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Contrasting paradigms of design thinking: The building thermal simulation tool user vs. the building designer

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This paper contrasts two different paradigms of design thinking: the one of the dynamic thermal simulation tool users with the one of the building designer. It shows that, in theory, the two paradigms seem to be incommensurable but complementary due to differences in knowledge and praxis between the two professions. The author discusses these differences side-by-side based on a review of the design science literature together with an analysis of the basic structure and knowledge involved in existing thermal simulation tools. This discussion aims to unfold a set of insights into the type of approach needed to move this research area further. It highlights the modus operandi of the building designer rather than focusing on collaborative efforts and sets up the backgrounds for designers to learn relevant concepts of building physics in an environment in which they can experiment with these concepts as 'craftsmen'.

Keywords: thermal simulation; paradigms of design thinking; role of simulation in design; integration of simulation in design; criticising integrated simulation

1. Introduction and Backgrounds

This paper proposes that one of the reasons for dynamic thermal simulation tools not being used throughout the whole building design process is a fundamental difference in worldviews between building designers and simulation tool developers. This fundamental difference in worldviews can be identified from the literature about building design as well as from an analysis of the basics underlying the structure and knowledge involved in existing dynamic simulation tools. It is the aim of this paper to discuss these differences side-by-side and provide a useful set of insights to provoke the building design and simulation communities to think further on what issues could potentially be addressed in order for building thermal simulation tools to be better used throughout the whole building design process. This is a review paper that aims at providing a theoretical basis to provoke the community to rethink and reassess the problem of integration from a different perspective, in order to gain further insights into alternative ways of solving it.

A review of the research literature about dynamic thermal simulation tools shows that the majority of responses to the problem of integration tend to be based on a direct manipulation of aspects related to data interpretation and practice [1]. Aspects related to improvements in thermal simulation tools data interpretation can be categorized as output interface data display systems[1] and output interface design advice systems[2]. Aspects related to improvements in the role of thermal simulation tools in building design practice can be categorized as strategies that address the problems as a whole (simplified tools for architects and different interfaces for different design stages)[3], strategies that focus on creating collaborative environments[4] and strategies that explore the use of simulation tools as design advisors in generating new design ideas such as simple generative forms or genetic algorithms[5].

However, this same literature suggests that in spite of all these attempts problems of integrating simulation tools throughout the whole design process still exist. There is a lack of knowledge from the building designer side about simulation in general [52,53]

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[1] Examples can be found in [2 to 5], [6] through IPV interface, [7 and 8] to cite a few.

[2] Examples can be found in [5], [9 to 19], [20 to 26] to cite a few.

[3] Examples can be found in [3], [7 and 8], [10], [27 to 34], [35 and 36] to cite a few.

[4] Examples can be found in [4], [27], [32], [34], [37], [38 to 42], [43 and 44] to cite a few.

[5] Examples can be found in [7], [45 to 48], [49 to 51] to cite a few.

as well as about the fundamentals of physics (mainly about heat transfer and dynamic phenomena) to understand simulation results and undertake design decisions based on them [52 and 53].

At the same time, building physicists offer tools with interfaces that do not function with vague design descriptions [52 and 55] and do not facilitate the detection of patterns in outputs or the reasons behind them [4, 9 and 31]; i.e. they do not offer tools that “aid understanding the relationships between design factors and building performance” [52]. Even though much has been achieved in terms of improving input interfaces and facilitating modelling in the early design stages [56 to 58], there is still much to be done about the content and format of building thermal simulation results for them to be effectively used in design decision making. The display of time-series graphs and tables with temperatures and loads connected to surfaces and volumes are meaningless for building designers to use. Designers are after results that effectively connect these temperatures and loads with the building elements they are manipulating.

Moreover, there are difficulties in coordinating architects and consultants due to dissociations between those who design and those who analyse [52] and it is not uncommon to have experts who tend to be ineffective in relating environmental issues to the interests and concerns of architects [3]. This is probably because research based on collaboration focuses on accepted modes of collaborative design in which specialists interact without taking into account fundamental differences in worldviews and praxis.

From these reasons, the issue of using dynamic simulation tools throughout the whole building design process seems to be a matter of interdisciplinary research in which critical thinking and reflections on knowledge, worldviews and other theoretical aspects involved in the two professions need to be discussed beyond empirical studies and practical propositions. The author proposes that the starting point of this discussion is the acknowledgement that building physicists and building designers, in spite of being ultimately design problem-solvers, subscribe to different worldviews and paradigms when undertaking their everyday activities.

Fundamental differences in knowledge and praxis are explored in this paper based on a review of the literature about building design as well as on an analysis of the structure and knowledge involved in dynamic thermal simulation tools. These differences are explored side-by-side aiming to unfold a useful set of insights to provoke the community to rethink further on the problem of how these tools can be better used throughout the whole building design process.

2. Why discuss paradigm differences?

Paradigm[6], a body of theoretical and methodological beliefs used to interpret things, determines how to solve a problem as well as how to identify the problems to be solved [59]. Paradigms are seen as a pre-requisite for perception, setting up the basis to define the fundamental entities that compose the universe practitioners work within [59]. They define how these entities interact with each other as well as what questions

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[6] Throughout this paper, paradigm is used following the definition proposed by Kuhn [59] which can be understood as a generally accepted perspective of a particular discipline at a given time as defined in Word Web dictionary.

may be legitimately asked about such entities together with the techniques employed in seeking solutions [59].

As a result, paradigms define the shape and scope of professions as well as the knowledge and praxis involved in them. Once the knowledge and praxis between two different professions forced to interact with each other are assumed as fundamentally different and possibly incommensurable, questions about potential common grounds to reach understanding arise. In this context, it seems important to map these knowledge and praxis side-by-side in order to unfold common grounds to reach some level of understanding, rather than using a single paradigms to dictate potential ways of interaction between both sets of professionals. In order to do so, a comparative study is proposed to compare and contrast the 'world' of simulationists and the 'world' of building designers.[7]

3. Differences in knowledge

3.1 The tool users

Dynamic thermal simulation tool developers, generally engineers or building physicists, focus on creating tools which apply science to solve design problems. They construct these tools within a paradigm of Systems Theory in which knowledge resides in the investigation of hierarchically organised wholes or structures 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 [61]. This whole or structure acts as an organism allowing general cognitive principles to

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[7] Comparative studies are commonly used in Social Sciences to investigate two distinct perspectives on approaching a specific subject. See Bryman [60] for further examples of comparative studies in different knowledge domains.

be identified from it. In other words, there is a concern about how the parts are organised and how they behave when in a higher configuration or when belonging to a whole. [61]

If neither the independence of the parts can be clearly identified nor the relationship between them described as linear, the whole is clearly more than simply a sum of parts [61] and the behaviour of this whole cannot be predicted by separating the parts from each other [62]. The interaction between the parts as well as the overall functioning of the whole tends to be represented as models. Models account for prediction as they describe the hierarchical order of the parts, i.e. the system structure, as well as the hierarchical and simultaneous order of the processes, i.e. the system functions. Models are powerful as the "known behaviour of the whole and the known behaviour of a minimum of known parts often make possible the discovery of the values of the remaining parts." [62]

The complexities involved in building thermodynamic phenomena are dealt within the paradigm of Systemic Thinking as the behaviour of the whole cannot be predicted "by the separately observed behaviours of any of the system's separate parts or any subassembly of the system parts" [62]. As the "currency" of physics is energy [61], building thermodynamic systems are systems in which energy exchange happens either through heat transfer processes and/or mass exchanges across the system/building envelope.

Thermodynamic systems are systems in which behaviour develops over time and therefore "there is no status quo or lasting steady state" [63]. Energy is expressed in terms of heat flow and temperature differences, the two main variables of interest, and *problems are structured and articulated to express the heat flow in terms of variations in temperature differences over periods of time.*

Buildings, once interpreted through the lens of thermodynamics, are transformed into models in which the inside building environment tends to be the focus of study, as it is generally where energy will be delivered to or consumed, and the building envelope tends to be the interface between this inside environment and the outside weather conditions[8]. 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). Temperatures affect and are affected by the heat balances between the inside and outside environment, which makes these *heat balances the heart of building thermodynamic problems.*

Recourse to mathematics is necessary to quantify overall building behaviour which involves accounting for the simultaneity of thermal phenomena happening together with the system responses to past and present situations. Simplifying assumptions concerning building properties need to be made so that a building can be modelled into a mathematically tractable situation [63]. This simplified version of the building is a mathematical model in which geometrical and thermophysical building related parameters are transformed into a set of non-linear partial differential equations with specific coefficients and boundary conditions.

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[8] This can be seen in any book referring to building thermal simulation [55] and [64] are just very clear examples of it.

Mathematical representation systems enable engineers and physicists to make extensive use of computer tools. Tools contain a set of algorithms developed to solve thermodynamic problems ([7, 55 and 64] are few examples) and to quantify thermal building behaviour.

As a result, the knowledge involved in the use of dynamic simulation tools is systematic and scientifically based on the laws of natural science. It resides on the fact that building thermal behaviour develops over time and can be quantified through the use of mathematical representations. In order for tools to be used, a real problem needs to be interpreted under the lights of building thermal physics. This interpretation comprises a series of simplified assumptions about building thermal physics related parameters (areas, volumes and thermophysical properties) and topological relationships (between surfaces and between surfaces and the outside as well as surfaces and the inside environments) that affect the heat balances to be investigated. Consequently, the degree to which a model represents reality depends on the validity of assumptions made in arriving at it [63].

Engineers and physicists using simulation tools are expected to be trained with regards to their judgement in simplifying real thermodynamic problems in order for these problems to be transformed into tractable mathematical models that follow the laws of physics. However, as good models are the ones with the information necessary for a professional to act [63], the validity of assumptions depends not only on judgement but also on the purpose of modelling a specific building (energy efficient design, refurbishment to reduce energy consumption, energy auditing, etc).

In this sense, good models depend enormously on the experience of the modeller most of which comes from *practical knowledge and understanding of the subject in the context of using it to solve problems*.

3.2 The building designer

Even though many computer tools are available to be used throughout the design process as well as to communicate building design information to third parties, most of these tools are either used to generate design ideas (generative component tools, [65]) or to manipulate aspects involved in the materialisation of the artefact (parametric tools, Graphisoft [66] or Autodesk Revit [67], and computer assisted design tools – CADs, Autodesk AutoCAD [68]). These tools are generally not used to enhance the application of scientific knowledge to help solving design problems; they tend to be restricted to treat visual characteristics and to the representation of design information.

The emphasis in visual capabilities comes from the fact that the product of building design is a tangible and visible artefact in which form is a paramount design concern. However, form includes not only articulations between surfaces and spaces affecting thermal, lighting and acoustic performances, but also building surface construction, organisation and assemblages limited by the laws of physics with regards to their mechanic stability. Form determines and is determined by inhabitable volumes of air organised and related to each other for human activities to take place within, governed by relationships described in the Social Sciences. Form is full of meaning related to individual and cultural expressions based on discourses from the Human Sciences and the Fine Arts.

Form will not be generated within a single paradigm of thinking, but will be based on a debate that involves different philosophical worldviews[9]. Relationships between structure and function are not as well-defined as in the case of thermodynamics and this is what makes form impossible to be described and assessed through a well-defined model [71].

However, the absence of a well-defined model to describe form does not prevent it to be constructed based on a series of organising and guiding principles [72 and 73], sets of rules, formal languages, functional spatial typologies [74], various analogies and metaphors coming or not from references or precedents [74, 75, 76].

Space and surface elements can be broken down into elemental units and their assemblage and sub-parts described by static rules or formal languages[10] (Figure 1). Organising principles are abstract systems of proportions used to create a 'geometrical discipline' which can be based on a theoretical aesthetic discourse, on the expression of a personal style, on the articulation of function and ergonomics, on complying with construction standards, etc. Functional spatial typologies comprise lists of types and number of activities to be accommodated and operational frameworks / tools (Figure 2) to connect form and function with social systems and organisation of social activities. Analogies and metaphors are important mechanisms of creativity and

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[9] Coyne [69] provides an extensive discussion of that and Venturi [70] is a clear example of it.

[10] [72] and [77] discuss this in detail including the most classical example of formal language presented by Le Corbusier in the 5 fundamental points of architecture which defined the pilotis, the roof gardens, the free plan and façade and the elongated window.

imagination [75 and 69] to provide conceptual and formal inspiration mostly through icons, archetypes / patterns of experiences[11] and spatial patterns.

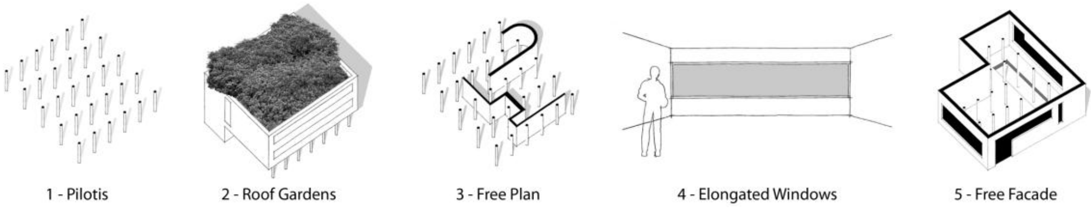

Figure 1 - Le Corbusier 5 points in architecture (Drawn by the author)

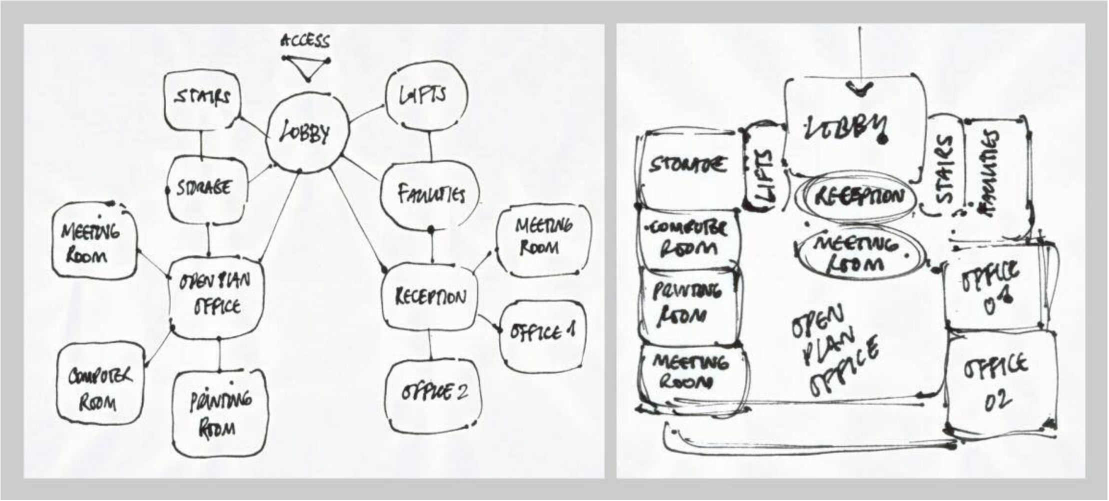

Figure 2 - Examples of a bubble diagram and zoning diagram (Drawn by the author)

Spatial patterns, in which the metaphorical position, dimension and shape of a coherent figure forming a whole have parts so interconnected that the whole cannot be described as simply the sum of them [74], are not systems. Spatial patterns can be interpreted under the light of the Gestalt psychology in which generalizations concerning figure perception are based on laws of similarity, closure, good continuation and symmetry[12] (Figure 3).

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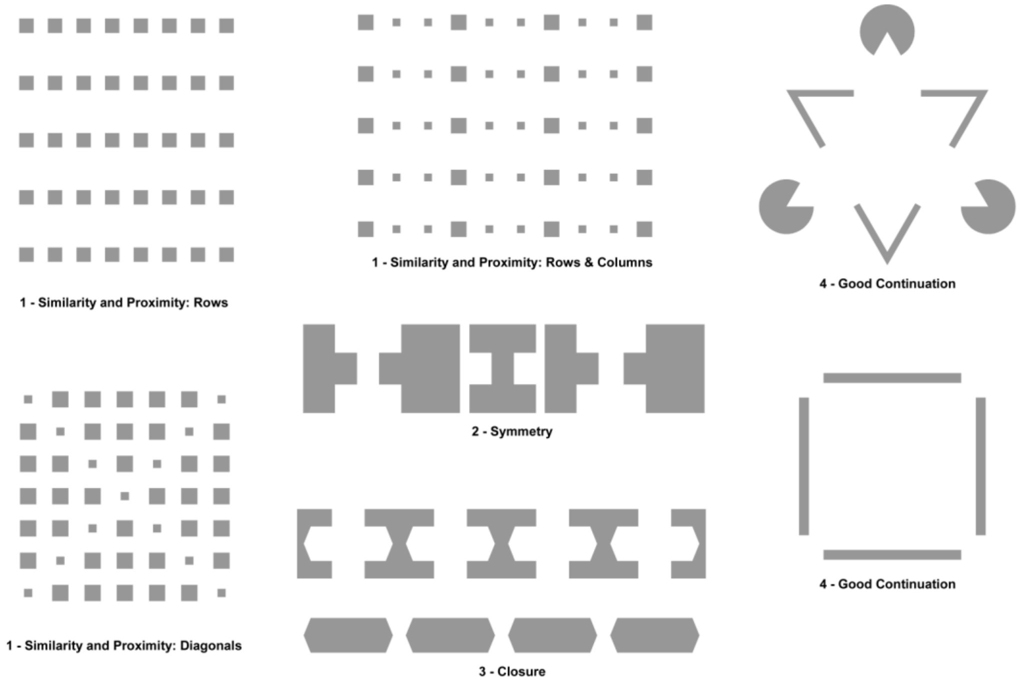
[11] Described in [74] as generative images for reasoning used when designers “put themselves in a position of moving through the spaces, feeling what it would be like to move in them” [74]

[12] Further details of the Gestalt laws can be found in [59] and Mitchell [77].



1 - Similarity and Proximity: Rows

1 - Similarity and Proximity: Rows & Columns

4 - Good Continuation

2 - Symmetry

1 - Similarity and Proximity: Diagonals

3 - Closure

4 - Good Continuation

Figure 3 – Examples of applications of Spatial Gestalt laws (Drawn by the author)

Functional spatial typologies and references / precedents tend to be explicitly invoked whereas spatial Gestalts and experiential archetypes tend to be implicitly invoked. References and archetypes “guide the selection of rules to be taken as salient” [74]. 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” [74]. Typologies as well as guiding and organising principles, 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” [74]. They illuminate how designers go from abstract to concrete and are used to derive sets of criteria to test and criticise a design proposal, by checking if “the rule ‘fits the case’ and fills the inevitable gap between the abstract rule and the concrete context of its application” [74].

As building design resides on the fact that *form primarily develops in space*, it tends to overlook on dynamic effects (form developing over time) but to simply treat isolated aspects of them in connection with spatial perception (walk through animations such as the ones produced with Autodesk 3ds Max [78] are an example of that). Form, dimensions, proportions, usage, visual effects, scale, disposition of elements, organisation of activities, accesses, circulations, etc. - mainly geometrical and material data – *can be visually represented enabling the complexity of interactions between the whole and the parts as well as among the parts to be grasped quantitatively.*

Computers are powerful in dealing with aspects involved in representing spatial phenomena concretely / visually because shapes used to compose form can be easily mathematically described 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 and means to virtually sculpt the object being designed as well as to simulate experiences that result from it, it becomes easier to experiment with form.

Designers design using leading ideas to define and derive sets of rules to test and criticise proposals. As these rules vary every time a new problem arises, they have to be trained with regards to their ability of solving the problem of solving a problem and their knowledge repertoire ends up being built based on learning by doing.
As a result, *the knowledge involved in building design is mainly constructivist*, it is a knowledge generated from experience lacking a specific unified method or structure.

This means every time a new problem is to be solved, *building designers tend to start from first principles by* simply dealing directly with the problem at hand without thinking about it, but mainly by thinking in it. They construct their knowledge on a case-by-case basis through designing and solving problems in which the product is interrelated with the problem of solving it.

Practice and skills are about not having to reason much “from features of the situation to the appropriate types” [74] 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” [74]. “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” [79] Knowing in practice becomes increasingly tacit, spontaneous and automatic.

4. Praxis derived from knowledge

4.1 The tool user experimenting like the systematic scientist

Engineers and physicists using simulation tools generally set up a very clear hypothesis to be investigated or worked upon when dealing with design problems [80]. This hypothesis is composed of the following elements:

- An initial model, in which simplified assumptions about reality are mathematically described;
- A reference state for investigations, a starting set of conditions to be applied in this model;
- A desired state or an aim to be achieved, to be mathematically verified in terms of behaviour;

- A set of actions to achieve this desired state, to be tested in terms of its success.

All the elements of the hypothesis are interconnected and interrelated as, according to previously stated, good models are the ones with the information necessary for a professional to act [63] and the validity of assumptions depends not only on judgement but also in the purpose of modelling a specific building.

As the simultaneity of the phenomena and the system response to past and present situation cannot be predicted by intuition, investigations consist in establishing quantitative cause/effect relationships between actions and specific desired states to be achieved. Progress happens when the differences between desired state and initial state are reduced. “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” [80]

However, because the search needs to be selective, reduced to manageable proportions, it can also be used to evaluate the model response to specific parameters and/or set of conditions, to simplify and short cut the achievement of a desired state. In any case, it consists on a structured series of perturbations in the initial model enabling cause/effect relationships to be quantified so that decisions can be taken based on concrete results. Search strategies are totally problem specific and might rely on trial and error or guessing, experience, systematic experiments or programming routines.

Sensitivity analysis, elimination parametric, factorial simulations, Monte Carlo simulations are examples of search strategies based on systematic experiments. 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 [81] 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, when disturbed, significantly change the outputs, even when the disturbances are small, or to understand the way input parameters propagate through the model causing a large variation in the outputs [82]. 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" [82]. Tomovic [81] discusses sensitivity analysis in depth, and includes several mathematical models to derive sensitivity coefficients, Hamby [82] provides an overview of the most common sensitivity analysis methods and Lomas and Eppel [83] together with MacDonald [39] discuss applications to building thermodynamic simulation problems providing examples.

Parametric runs or differential sensitivity analysis are calculations on the effect of independent individual input parameter variations [94]. 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 [10]. This approach is actually very useful for building 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 [84].

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" [84]. 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" [84]

Optimization algorithms, genetic algorithms and cellular automata are examples of formally implemented programming routines that perturb the parameters of a model and assess the results of these perturbations automatically. The engineer or physicist simply needs to specify parameter ranges to be tested as well as a set of assessment criteria.

In optimization algorithms "all alternatives must be measured in terms of a common utility function" [80]. 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 [85 and 86] 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. Simplified versions of genetic algorithms are simple generative forms, scripts in which rough shapes are generated in response to certain performance criteria [47]. The shapes generated are actually optimised forms which provide boundary conditions for the building designer to act within [1]. Some generative form scripts have been incorporated into Ecotect through the ‘Shading design calculation wizard’, the ‘extrude objects from solar envelope’, the ‘generate optimised shading devices’ and the ‘project solar shading potential’ to cite a few.

As the contribution of each variable in the overall response cannot be traced back directly, perturbations in the original design idea are the most common method used to set up systematic and structured ‘hypothesis-test’ procedures. This hypothesis-test procedure is similar to the one used in the natural sciences; it is rational and objective.

Typical strategies of scientific experimentation are the isolation of variables in order to determine the effect of changing one while keeping the others constant [87]. Even though there is awareness about the limitations of this approach, as interactions between variables can well compromise any conclusions [87], tool users find them valid strategies and use them anyway. When not using them directly, they use them indirectly by developing search strategies that attempt to take parts of these interactions into account, for instance in Factorial analysis, Monte Carlo simulations and Genetic Algorithms.

Within this scientific context, 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” [80]. They are therefore predictive/causal tools. They allow the problem to be interpreted under the law of natural sciences through evaluation and testing of cause/effect relationships. Interpretations of behaviour require specialized scientific knowledge that, although provided by specific handbooks [88], 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 [79].

After mapping cause/effect relationships the problem becomes clearly defined.[13] 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" [79]. 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 [80]. The solutions are most of the time deterministic as the search for them depends on the problem structure [80].

4.2 The building designer experimenting like the human scientist and the artist

Contrarily to building physicists, building designers, when dealing with design problems, are not likely to set up a hypothesis to be investigated as clearly. As each building is unique in terms of location, weather, usage, client, budget and culture i.e. in terms of its context, the object of design cannot be separated from the design activity. Creative solutions, the heart of architecture design, tend to be product driven and emerge mainly from creative strategies in which it is up to the practitioner to construct a structure that will guide him to generate the artefact. As a result, each

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[13] See Simon [89] for definitions and differences between well-defined problems and ill-defined problems

building design problem is approached in terms of constructing a way to solve the problem of solving the problem at hand[14].

In this context, the hypothesis tends to be constructed based on the 'framing' of a unique situation. 'Framing' is not as clear as proposing an initial model, deciding on a reference state for investigations and on a desired state to be achieved together with a set of actions to achieve this desired state. 'Framing' means identifying the ends to be sought and the means to be employed taking actions integrated with deciding, i.e. it means shaping a situation not fitting it into a standard structure so that it can then be manipulated and evaluated (Figure 4).

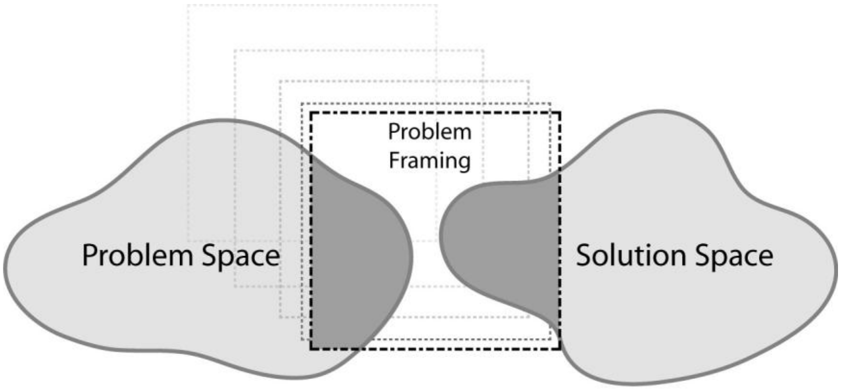

Figure 4 – A proposed diagram for problem framing (Drawn by the author)

This means the hypothesis is not a simple 'what if' exercise. The hypothesis in building design is blurred as the "situation is understood through the attempts to change it and changed through the attempts to be understood" [79]. It also means

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[14] Design scientists moved away from trying to provide 'rational templates' to describe the design process. They are now focused on analysing subjects undertaking design activities in order to gain new insights into how designers design. Examples of that can be found in [76, 90 to 99].

"framing is seldom done in one burst at the beginning of a design process" [74].[15] 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" [74]. 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" [74] whereas judgements can be generalised in terms of how moves are evaluated which explains "how designers build up repertoires of broadly usable design knowledge" [74].

Thus, the testing and assessment of the hypothesis happens though a continuous cycle of seeing – moving - seeing in which the designer "shapes the situation in accordance with his 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 moves" [79].

Through a web of moves, designers discover the consequences, implications, appreciations and further moves. Within these moves, phenomena are understood,

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[15] Note that architectural practice handbooks such as the RIBA [100] do not describe the design process itself but the products of this process. They are suitable for management purposes to control and set up budgets and deliverables to clients. They are highly controversial among design scientists as half of them believe the process itself might not necessarily be sequential and the "development of solutions rarely goes smoothly to one inevitable conclusion" [101].

problems are solved and opportunities are exploited (Figure 5). “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” [79] 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” [79]

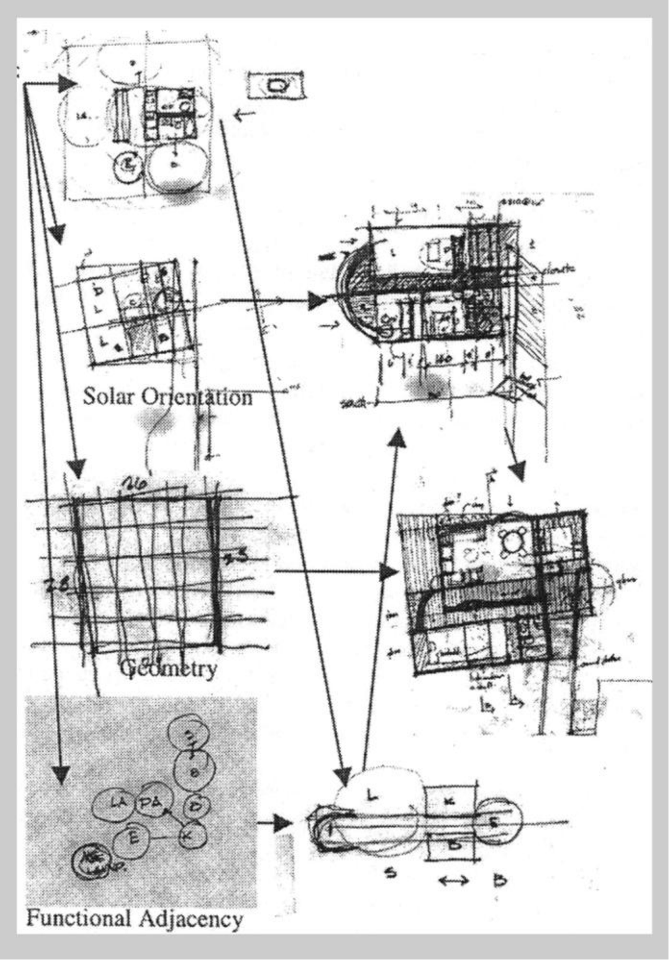

Figure 5 – Example of different snapshots of a building designer’s moves [102].

Once coherence is achieved the 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 [79]. “Designers discover or construct many different variables. They interact in multiple ways, never wholly predictable ahead of time.” [74] Each move satisfies a variety of requirements and each move has not only the consequences intended for it [74] (Figure 5). “Designing triggers awareness of new criteria for design: problem-solving triggers problem-setting” [74] 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” [79] 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” [79] 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” [79]. 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 (Figure 5 – Example of different snapshots of a building designer's moves [102]. 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." [79] 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" [79]. 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" [79] "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" [74].

In a nutshell, “architectural designing can be understood as a kind of experimentation” [103], 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[16] 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/her own prejudices, assumptions and also understands the scope, latitude and nature of the design problem. He/she learns about the problem while attempting to create a solution for it [101]. “Design problems generally take on meaning as they are being worked upon” [96].

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” [79]. 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 inseparable from doing.

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[16] Further studies about reasoning with sketches can be found in the work of [91 and 102] among others.

5. Highlighting contrasts

Differences between dynamic simulation tool users and building designers can be perceived in terms of the type of formal / intellectual and practical knowledge they have which comes from the type of phenomena they manipulate and how these phenomena are represented consequently impacting on the way reality is interpreted (Table 1).

	Simulation tool users	**Building designers**
Formal / Intellectual knowledge	Systematic and scientifically based	Constructivist with product and process interrelated
Nature of phenomena	Phenomena develop over time	Phenomena develop in space
Representation of phenomena	Mathematical representations Partial differential equations	Visual representation systems Quantities directly derived from visual representations
Interpretation of reality	Thermophysical related parameters and topological relationships are mapped into a predefined heat balance structure	Leading ideas are used to define and derive sets of rules to test and criticise proposals.
Practical knowledge	Judgement of what to model and why Capability of simplifying reality to achieve it	Build up a knowledge repertoire based on learning by doing Ability of solving the problem of solving the problem at hand

Table 1 - Differences in Knowledge between dynamic simulation tool users and building designers

Differences can also be perceived in terms of the way practitioners approach the design experiment which influences the way they set, test and assess their design hypothesis (Table 2).

	Simulation tool users	**Building designers**
Approach to experiment	Similar to the one of the Natural Sciences: Realist / Rationalist / Objective	Similar to the one of the Humanities and Arts: Relativist / Constructivist / Subjective
Hypothesis	Model, reference and desired states + set of actions	Contstructed based on the uniqueness of a situation
Test method	Structured series of perturbations to be tested	Web of 'moves' to improve a perceived situation
Assessment method	Quantifying cause/effect relationships	Evaluation of 'moves' through a 'reflective conversation with th situation'

Table 2 – Differences in Praxis between dynamic simulation tool users and building designers

The outlined differences prove paradigms are incommensurable. However, these differences unfold important aspects of each paradigm that need to be taken into account while attempting to produce dynamic simulation tools which integrate better within the building design process.

It can be seen that the knowledge of the tool users and the knowledge of the building designers are complementary. Tool users are able to explain and propose the way for a piece of design to fulfil aspects related to thermal performance whereas building designers are able to explain and propose the physical structure of this piece of design within which human activities take place and individual and cultural expressions are addressed. This might be perceived as an obvious finding but the consequences of it are directly related to different aims and different design actions and that is where limitations in understanding among practitioners tend to lead to 'disjointed' solutions.

As structure and function are interrelated it is impossible to dissociate them. This means it makes no sense to take two separate actions on the matter (one proposed by the designer and one proposed by the simulationist or one related to the object structure and the other related to the object function). In this context, designers would benefit from a deeper understanding on how buildings thermally perform and tool developers would benefit in understanding more about how buildings 'are structured'. This situation calls for a discussion in the two following aspects:

- What do building designers need to know about physics in order to explain and propose the physical structure of an artefact that fulfils aspects related to thermal performance?
- What do simulation tool developers need to know about building design so that they can either take the 'structure' of an artefact into consideration when proposing solutions (in the case of collaboration)

or develop interfaces to inform designers about how the proposed ‘structure’ for an artefact is fulfilling aspects related to thermal performance (in the case of the early design stages for instance)?

These considerations are especially important and have been empirically approached by several researchers and institution since the early 1990 [7, 8, 12, 13, 27, 28, 29, 30, 35, 36, 39, 44, 47, 48, 51, 56, 57 and 58 to cite a few]. The same type of problem is also recurrent in industrial design (see [104] as an example) in which structure and function are also an issue even when proposed by the same professional.

In this context, the education of building designers in building thermal physics should consider the following:

- Understanding that thermal phenomena are extremely complex and cannot be intuitively or simply qualitatively assessed.
- Understanding of the simplification strategies involved in mapping thermal phenomena into predefined structures (modelling tools) that follow the laws of natural science.
- Understanding the fundamentals of the basics behind heat balance and why it calls for systematic investigations about the role of thermophysical properties and topological relationships in the overall performance.

The aforementioned points may seem quite obvious to a simulationist but are definitively not obvious among building designers who tend to be educated within a ‘naïve’ physics environment mainly through directly relating its content to design applications contradicting the dynamic aspects involved in it.[17] Clear examples of that can be seen in a series of publications[18] who show designers are informed on applications of building physics to building construction assemblages and material selection (such as for instance simple calculations of U-values and glazing transmittance) as well as fundamentals and applications of 'environmentally friendly' building components and design strategies (such as for instance Trombe walls, double skin facades, etc).

On the other hand, simulation tool developers need to understand building designers are not systematic about making a design proposal. As they deal with phenomena that develop mainly in space, they derive quantities directly from visual representations and therefore want information as coherent as possible within this type of representation system. As they set up and investigate design proposals in a non-systematic but constructivist way, they want information about how their *moves* affect the overall thermal performance and expect propositions from collaborators as well as simulation inputs and outputs to be coherent with it. This means collaboration can be improved if the simulationists understand the way building designers set up and evaluate design hypothesis. It also means tool developers should connect the meaning of performance results somehow with the structure of the artefact if simulation outputs are to be more informative to building designers.

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[17] Even though [105 to 107] to cite a few do refer to heat transfer processes and go a bit more in detail into the fundamentals of physics, they do not fully explore the dynamic aspects, interdependences between variables and overall heat balance structures in a way that can be clearly related to building design.

[18] Examples of application of building physics to building construction assemblages can be seen in [108 to 110]; to cite a few. Examples of fundamentals of applications of 'environmentally friendly' building components and design strategies can be seen in [111 to 119] to cite a few.

As the point of bridging the gap between thermal performance and structural descriptions of an artefact[19] necessarily involves a combined approach to the design experiment, it is impossible to dissociate knowledge from praxis. As building design praxis is about constructing the problem of solving the problem at hand, two following points for discussion arise:

- Where is the place for systematic and scientific experimentation in building design every time a new design problem is to be considered?
- How can collaborators adapt to this proposition and how can software developers create environments that respond to this constructivist approach based on less systematic experimentations that provide appropriate responses to designer's *moves*?

The author believes the answers to these two questions can only be provided by the building designers. The current methods employed by the simulation community to find successful solutions to the problem tend to produce imprecise information for responses to specific designer's needs. I.e. research methods used so far (interviews with building designers, structured on-line survey, reports of specific case studies and reporting experiences of interactions between specialists and building designers while working in collaboration to solve specific design problems)[20] *simply describe a problem without showing how it can be solved.* Consequently, responses to the problem tend to be interpretations of what the simulation community assumes the building designer needs rather than actual information from designers about what they effectively need.

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[19] Further studies on bridging the gap between function and structure of an artifact can be found in publications referring to industrial design. Kroes [104] discusses this aspect by referring it to a discussion in design methods.

[20] Examples can be found in [120 to 125] to cite a few

Even though collaboration cannot be ignored and collaborative reports could actually be useful in informing how this research area can be moved forward, the author believes it is time for the building designers to provide their contribution to this research area. One way of making this happen is by creating environments in which designers have learnt the relevant concepts of building thermal physics and are prompted to apply these fundamentals into specifically tailored design tasks.

The hypothesis, to be verified by further studies, is to make designers learn the relevant concepts of building thermal physics in an environment in which they can experiment with these concepts as ‘craftsmen’ rather than using rigid scientific methods of investigation. Different and more integrated design solutions can emerge when structure and function (thermal performance) are merged together since problem framing as there is no separation anymore between design proposition and performance assessment.

The idea of using data from practical exercises comes from the fact that the meaning of knowledge comes through the effects of applying it. That is, one should *aim at getting insights into ways of using simulation within the design process in an experimental way*. As “true knowledge lies in our ability to use it, (…) it is not by looking at things but by dwelling in them that we understand their joint meaning” [126]. This implies shifting the current paradigm of using quantitative and empirical research methods to approach the problem using qualitative and participatory research instead. Quantitative surveys will only contribute to this research area if a series of ‘suggestions’ of useful building physics information to design decision making have already been outlined. At the moment, there is a need for opening up the community to interesting insights from experimentation.

6. Conclusions:

The aim of this paper was to open a debate on rethinking and reassessing which issues could potentially be addressed to allow building thermal simulation tools to be better used throughout the whole building design process. The paper looked at this by contrasting paradigms of design thinking with the paradigms used by building simulationists.

The paper proposes starting points or insights to move the research in this field towards a more effective set of outcomes. The reasoning and ways of achieving it can be summarised as follows:

- Current research in the field tends to be quite unilateral and seems to be based on interpretations of what the building physics / simulationists community assumes the building designer needs. As this community lacks a comprehensive understanding on the paradigms of knowledge and praxis of the building designer, it tends to be quite limited in terms of their propositions.
- There is a need to discuss a place for scientific experimentation every time a new design problem is considered because building design praxis is all about constructing the problem of solving the problem at hand. Therefore, it seems logical that designers should propose what they think are useful building physics information to support design decision making rather than building physicist / simulationists.

- Potential effective ways of making designers propose what they think are useful building physics information to support design decision making presupposes two things: (i) That designers know the relevant concepts of physics that are likely to affect their design decisions and (ii) that they at the same time are in a situation in which they are able to experiment with these concepts by engaging into a design task specifically tailored to apply them.

The author believes that from a discussion in paradigm differences both communities understand it is time to explore and expand the scope of possibilities of research in this area by experimenting with new methods focused initially on qualitative and participatory investigations. This approach could potentially lead to a new contribution to this research field once it foments the creation of an environment to explore this theme that is coherent with the modus operandi of the building designer.

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Captions for images:

Figure 1 - Le Corbusier 5 points in architecture (Drawn by the author)

Figure 2 - Examples of a bubble diagram and zoning diagram (Drawn by the author)

Figure 3 – Examples of applications of Spatial Gestalt laws (Drawn by the author)

Figure 4 – A proposed diagram for problem framing (Drawn by the author)

Figure 5 – Example of different snapshots of a building designer's moves (Akin 2001).

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