoel, ed. *Building Simulation '03, 8th International IBPSA Conference,* Eindhoven, Netherlands, September 18-21, 2003, 1409-1416.

de Wilde, P. de, Voorden, M. van der, Brouwer, J. et al, 2001. The need for computational support in energy-efficient design projects in the Netherlands. *In*: Lamberts, Negrao and Hensen ed. *Building Simulation '01, 7th International IBPSA Conference*, Rio de Janeiro, Brasil, August 13-15, 2001, 513-519.

de Wilde, P., Augenbroe, G., Voorden, M. van der., 1999. Invocation of building simulation tools in building design practice. *In*: Kakahara, Yoshida, Udagawa and Hensen, ed. *Building Simulation '99, 6th International IBPSA Conference*, Kyoto, Japan, September 13-15, 1999, 1211-1218.

de Wilde, P., Augenbroe, G., Voorden, M. van der., 2002. Design analysis integration: supporting the selection of energy saving building components. *Building and environment,* 37 (8-9), 807-816.

Winograd, T., Flores, F., 1986. *Understanding computers and cognition: A new foundation for design.* Norwood: Addison-Wesley Publishing Company Inc.

Zardini, M., 1996. *Santiago Calatrava – Secret sketchbook.* New York: The Monacelli Press.

Zimring, C., Craig, D. L., 2001. Defining design between domains: An argument for design research a la carte. *In*: Eastman, McCracken, Wendy and Newstetter, ed. *Design Knowing and Learning: Cognition in Design Education*. Atlanta: Elsevier, 125-147.