Studies into the use of building thermal physics to inform design decision making

Clarice Bleil de Souza

Welsh School of Architecture, Cardiff University, Cardiff UK

Bute Building,
King Edward VII Avenue
Cardiff CF10 3NB
Wales UK
Phone: +44 29 2087 5017
Mobile: +44 79 1310 8234
Fax: +44 29 2087 4623
Email: bleildesouzac@cardiff.ac.uk

This paper describes an experiment in which building designers were trained to use building thermal physics to inform design decision making. Designers were presented with a task specifically tailored to facilitate the extraction of what they consider useful parameters, indices, diagrammatic and multimodal ways of representing results as well as possibilities of undertaking design changes when building thermal physics was embedded in their design decisions. The experiment generated design journals with all the steps these designers undertook in solving a design problem which included thermal comfort, energy efficiency targets and the testing of passive design strategies. A qualitative research method, from social sciences, was used to analyze these design journals. Examples extracted from the analysis are useful information to thermal simulation tool software researchers who are rarely provided with adequate examples about how to connect time-series graphs and tables containing temperatures and loads with building elements designers manipulate.

Keywords: Thermal simulation for design decision making; Thermal simulation and design; Role of simulation in design; Integration of simulation in design; Meaningful simulation outputs to building designers.

1. Introduction

The aim of this paper is to promote and aid the next generation of energy-efficient low carbon buildings by discussing and analysing results from the implementation of a different method to train building designers to use building thermal physics to inform design decision making. In this method, designers are taught the fundamentals of building thermal physics and presented with a task specifically tailored to facilitate the extraction of examples of what they consider useful parameters, indices, diagrammatic and multimodal ways of representing results as well as possibilities of undertaking design changes when building thermal physics is part of decision making. This information is seen as valuable to simulation software researchers who seek to improve current building thermal simulation tool features.

Building thermal simulation tools still have a low impact in the building design community, even with legislation, industrial and technological development requiring performance oriented and energy efficient buildings. Ways to overcome this problem and the research methods used to investigate it tend not to be interdisciplinary. Current outputs from simulation tools tend to be unrelated to concepts that are meaningful to the building designer and incompatible with his constructivist / experimental / 'learning by doing' way of approaching problem-solving. Developers are rarely provided with adequate information about how simulation results can be used to inform design decisions. Consequently, *responses to the problem tend to be interpretations of what the simulation community assumes the building designer needs*.

The majority of responses to the problem of integration tend to be based on 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

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[1] A list of references for interface data display systems can be found in Bleil de Souza [1]. Examples of data display systems implemented in simulation software can be found in Energy System Research Unit [2] through IPV interface, AutoDesk Ecotect [3], Design Builder Software [4], to cite a few.

[2] A list of references for output interface design advice systems can be found in Bleil de Souza [1]. Further examples can also be found in Gratia and De Herde [5, [6 and [7], Diakaki et al [8], Chlela et al [9], Yu et al [10], Dondeti, and Reinhart 2011 [11], Pratt and Bosworth 2011 [12] to cite a few.

[3] A list of references for simplified tools for architects and different interfaces for different design stages can be found in Bleil de Souza [1]. Further examples can also be found in Ochoa and Capeluto [13], Petersen and Svendsen [14] to cite a few.

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] .

These responses tend to be based on research methods that are ineffective in matching needs with their appropriate solutions. Research methods tend to be limited to 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 [25 to [32 to cite a few]. Even when using questionnaires to scrutinize design decisions (Venancio et al 2011b [33]), these methods produce imprecise information for responses to specific designer's needs. They *simply describe a problem without showing how it can be solved.*

Building designers end up needing "to work within the model offered by the authors of the tools" [34] when they are actually used to work within an environment in which constructivism prevails and organising principles, sets of rules, formal languages, functional spatial typologies and various analogies and metaphors coming from references and precedents are actually the main strategies used in problem-solving[6]. The generally limited and fragmented education in building thermal physics[7] together with a lack of tools to support design decision making, pushes the

[4] A list of references for strategies that focus on creating collaborative environments can be found in Bleil de Souza [1]. Further examples can also be found in Augenbroe et al [15], Clarke et al [16], Prazeres et al [17], Donn et al [18], Reinhart et al 2011[19], to cite a few.
[5] A list of references for simple generative forms or genetic algorithms can be found in Bleil de Souza [1]. Further examples can also be found in Mardaljevic [20], Jaffal et al [21], Yi and Malkawi [22], Okeil[23], Capeluto 2011 [24] to cite a few.
[6] Further discussions on paradigm differences can be found in Bleil de Souza [35].
[7] Even though Szokolay[36], Givoni [37], Moore [38] 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

design community to depend heavily on specialists[8]. However, in many cases collaboration cannot be achieved such as for instance in the early design stages, in small design practices that cannot afford hiring consultants, in design education willing to incorporate building thermal simulation into the building design process to cite a few. This means there is a need to better integrate thermal simulation tools throughout the whole building design process and that explains why the main software developers are still pursuing ways to achieve that (Open Studio [51], Haves [52], See et al 2011 [53], AutoDesk Project Vasari [54]). It also means that a more effective methodology is needed to provide evidence based data for software developers on meaningful information to building designers.

2. Proposing a Different Research Hypothesis

The hypothesis behind this research is based on the fact full integration can only be reached if the building designer is asked to actively take part in research teams investigating and proposing how building thermal simulation tools can be used in design decision making. In order for a designer to actively taking part in a research team, he needs to be trained and at the same time be set free to experiment with the fundamentals of physics learnt. This strategy, seeming to be quite underexplored by the building simulation research community[9], is likely to be successful as it guarantees solutions are coherent with the way of thinking and the modus operandi of the

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between variables and overall heat balance structures in a way that can be clearly related to building design. Besides these references, examples of fundamentals of applications of 'environmentally friendly' building components and design strategies can be seen in Contal and Revedin [39]; Daniels[40]; Daniels and Hamman [41]; Hawkes [42]; Kibert [43]; Smith [44]; Sassi [45]; Habermann and Gonzalo [46]; Lechner [47]; to cite a few. Examples of application of building physics to building construction assemblages can be seen in Hindrichs and Daniels [48]; Pearsons [49]; Hegger et al [50]; to cite a few.

[8] Recent academic research in the area tends to focus on accepted modes of collaborative design in which specialists interact without taking into account fundamental differences in worldviews and praxis.

[9] Even though, Reinhart et al 2011 [19] and Hetherington et al 2011 [55] use the strategy of having designers designing as part of their research methods, neither of them explore the use of designers designing to propose the generation of meaningful and useful information to designers. Reinhart et al 2011 [19] uses information to set up strategies to improve collaboration and Hetherington et al 2011 [55] uses information to survey design requirements rather than to set up design solutions.

building designer[10]. Experimenting can be a quite straight forward strategy to lead to *the creative use of science to design decision making.*

The emphasis on experimenting comes from studies of psychology of reasoning which shows that:

> *"We assemble a strategy 'bottom up' from our explorations of problems using our inferential tactics. (...) We explore different sequences of tactics. These explorations can lead us, not just to the solution of a problem, but also to a new reasoning strategy. (...) Once we have mastered its use in a number of problems, it can then constrain our reasoning in a top-down way. A top-down method may be possible for experts who think in a self-conscious way about a branch of logic. But we develop a strategy bottom-up."* (Johnson-Laird [56]).

By experimenting, one constantly updates his/her knowledge on the subject, creates a repertoire of tested solutions for a set of different problems and, more importantly, manipulates and tests different ways of applying knowledge to solve a problem, i.e. develop different strategies. Besides that, experimenting also provides another valuable source of learning: learning from ones mistakes. When learning from ones mistakes one learns the consequences of its moves [56]. In learning through experimenting one can test his/her moves and evaluate them as good or bad within a specific context of trying to solve a problem. Learning from tactical steps may lead nowhere in a particular problem being solved but may be useful and handy when used to solve another problem as it implies the learning of a tactic anyway [56].

[10] Further information on how designers design can be found in Bleil de Souza [35]

Experimenting sets one free to manipulate the ways of solving a problem and therefore opens the possibilities for one's imagination to interfere in the process. "…imagination helps us to reason, and reasoning helps us to imagine" (Johnson-Laird [56]) and that is what should be emphasized if a creative use of science within building design propositions is the ultimate aim to be achieved because it enables the accommodation of design 'moves' and actions within non-procedural and non-methodical architectural design decisions which is consonant with how designers design.

3. Creating an Experimental Environment

An environment to undertake this study was created in the Welsh School of Architecture (WSA) in the academic year of 2009-2010. As "experience cannot be represented by any exact theory" (Polanyi [57]), designers were requested to interiorize the learning of the fundamentals by applying them into a specific design task which at the same time was tailored to extract multimodal mock ups of what they would consider meaningful information to design decision making. The task comprised the design of a façade for an office building which already had a structural skeleton and a customized internal layout. The design of a façade offers rich possibilities of exploring heat and mass transfer processes. It can easily be connected to the building usage and made parametric, i.e. split up into modules increasing the degree of control and the possibilities of design investigations.

Prior to proposing a façade, designers were instructed to undertake a weather analysis using Ecotect Weather Tool, to easily and quickly process and extract relevant weather data to be used in the thermal performance calculations. They would then start the experiment by setting up several iterative loops which included designing the building façade and assessing its thermal performance. The use of any kind of building thermal simulation tool was not allowed throughout the whole experiment. The reason for that was to free up designers from constraints, potentials and pitfalls from building simulation input and output interface systems or any other kind of software structure that could interfere or be deterministic with regards to how thermal building physics could be used throughout this façade design task.

The training provided in fundamentals of building thermal physics was enough for these designers to be able to set up simplified heat balance calculations to undertake their experiments. Whilst these calculations are far from advanced in terms of thermal performance analysis, they are easy to handle and understand. They are good in providing a first grasp on how the building is going to behave when design information is vague and design proposal are under testing. Besides that, simplified heat balance calculations prevent diversions into higher levels of detail and keep the individuals focused on the investigations of cause and effect that would be suitable to asses each design 'move'. They can be easily handled with electronic spreadsheets and if used in conjunction with hourly incident solar radiation calculations from Ecotect, provide sufficient means to set up and control thermal performance calculations.

This thermal assessment system guarantees a certain level of rigor and speed in calculations and analysis enabling more freedom in the setting of propositions and in the decisions about the course of the design process including the most appropriate moments to evaluate cause / effect relationships. Designers are forced to rely on themselves rather than on computer tools and by doing that they need to reflect on their 'moves' and on the consequences of their actions. They are also free and encouraged to look for alternative ways and short cuts to assess their propositions which can potentially lead to the specification of parameters, indices, diagrammatic and multimodal ways of representing results as well as possibilities of undertaking design changes when building thermal physics is part of decision making.

3.1. Description of the Experiment

The study was conducted with a sample of 75 novice designers who had no previous knowledge of building thermal physics but had 2.5 years of experience in building design. The training consisted of around 20 hours of formal taught sessions on fundamentals of heat and mass transfer applied to buildings through the use of simplified steady state heat balance calculations. This was to ensure individuals could understand qualitatively and quantitatively the way these processes are interconnected and how they affect building performance. Lectures were complemented with two 'question and answer' sessions plus assigned readings [36]. Fundamentals were to be applied in the design of a commercial building skin. Five individuals would work with the same 'base building' and were told to individually propose a façade that would minimise the use of HVAC systems. The building was to be constructed in the city of Zurich (Switzerland) and weather data for a full year was digitally provided in an Ecotect / Weather tool format (.wea) so that each person could undertake a weather analysis prior to any façade design proposal.

4. Data Analysis

Results were collected in the format of a design journal in which designers described their design processes in detail specifically pointing out how and in which parts of it performance assessment was undertaken. Design journals were examined one-by-one to extract as much information as possible about how building thermal physics was integrated in design decision making. The idea was to collect different ways of approaching the design of the building skin and its relation to internal layout, scrutinizing how building thermal physics assisted design decisions in the set up, development and changes to optimize performance.

From the sample of 75 design journals, 6 were selected to be used in a detailed analysis as they portrayed very different ways of integrating building thermal physics to the building design process. The information collected was not exhaustive and more approaches could potentially emerge from different samples with different individuals. As a result, this is a qualitative study in which Social Science research methods were used to categorize and analyze different design approaches and decisions undertaken with the assistance of building thermal physics. The author believes more needs to be explored at a qualitative level before any quantitative study can be set up. At the moment, it is important to expand the information available about how building thermal physics can be embedded in design decision making rather than tracing statistical panoramas related to different types of integration.

The qualitative analysis was explored using a 'Thematic Analysis' approach. Thematic Analysis is one of the most common approaches to qualitative research in social sciences [58]. It basically consists in the search for themes in written pieces of data that can be further detailed into groups of codes that break the major themes into subthemes. "The themes and subthemes are essentially recurring motifs in the text that are then applied to the data" (Bryman [58]). "The idea is to construct an index of central themes and subthemes, which are then represented in a matrix" (Bryman [58]). The matrix is used as a basis to categorize and analyse data from the 6 selected design journals.

The analysis began by focusing on identifying different ways of framing[11] the problem with regards to how the design of the building skin can be related to the internal layout. Table 1 displays the themes, subthemes and coding system used to categorize different approaches used in design problem framing. Five subthemes related to the design of the building skin and three subthemes related to assumptions about the internal layout were identified. Combinations of different ways of approaching the design of the building skin and its relation to internal layout are extracted from the 6 selected design journals and displayed in Table 2.

Theme	Subtheme	Subtheme Code
Approach to skin	Overall envelop strategy - No panels or modular system used	Envelope all
	Façade arrangement composed of one panel	Uni-modular
	Orientation dependant modular façade arrangements	Orientation Modules
	Simple modular façade arrangement (2 or 3 different panels used)	Simple Modules
	Complex modular façade arrangement (4 modular façade panels composing larger façade modules)	Complex Modules
Approach to layout	Customized layout - all building was studied	Customized all
	Customized layout - 4 'case study' rooms were selected to be studied	Customized 4
	Speculative layout	Speculative

Table 1 – Coding system used in problem framing

Theme	Combinations chosen by the 6 subjects					
	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6
Approach to skin	Simple Modules	Simple Modules	Complex Modules	Orientation Modules	Envelope all	Uni-modular
Approach to layout	Customized all	Customized 4	Customized 4 + Speculative	Customized all	Customized all	Speculative

Table 2 – Using the coding system to extract data from the 6 selected design journals using 6 different combinations of building skin and building layout approaches to frame the problem.

[11] Building designers tend to 'frame' design problems by identifying the ends to be sought and the means to be employed taking actions integrated with deciding, i.e. they tend to shape a situation not fitting it into a standard structure so that it can then be manipulated and evaluated.

After problem framing, subthemes related to Sequence of Design Decisions were mapped and coded from a thorough assessment of the design journals. The Sequence of Design Decisions subthemes provide a description of the sequence of decisions in a design proposal/evaluation cycle, i.e. they summarize sequences of design actions. They display spontaneous associations of design ‘moves’, actions and strategies with fundamentals of thermal building physics. They are useful to illustrate that the role of physics within the design process is quite complex and integrated. Fundamentals of physics can be related to regulations and standards as well as provide useful insights into hierarchies and standardization of a series of design parameters and decisions. These subthemes also illustrate how the overall design process is structured so that performance assessment can further inform the design process. The list of Sequence of Design Decisions used on this study is presented in the Table A 1 with its associated coding system composed of one action word plus two other key words. The Sequence of Design Decisions is the basis to extract strategies and approaches to be further analyzed with regards to the two following post-rationalized themes:

- *Approach to Physics*: Theme which provides a description of strategies and approaches used to interpret building thermal physics. They are concepts, variables, calculation procedures and scientific strategies used throughout the design process. They are coded using the language / jargon of building physics and presented in Table A 2
- *Approach to Design*: Theme which provides a description of strategies and approaches used to undertake design decisions and actions, i.e. the series of assumptions behind each action illustrating how physics is used as part of setting and assessing design aims. They are coded using the language of building designers and presented in Table A 3.

The content of each of the 6 design journals was translated, using the aforementioned coding system, into a map that illustrates the way of thinking and the actions undertaken by each designer from the beginning to the end of the task. This information was useful to understand why courses of action happened the way they did and how each decision affected the sequence of events that followed them. It was also useful to illustrate each designer thinks differently and that this impacts not only on their design 'moves' but also on the way they make sense of building thermal physics by embedding it into these 'moves'.

4.1. Analysis of Individual Design Processes

From an analysis of individual design processes it was possible to see that different sequences of 'moves' and different sequences of thinking process lead to different final results. Subjects many times undertook similar types of actions but the position of them within the process varied quite a lot depending on the aims and the design starting point. Some subjects (1 and 5) reached a final design solution using lesser steps than others. Three main design streams could be clearly identified from this analysis: one that focuses mainly in manipulating heat losses, another one that focuses mainly in maximizing solar gains and a third one that is faithful to a strong design idea of using a single façade panel throughout the whole building envelope.

4.2. Cross-comparisons of the Different Design Processes

Once the way of thinking and the actions undertaken by each designer, from the beginning to the end of the task, were coded and mapped they could also be cross-compared. Cross-comparisons exposed side-by-side different possibilities for design 'moves' in each design step facilitating insights into more generic conclusions. Cross-comparisons were organized roughly according to the three following stages:

- *The set up,* which defines the starting point of the design problem based on the premises of problem framing
- *The development*, in which main design actions are undertaken, assessed and acted upon with the help of building thermal physics
- *Changes to optimize performance*, in which design actions are refined with the help of building thermal physics

Table 3, displays the coded content of the 6 design journals in detail. Different procedures and 'moves' undertaken by each designer are recorded as different 'Options' and described using the coding system of each of the three main sub themes. An extra column indicating which subject undertook the recorded procedure or 'move' is added at the end of the table to facilitate the analysis.

	Steps		Theme: Sequence of decisions	Theme: Approach to physics	Theme: Approach to design	Subjects
The set up	Step 1	Option 1	Optimizing Customized Layout	Internal Gains Oriented	Layout Oriented	**1**
		Option 2	Optimizing Customized Layout + Selecting Key Rooms	Internal Gains Oriented	Layout Oriented	**2**
		Option 3	Comparing Layouts + Selecting Key Rooms	Internal Gains Oriented	Layout Oriented	**3**
		Option 4	Optimizing Customized Layout + Outlining Façade Design	Gains & Envelope Oriented	Layout & Skin Oriented	**4 & 5**
		Option 5	Proposing Uni-modular Solution	Envelope Oriented	Skin Oriented	**6**
	Step 2	Option 1	Designing Compliant Panels	Conductions Losses	Code Compliance	**1 & 6**
		Option 2	Investigating Panel Assemblages + Defining Façade Panels	Conductions Losses	Beyond Code Compliance	**2**
		Option 3	Investigating Panel Assemblages + Composing Panels into Modules	Conductions Losses	Beyond Code Compliance	**3**
		Option 4	Designing Shading Masks	Solar Gains	Form for Solar	**4**
		Option 5	Designing Standards Panels	Conductions Losses	Meeting Standards	**5**
The development	Step 3	Option 1	Distributing Panels	Internal Gains Deterministic	Customized Panel Placement	**1**
		Option 2	Investigating Panel Performances	Panel Heat Balances	Average Panel Performance	**2 & 3**
		Option 3	Studying Windows in Panels + Distributing Panels	Internal Gains Deterministic	Customized Panel Placement + Customized Window Shapes	**4**
		Option 4	Designing Shading Devices	Solar Gains	Form for Solar	**5**
		Option 5	Generating Layout Factors	Internal Gains Panel Indices	Speculative Panel Indices	**6**
	Step 4	Option 1	Designing Panel Windows	Window Heat Balances	Average Window Performance	**1,2,3 & 5**
		Option 2	Designing Shading Iteratively	Solar Gains	Form for Solar	**4**
		Option 3	Generating Ventilation Factors	Ventilation Panel Indices	Speculative Panel Indices	**6**

Changes to optimize performance	Step 5	Option 1	Investigating Panel Performances	Panel Heat Balances	Average Panel Performance	**1**
		Option 2	Investigating Energy Performances	Room Loads	Key Rooms Performance	**2, 3**
		Option 3	Investigating Panel Assemblages + Designing Customized Windows	Panel Orientation Heat Balances	Orientation Window Performance + Average Panel Performance	**4**
		Option 4	Investigating Passive Performances	Room Heat Balances	Perimeter Rooms Performance	**5**
		Option 5	Designing Panel Windows + Investigating Panel Performances	Window Heat Balances + Panel Heat Balances	Average Window Performance + Average Panel Performance	**6**
	Step 6	Option 1	Investigating Passive Performances	Room Heat Balances	All Rooms Performance	**1**
		Option 2	Optimizing Ventilation + Designing Shading Devices + Investigating Energy Performances	Non-Panel Perturbations	Non-Panel Changes + Key Room Performance	**2, 3**
		Option 3	Distributing Panels + Refining Facade Design	Parametric Perturbations - Windows + Non-parametric Perturbations - Panels	Optimizing Windows + Optimizing Panel Distribution	**4**
		Option 4	Investigating Panels Passive Performance	Space Heat Balance Indices	Performance Panel Indices	**6**
	Step 7	Option 1	Optimizing Façade Performance + Meeting Ventilation Standards	Non-parametric Perturbations - Panels	Optimizing Panel Distribution + Non-Panel Changes	**2**
		Option 2	Optimizing Façade Modules	Non-parametric Perturbations - Modules	Optimizing Larger Modules	**3**
		Option 3	Investigating Panel Performances	Panel Heat Balances	Average Panel Performance	**4**
		Option 4	Investigating Window Shapes	Non-Parametric Perturbations - Windows	Optimizing Window Shapes	**6**
	Step 8	Option 1	Adding Mechanical Ventilation + Adding Heat Recovery + Adding Passive Heating Louvers	HVAC Solution		**1**
		Option 2	Investigating Passive Performances	Room Heat Balances	Key Rooms Performance	**2**
		Option 3	Investigating Passive Performances + Results - Annual Passive Performance	Room Heat Balances	All Rooms Performance	**4**
	Step 9	Option 1	Adding Passive Heating Louvers			**1**
		Option 2	Results - Super Insulation	Quantifying Insulation		**2**
		Option 3	Results - Complex Modules	Quantifying heating and Cooling		**3**
		Option 4	Results - Influence of Room Usage	Ranking Room Performances		**4**
		Option 5	Adding Mechanical Ventilation + Adding Heat Recovery	Important Parameters Identification		**5**
		Option 6	Abandoning Uni-modular Solution			**6**

Table 3 – Summary of the design process contained in each of the 6 design journals analyzed.

4.2.1 Analyzing the project approaches taken (The set up)

When analyzing the projects set up, mainly steps 1 and 2 in Table 3, the following two extreme approaches could be identified:

- Internal gains and fabric totally connected with each other
- Internal gains and fabric treated completely disconnected from each other

In the first approach, internal gains and building envelope were thought about together. Figure 1 illustrates a map of different internal gains of a specific office layout together with a series of annotated façade design solution criteria. It shows that the building skin is designed in connection with the proposed internal layout. The customized layout was mapped, optimized and used as a basis to outline façade requirements and the first attempt to approach fabric design was through investigating the manipulation of solar gains. This initiative, undertaken by subject 4 and 5, is interesting and likely to provide the best resultant thermal behavior because envelope and building use are designed to perform together. However, in the design of commercial buildings this approach can be questioned because either the layouts tend to change constantly or, in the case of speculative buildings, they tend to be unknown in the building design phase. On the other hand the strategy is clever if applied to the design of other building typologies, especially in the residential sector when layouts are easier to be predicted and tend not to change so often.

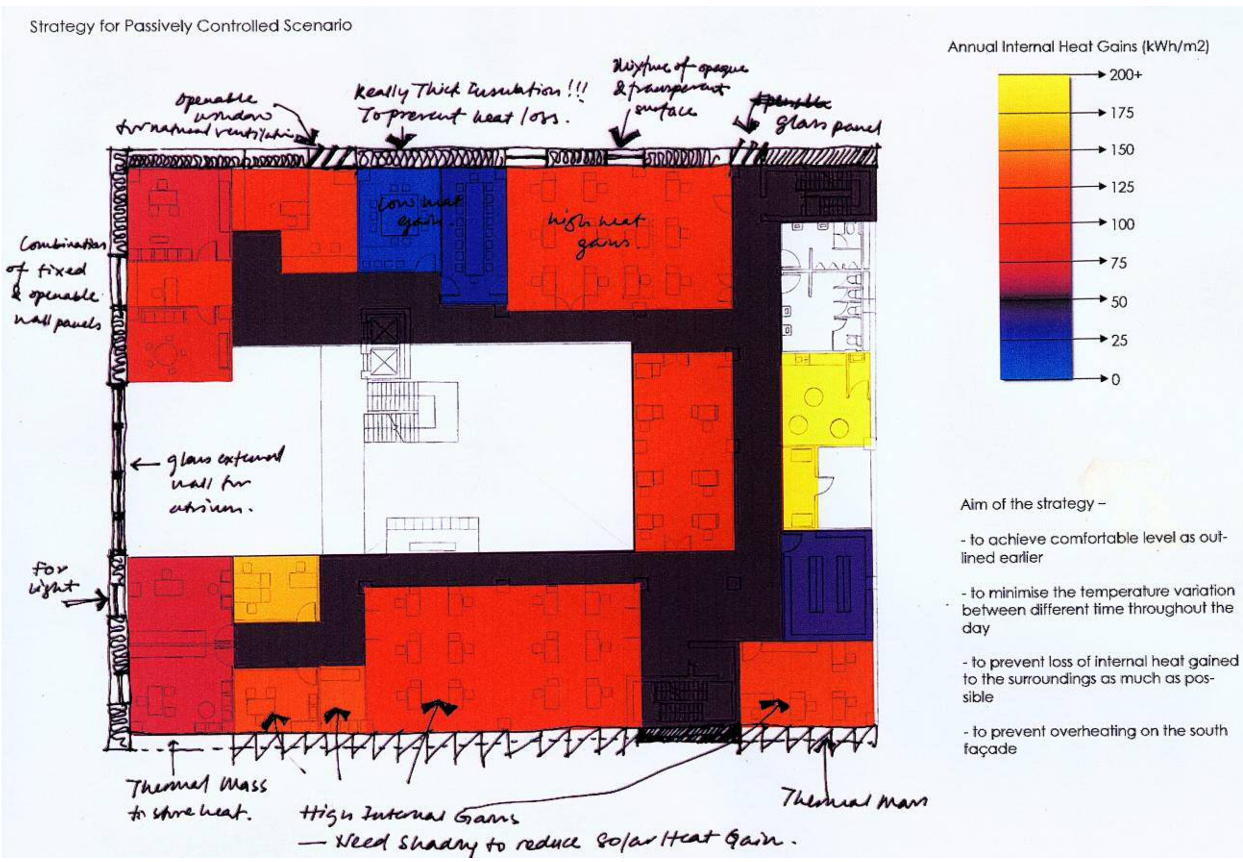
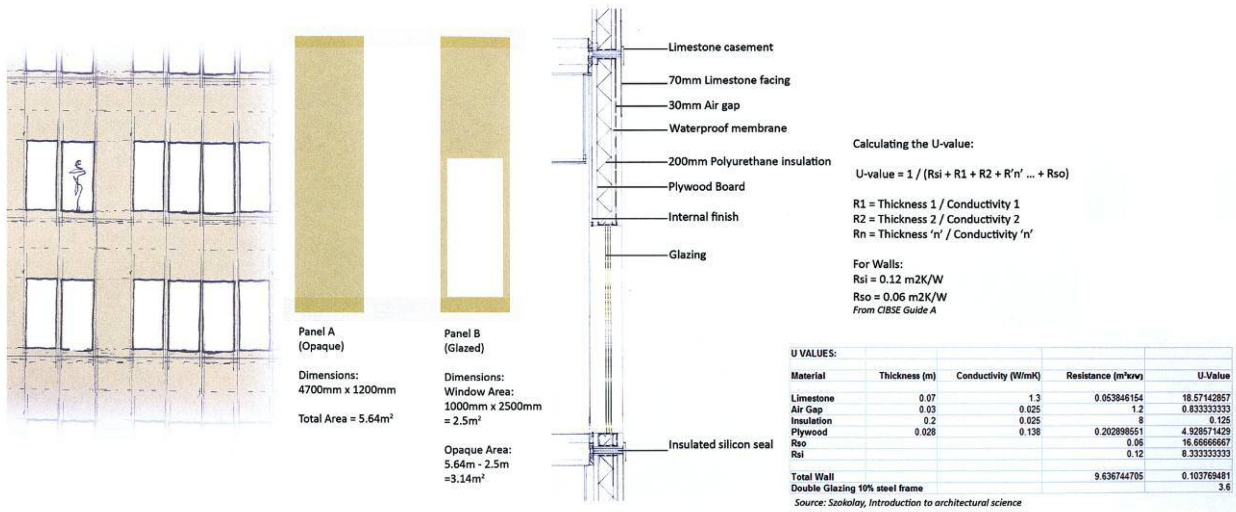


Figure 1 – A map of different internal gains of a specific office layout together with a series of annotated façade design solution criteria.

In the second approach, subjects 1, 2 and 3 mapped the customized layouts into a set of internal gains but did not use them directly to outline façade requirements. The façade was examined independently and subdivided into a series of modular panels which were analyzed mainly in terms of their heat losses through conduction either using code compliance or going beyond it. Figure 2 illustrates a snapshot of the façade and the rationale behind the subdivisions into different panels, together with material specification tied to the calculation of U-values. Subject 3 expanded the idea of using the panels further and proposed a more complex system in which 4 basic façade panels were combined into 6 different façade modules. The focus on modular façade optimization separately from internal layouts is a common approach to the design of commercial buildings. This thinking leaves room for flexible propositions for the internal layout by guaranteeing the façade will enable the building to perform according to minimum standards. Subject 6, realizing that flexibility was a major design issue, simply ignored any customized internal layout and considered the building as completely speculative, assuming a single value for the internal gains to be distributed throughout the whole typical floor plan. It could be argued that this last approach would have been more useful had a range of potential internal gain values been explored.



Material	Thickness (m)	Conductivity (W/mK)	Resistance (m²K/W)	U-Value
Limestone	0.07	1.3	0.053846154	18.57142857
Air Gap	0.03	0.025	1.2	0.833333333
Insulation	0.2	0.025	8	0.125
Plywood	0.028	0.138	0.202898551	4.928571429
Rso			0.06	16.66666667
Rsi			0.12	8.333333333
Total Wall			9.636744705	0.103769481
Double Glazing 10% steel frame				3.6

Figure 2 – A snapshot of the façade and the rationale behind the subdivisions into different panels together with material specification tied to the calculation of U-values.

4.2.2 Assessing the development of the approaches towards a solution (The development)

When analyzing the project development, mainly steps 3 and 4 in Table 3, the following three different approaches could be identified:

- Intensive investigations of building envelope characteristics after careful considerations of the needs from customized layouts
- Coupling the proposed façade panels with a map of customized layout out requirements
- Creating façade panel indices to aid performance calculation of speculative office buildings

The first approach is a natural follow up from set ups in which internal gains and building envelope were totally connected. The design development in this case focused on a combination of three different strategies used to optimize solar performance of the building. These strategies, illustrated in Figure 3 comprehend the following and were used through several iterations until a satisfactory set of shading devices was achieved:

- Using Ecotect shading optimization algorithms
- Creating shading masks by overlaying solar site analysis with customized layout performance targets
- Using aesthetic design considerations and building construction constraints to rationalize design proposals.

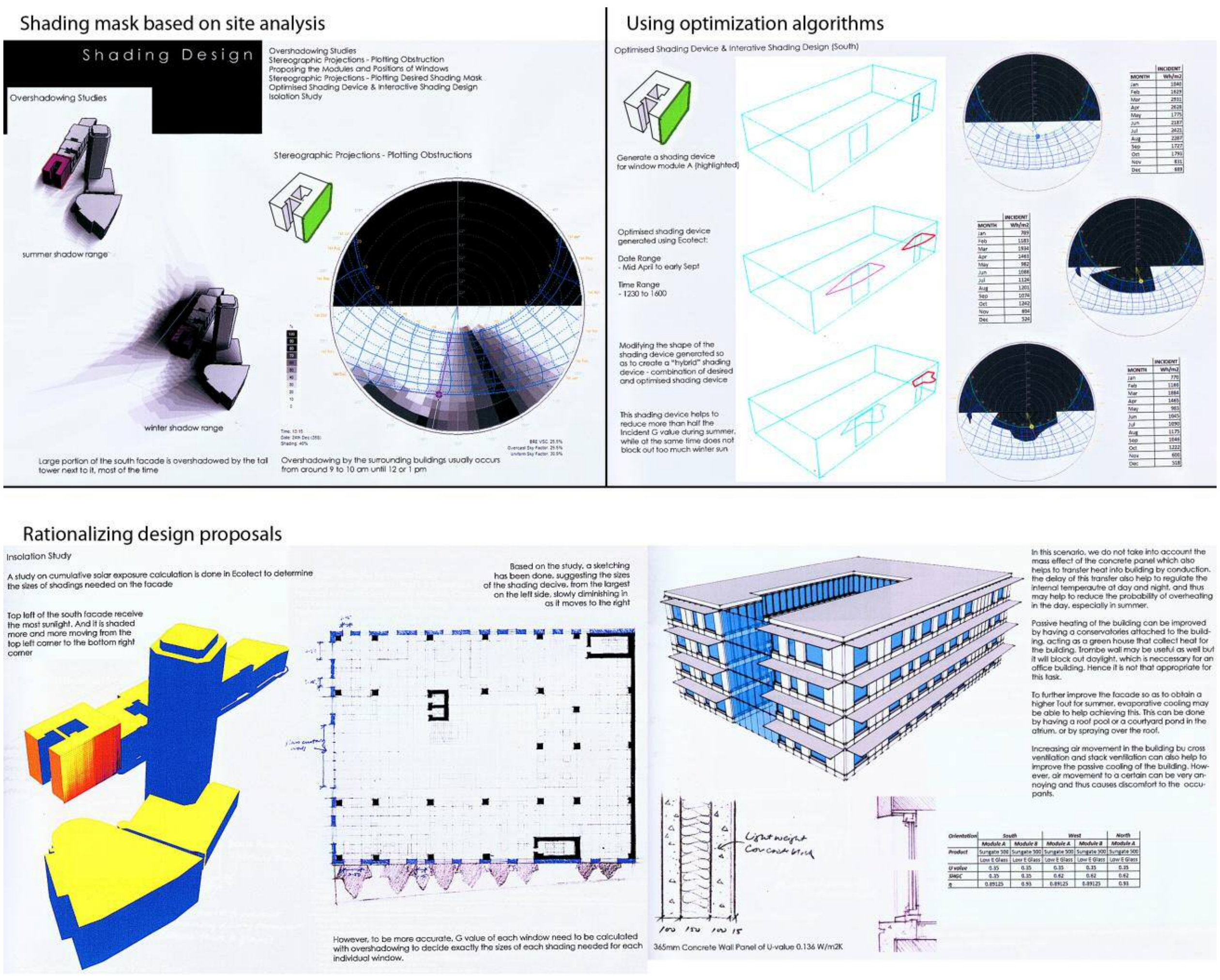


Figure 3 – Combination of strategies used to optimize solar performance of the building envelope.

In the second approach, the integration of customized layout requirements with building envelope happened as a follow up of set ups in which internal gains and fabric were treated completely disconnected from each other. Even though façade panels were investigated in isolation from customized layout needs, the latter determined the criteria for panel distributions along the facades. Figure 4 illustrates that sub-panels were assembled into panels distributed across the façade according to what would best meet the specific layout needs annotated in the plan. This coupling meant that the façade design ended up influenced by customized layout arrangements jeopardizing the initial flexibility of the project.

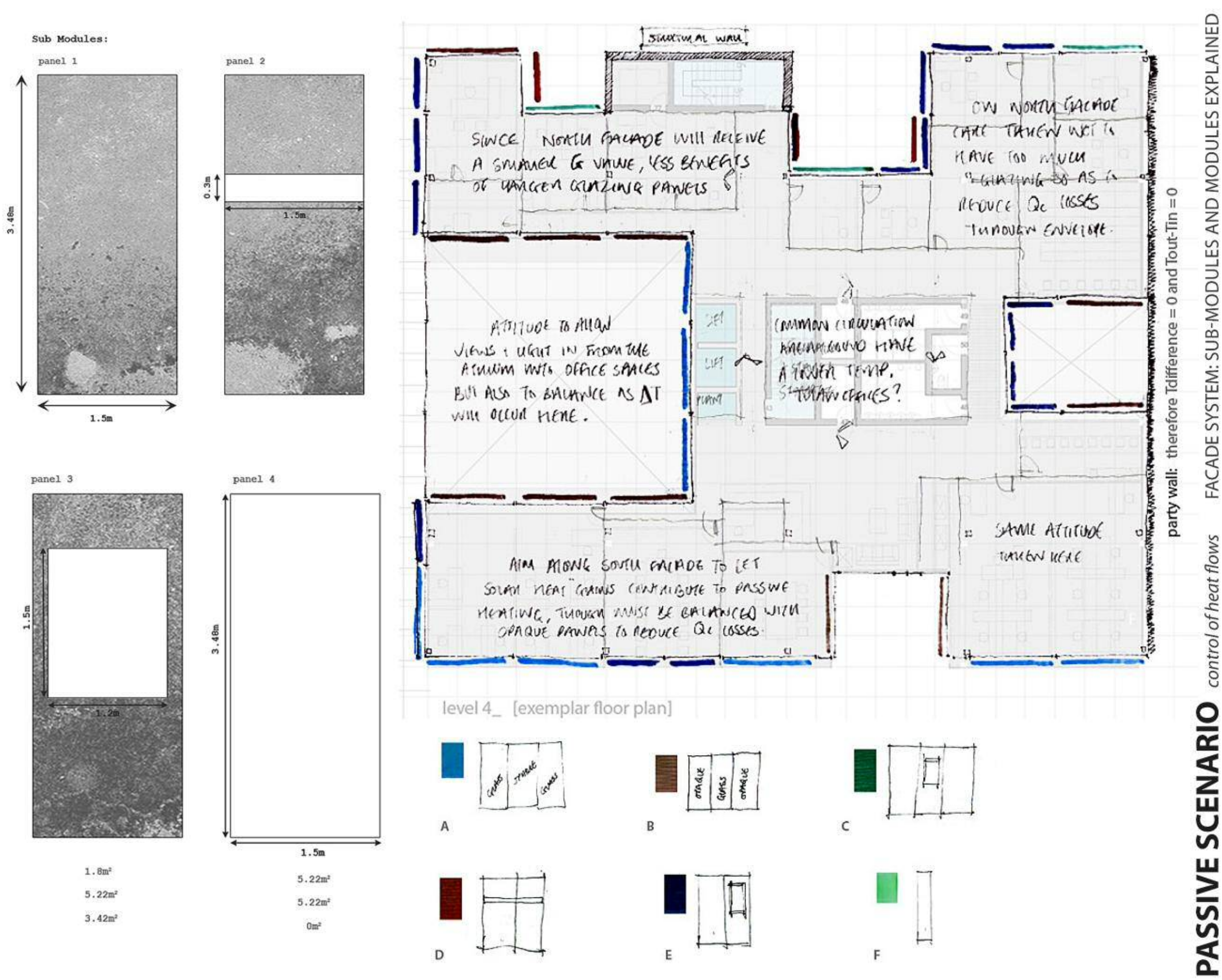


Figure 4 – Sub-panels assembled into panels distributed across the façade according to what would best meet the specific layout needs annotated in the plan.

In the third approach, internal gains were never made spatial as the layout was always considered speculative. Aware that this would somehow influence building performance, subject 6 decided to abstractly relate generic data for internal gains and ventilation requirements with façade panels through numerical indices. By doing this, all parameters affecting thermal performance would be directly connected to the façade elements providing a tangible access to the overall performance of the building.

The performance of each design proposal was assessed through simplified heat balance calculations. Subjects 1 and 6 calculated the performance of their typical office floor plan. Subjects 3 and 4 decided to assess only the performance of key rooms (the ones with the worst case scenario) whereas subject 5 calculated the performance of the perimeter rooms only. Subjects 1, 4, 5 and 6 aimed to discover which minimum and maximum outside temperatures would be passively offset by their design proposals. Subjects 2 and 3 preferred to initially assess heating and cooling loads to experiment with different ventilation rates and shading devices to respectively reduce heat losses in winter and heat gains in summer.

4.2.3 Assessing the changes used to optimize performance (Changes to optimize performance)

When analyzing design changes undertaken to optimize performance, mainly steps 5 to 8 in Table 3, the following four different approaches could be identified:

- Optimizing façade panels as function of customized layout requirements

- Optimizing panels distribution to improve performance
- Optimizing parameters that are panel independent but affect thermal performance (ventilation and shading)
- Characterizing façade panels based on overall thermal performance results.

The first approach is a follow up from intensive investigations of building envelope characteristics after careful considerations of the needs from customized internal layouts. The optimization of envelope solar performance enabled the subject to propose different façade panels for each orientation taking into consideration an optimum combination of window U-value and SHGC.

The second and third approaches are a follow up from coupling the proposed façade panels with a map of customized layout out requirements. The second approach illustrates an attempt to improve performance in a discrete / non-parametric way, i.e. subjects 2 and 3 decided to play with different panel distribution to achieve better internal conditions. As panels were optimized based on compliance with regulations or energy standards and distributed along the facades to provide an internal performance as best as possible, there was room to optimize only parameters that were panel independent such as ventilation and shading which characterized the third approach.

Having transformed the internal gains and ventilation requirements into façade panel indices, subject 6 proceeded to calculate the overall thermal performance of her proposal using a similar logic. She connected thermal performance results directly to the façade elements rather than to the volume of the internal environment. She could then focus in analyzing each façade orientation individually and propose local changes that could be easily re-assessed by simply recalculating the indices associated to the panels placed in each specific orientation under study. This strategy would enable her to have a direct access to the performance of the envelope without having always to reinterpret the consequences of her design 'moves' in the resultant performance of the interior environment.

5. Results and Discussion

From the cross-comparisons it was possible to identify different *Design Proposals*, different *Design Changes* and different types of *Performance Results* in each step. These are useful data to be further explored if simulation software developers want to improve current building thermal simulation tool features for building design decisions making.

Design Proposals essentially referred to ways of producing and controlling spatial information as well as ways of creating meaningful numerical variables which associate more directly the building skin with the building performance. *Design Changes* refer to data used in the set up and development of 'moves' aiming towards specific thermal performance targets. They were classified as parametric or non-parametric, changes associated to continuous variables and changes associated with discrete variables respectively. *Performance Results* refer to data that is tangible and meaningful to building designers. These data report which variables building designers used to assess their design proposals and if the assessment was of a qualitative or quantitative nature. *Design Proposals, Design Changes and Performance Results* from this study are summarized in Table 4 and commented on one by one in the following subsections.

Design Proposals	
Producing and controlling spatial information	**Connecting building skin with thermal performance - Generating indexes**
Internal gains and thermal results made spatial	Façade panels compliance with building regulations (U-values)
Iterative solar performance investigation	Indexes of partial performance (window heat balance, opaque panels heat losses, average panel performance)
Façade fragmented into modular panels	Indexes of relationships between the skin and the internal usage (internal gain and ventilation façade factors)

Design Changes	
Parametric changes	**Non-parametric changes**
Varying thermal insulation and thermal mass	Testing different panel compositions
Varying ventilation and shading device dimensions	Testing different panel distributions
Varying window related parameters (SHGC and U-value)	Testing different panel distributions within different façade modules Testing different types of windows and window shapes

Performance Results	
Tangible quantities & Quantitative analysis	**Intangible quantities & Qualitative analysis**
Minimum and maximum internal air temperatures without HVAC	Overall trends in heating and cooling demands
Frequency distribution of minimum and maximum internal air temperatures without HVAC across a year	Internal gains and ventilation heat losses to be offset by solar gains and conduction heat gains and losses
Resultant internal air temperature in a peak Summer day	

Table 4 – Summary of how performance results were used by building designers.

5.1. Design Proposals

An analysis of the design process of each different subject enables some common points to be generalized with regards to their design proposals. General conclusions referring to ways of producing and controlling spatial information are the following:

- Internal gains and thermal results were looked at spatially to understand the connection between the building envelope and its interior usage in terms of the set up and evaluation of the design 'moves' and performance targets.
- Investigations of solar performance of form were undertaken based on iterative processes comprising the use of optimization algorithms and solar site analysis bounded by passive performance targets and aesthetics and constructive considerations.
- The fragmentation of the façades into a series of modular panels improved the control over the design proposals and the resultant performances of the skin by providing a flexible and fast way of experimenting with different possibilities of panel compositions, panel assemblages and panel distributions along the facades.

Common conclusions referring to controlling the building skin and building performance through meaningful numerical variables are the following:

- Façade panel indices that indicate compliance with regulations and the meeting of energy standards (such as U-values for example) were extensively used and considered meaningful, especially in short cutting initial design decisions about the building envelope.
- Façade panel indices that indicate partial building thermal performance (opaque panel heat losses and window heat balances) were also extensively used and considered meaningful to provide qualitative trends, i.e. if thermal behavior was in equilibrium, losing or gaining heat under unfavorable conditions.
- Façade panel indices that indicate relationships with internal layout (internal gains façade factors and ventilation façade factors) were used by one of the subjects to facilitate the

direct control of design parameters without having always to reinterpret the consequences of each design 'move' in the resultant performance of the interior environment. They were a tangible indicator of the performance of the façade and could be easily re-assessed every time a different design 'move' was undertaken.

5.2. Design Changes

The data analysis also enables some common points to be generalized with regards to the set up and evaluation of design changes aiming towards specific thermal performance targets. The most common parametric changes, changes associated to continuous variables, were the following:

- Varying the thickness of insulation and mass layers of façade panels to achieve targeted U-values
- Varying ventilation (usage related parameter) and external shading device dimensions (non-modular façade element) to achieve targeted internal temperatures or to reduce hours of discomfort
- Varying window related parameters, U-value and SHGC, to achieve window heat balances near null improving passive winter and summer conditions.

The most common non-parametric changes, changes associated with discrete variables, were the following:

- Proposing different façade panel compositions to achieve targeted U-values
- Proposing different panel distribution along the facades according to different orientations and customized internal layouts to achieve a better overall building thermal performance

- Proposing different façade panel distributions within a set of larger façade modules according to different orientations and customized internal layouts to achieve a better overall building thermal performance
- Proposing different window shapes to achieve a heat balance near null improving winter and summer passive conditions.

Parametric and non-parametric changes overlap and might relate to the same building element. For instance, it is not uncommon to undertake parametric and non-parametric changes at the level of the modular façade panels when investigating respectively the variations in insulation layers together with different possibilities of panel compositions to achieve targeted U-values. Parametric and non-parametric changes can happen in any order or simultaneously meaning it is not uncommon to have non-parametric change following parametric change. Changes are completely controlled and defined by the designer and they display a mixture of systematic investigations with design experiments.

5.3. Performance Results

Design journals from individual design processes together with Table 3 also enable interesting points to be generalized with regards to how performance results were analyzed by these designers. *Results tend to be analyzed quantitatively through performance variables that are tangible and meaningful to building designers. These variables are mainly the air temperatures*. However, *unfamiliar and intangible quantities, such as heating and cooling demands, are not neglected but used as a qualitative indication of behavioral trends*. The following points illustrate the use of air temperatures in assessing building behavior quantitatively:

- Minimum and maximum outside air temperatures for which the building would still provide comfortable internal air temperatures without needing to be heated or cooled were the most important quantitative variables calculated. These temperatures would indicate thresholds of passive performance. Aiming for a minimum value possible in winter and a maximum value possible in summer would provide a reasonable performance indicator for the building.
- These temperatures were investigated for the building as a whole, for perimeter rooms, for specific rooms and for each façade orientation, depending on which approach to physics each subject decided to undertake when assessing the overall heat balance of the building.
- Some designers even plotted a frequency distribution of these temperatures throughout the whole year and compared this distribution with a frequency distribution of the outside air temperatures from the weather file they were using determining for how long the building would perform passively.

The following two points illustrates the use of energy demands in assessing behavior qualitatively:

- Qualitative analysis was undertaken at the level of heating and cooling demands aiming at indentifying overall trends: is the building mainly in equilibrium, losing or gaining heat from the outside? In these cases, internal air temperatures were assumed to be controlled to specific set points and the heating and cooling demands were calculated considering the system in place was 'unlimited and ideal' in terms of its capacity.
- In an isolated situation, one of the 75 designers decided to 'respond' with each part of the façade design to ventilation requirements and internal gains from a customized office

floor layout. Internal gains were added to ventilation gains and losses for each individual room and aimed to be offset by a combination of solar gains and conduction gains and losses provided by different distribution of façade panels. This strategy was quite clever and speeded up his calculations and design changes quite a lot.

6. Conclusions

From the aforementioned points and Table 4 it is possible to conclude the following:

- It is important that designers can work with and manipulate façade panels or any other kind of modular systems that includes assemblages and combinations of building construction information. This would enable designers to manipulate design variables in connection with their thermophysical properties preserving the strong and non-dissociable relationships between the skin design, construction and thermal performance (in which for instance changing a type of glass to improve a SHGC would generally mean changing also the U-value of it and potentially its aesthetic qualities). This connection is essential to create meaningful cause/effect relationships between building physics and building design.
- It is important for designers to visualize the results of customized internal layouts in terms of thermal loads distributed in a 2D plan. This can be used to assist in iterative proposals to design a façade that responds to the building usage which might be a desirable aim in the design of non-commercial buildings.
- ‘Intermediate’ calculation results, i.e. partial heat balances, can be a good resource to short cut thermal calculations and assist in design decisions. Examples from this study are:

(i) Window heat balances that can be used to short cut the façade design as they provide a pre-assessment of the potential benefits and drawbacks of panels with transparent components

(ii) Desired shading masks for each orientation can be used as guidance for windows placement and the design of shading devices

(iii) Optimized shading algorithms that can be used to provide useful boundary conditions to design shading devices

(iv) 'Internal gain façade factors' and 'ventilation façade factors' attributed to different façade modules or panels can be used to facilitate the direct control of design parameters without having always to reinterpret the consequences of each design 'move' in the resultant performance of the interior environment.

- Temperatures are a more useful quantitative output parameter for designers than thermal loads because it is not difficult to spot an error in the calculations when they are out of range. Moreover, as the designer's major aim is to make a building work passively, it seems more logical to target an outside air temperature to be passively offset by the building envelope and usage, than to work with heating and cooling loads.
- Thermal loads still provide good indications about building performance trends and therefore can still be useful outputs to building designers.

Apart from that, designers can work independently without needing the help of a consultant in the early design stages if they are trained in the following:

- Designing shading devices, calculating U-values, choosing adequate wall constructions for opaque and transparent materials and making decisions about types of glazing
- Doing a quick assessment of their projects using simplified steady state heat balance calculations to work out comfort conditions to be achieved in the indoor environment in passive situations as well as to estimate peak and monthly energy demands if an 'ideal' HVAC system is to be installed

Understanding that a lot can be done at the level of the building skin to improve thermal performance before introducing any kind of HVAC system to improve internal comfort conditions is important for designers to be confident in spending time investigating and experimenting with different passive scenarios. The knowledge that relates building construction to thermal simulation is essential in speeding up investigations that try to make design proposals work with regards to thermal performance as this is an efficient way to connect design ideas to the laws of physics.

Even though the experiment was undertaken under steady state conditions, it provided useful insights into how thermal building physics can be potentially integrated into parts of the building design process. Trained designers are better equipped to create integrated facades as well as to be creative about the design of the building skin as they can make sense of the concepts of building thermal physics throughout their design processes by integrating these concepts into their design 'moves' or actions.

This paper reinforces the understanding of what requirements are necessary for building designers to better integrate building thermal physics requirements throughout their building design process. It contributes to the body of knowledge in this field by showing the results of making designers design the potential ways to achieve integration. Trained designers provide useful insights into the following:

- How to make thermal results spatially relevant
- How to connect design decisions with building physics requirements and results by using façade modular systems and suggesting façade panel indices that are meaningful to them
- That their preferred way of using building physics to advise design decisions includes partial thermal results and iterative systems to explore changes associated to specific continuous and discrete façade design variables
- That they are happy and confident at working with temperatures to assess thresholds of passive performance

This information is seen as valuable to simulation software researchers who seek to improve current building thermal simulation tool features. Considerations for future research would include training designers further to refine their understanding about physics by introducing time related aspects of thermal performance such as, for instance, explorations in using thermal mass. As hand calculations would be difficult to explore in this case, this training could be undertaken through experiments with new simulation tools whose capabilities were derived from the aforementioned scenarios – thus creating an iterative and cyclical system for improving these tools.

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8. Appendix

Code	Theme: Sequence of Design Decisions
Optimizing Customized Layout	Mapping and optimization of internal gains for a proposed office layout
Comparing Layouts	Comparing internal gains of a customized layout with the internal gains of a speculative layout
Outlining Façade Design	Setting up criteria to be addressed in the design of the façade
Proposing Uni-modular Solution	Proposing a single façade module to be investigated considering a speculative internal office layout
Investigating Panel Assemblages	Investigating different opaque façade panel compositions and analyzing their U-value to choose the panel with the best performance
Designing Compliant Panels	Studying opaque parts of façade panels and calculating of their U-values to be compliant with Part L
Defining Façade Panels	Defining different façade panels - all with the same opaque composition
Studying Windows in Panels	Proposing façade panels with different window sizes
Investigating Panel Performances	Investigating overall panel performance considering the opaque and transparent portions of them as well as losses due to potential thermal bridges
Composing Panels into Modules	Composing the different panels created into a series of different façade modules
Distributing Panels	Outlining the distribution of panels along the façade as function of internal gains map
Selecting Key Rooms	Selecting 4 rooms to undertake a detailed design and thermal performance analysis
Designing Shading Masks	Investigating the solar radiation in each façade to develop desired shading masks to guide the windows placement and the design of shading devices
Designing Standards Panels	Selecting a opaque and transparent fabric compositions to set up façade panels that meet the Passive Haus Standards
Designing Shading Devices	Designing shading devices by aesthetically rationalizing shading elements using the Ecotect optimized shading device generator
Designing Panel Windows	Investigating incident solar radiation in each orientation + calculating of simplified window heat balances for the average coldest and hottest days for each months of the year
Designing Shading Iteratively	Designing shading devices iteratively for each façade orientation by combining desired shading masks with optimized shading results from Ecotect optimized generator
Designing Customized Windows	Investigating thoroughly the combinations of U-values and SHGC for the glazed parts of façade panels considering each façade orientation
Investigating Panels Passive Performance	Assessing the resultant performance of the internal space aiming to determine what would be the minimum and maximum temperatures that would be passively offset displaying results per unitary panels
Investigating Window Shapes	Experimenting different window shapes in unitary panels
Generating Layout Factors	Generating a façade panel 'internal layout' factor by dividing the internal gains of each typical office floor space by the total number of façade panels per floor.
Generating Ventilation Factors	Generating a façade panel 'ventilation' factor by dividing the overall ventilation requirement of each typical office floor space by the total number of façade panels per floor.
Investigating Passive Performances	Assessing the resultant performance of rooms aiming to determine what would be the minimum and maximum temperatures that would be passively offset by this design proposal
Investigating Energy Performances	Assessing the resultant performance of rooms aiming in the average coldest and hottest days of the year considering the internal temperature is controlled within the comfort range
Refining Facade Design	Refining the façade panels with 2 different window sizes considering 4 different glazing types depending on each façade orientation
Meeting Ventilation Standards	Using ventilation rates suggested by the passive haus standards
Optimizing Ventilation	Experimenting with different ventilation rates to reduce the heat losses in winter
Optimizing Façade Performance	Optimizing the distribution of panels along the façade as function of internal gains map together with the calculation of panel performances
Optimizing Façade Modules	Optimizing façade panel arrangements to better calibrate the amount of glazed and opaque portions in each of the rooms under investigation
Adding Mechanical Ventilation	Adding mechanical ventilation system to improve overall building performance
Adding Heat Recovery	Adding heat recovery system to improve overall building performance
Adding Passive Heating Louvers	Proposing louvers in the form of solar hot water pipes to reduce solar gains in Summer but not in Winter
Results - Good Summer Performance	Results show cooling is unlikely to be needed if ventilation is increased in summer
Results - Annual Passive Performance	Displaying results as frequency distribution of passive performance throughout a year
Results – Uni-modular Performance	Evaluating the pros and cons of using a single façade panel as well as a speculative layout in terms of their implications in passive performance
Results - Super Insulation	Evaluating the pros and cons of using super insulators in terms of Winter and Summer performances
Results - Complex Modules	Evaluating the pros and cons of using complex modular systems in terms of designing and assessing building performance
Results - Influence of Room Usage	Grouping results in terms of different types of room usages to show the influence of them in the building passive performance
Abandoning Uni-modular Solution	Exploring more façade panels and their relationships with a customized floor layout to refine the study

Table A 1 – Coding system used in the *Sequence of Decisions* theme

Code	Theme: Approaches to Physics
Internal Gains Oriented	Using internal gains analysis as a starting point
Envelope Oriented	Using building envelope proposal as a starting point
Gains & Envelope Oriented	Approaching internal gains and building envelope together
Internal Gains Deterministic	Using internal gains to determine what happens with the building envelope
Conductions Losses	Focus on manipulating envelope heat losses through conduction
Solar Gains	Focus on manipulating solar heat gains
Panel Orientation Heat Balances	Calculating simplified panel heat balances for each facade orientation
Internal Gains Panel Indices	Relating internal gains and façade panels through mathematical indices
Ventilation Panel Indices	Relating ventilation requirements and façade panels through mathematical indices
Window Heat Balances	Calculating simplified window heat balances (transmitted solar radiation - conductive heat losses)
Panel Heat Balances	Calculating simplified average panel heat balances (transmitted solar radiation - conductive heat losses)
Room Heat Balances	Calculating simplified room heat balances (coupling layout and envelope) to discover offsetting passive design temperatures
Space Heat Balance Indices	Calculating internal space heat balance indices related to offsetting passive design temperatures for each façade orientation
Room Loads	Calculating simplified room heating and cooling loads (coupling layout and envelope)
Non-Panel Perturbations	Perturbing parameters that do not relate to façade panels and assessing the results of these perturbations
Non-parametric Perturbations - Panels	Undertaking non-parametric perturbations by redistributing façade panels
Non-parametric Perturbations - Modules	Undertaking non-parametric perturbations by regrouping façade panels into larger façade modules and redistributing them
Non-Parametric Perturbations - Windows	Undertaking non-parametric perturbations by changing window shapes
Parametric Perturbations - Windows	Undertaking parametric perturbations in windows SHGC and U-values in each façade orientation
Parametric Perturbations - Panels	Undertaking parametric perturbations in panels U-values in each façade orientation
Important Parameters Identification	Identifying the most important parameters affecting building performance
Quantifying Insulation	Quantifying the effects of different amounts of insulation in the proposed façade panels
Quantifying heating and Cooling	Quantifying the heating and cooling needs based on worst case scenarios in the building
Ranking Room Performances	Ranking all the rooms in the building in terms of their usage and correspondent performance
HVAC Solution	Adding actively controlled devices to improve performance

Table A 2 – Coding system used in the *Approaches to Physics* theme

Code	Theme: Approaches to Design
Layout Oriented	Using a customized internal layout as a starting point
Skin Oriented	Using the building skin as a starting point
Layout & Skin Oriented	Thinking on the building skin together with the building layout in the beginning of the project
Code Compliance	Focusing on manipulating fabric assemblage for code compliance
Beyond Code Compliance	Focusing on manipulating fabric assemblage to go beyond code compliance
Meeting Standards	Focusing on manipulating fabric assemblage to meet energy efficiency standards
Form for Solar	Investigating façade form to optimize seasonal solar heat gains
Speculative Panel Indices	Creating façade panel indices based on speculative layout data (layout and ventilation)
Customized Panel Placement	Proposing the distribution of modular façade panels according to needs determined by a customized layout
Customized Window Shapes	Adjusting window shapes in façade panels according to customized layout needs
Average Window Performance	Verifying the thermal performance of windows contained in the proposed façade panels
Orientation Window Performance	Verifying the thermal performance of windows contained in each façade orientation
Average Panel Performance	Verifying the thermal performance of proposed façade panels
Key Rooms Performance	Verifying the thermal performance of 'key' rooms in the building
Perimeter Rooms Performance	Verifying the thermal performance of perimeter rooms in the building
All Rooms Performance	Verifying the thermal performance of all rooms in the building
Non-Panel Changes	Undertaking design changes unrelated to façade panels (ventilation rates and external shading devices)
Optimizing Windows	Optimizing the thermal performance of the windows contained in the proposed façade panels
Optimizing Window Shapes	Optimizing window shapes contained in the proposed façade panel to improve performance of the rooms
Optimizing Panel Distribution	Optimizing panel distribution to improve performance of the perimeter rooms
Optimizing Larger Modules	Studying optimal panel arrangements in the different large façade module compositions to improve performance of the perimeter rooms
Performance Panel Indices	Characterizing façade panels using indices that represent space heat balance requirements to be passively offset

Table A 3 – Coding system used in the *Approaches to Design* theme