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Tools for low-energy building design: an exploratory study of the design process in action

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ABSTRACT

Building designers face increased pressure to design low-energy buildings. Consequently, there is a growing interest in providing computational support for low-energy design via building performance simulation. This article presents an ethnographic study that investigated the design process of five low-energy buildings in England and Wales. The study was informed by design science literature and phenomenology of technology. The investigation analysed the methods deployed by designers to embed low-energy performance during design problem-solving. The findings illustrate how experience-based methods and simulation tools were used to inform low-energy building design. The work identified some of the challenges faced by designers to incorporate simulation methodologies during a routine design process. It illustrates the status of simulation tools as boundary objects that mediate the communication and negotiation between design team members. The work advocates considering the design problem-solving patterns and preferences in the development and improvement of support methods for low-energy design.

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Introduction

Despite the benefits of using building performance simulation being widely recognised, it is increasingly clear that there are difficulties in incorporating building performance simulation in routine design. Referring to the challenges in delivering zero carbon buildings, the UK Zero Carbon Hub suggests that ‘... the performance issues are much more concerned with the processes and cultures within the industry than with the model that is used to predict carbon emissions’ (Zero Carbon Hub, 2010).

Simulation techniques have been widely documented, although their use is unlikely to be widespread throughout the design process; so the potential use of simulation as a design-aid remains latent (Augenbroe, 2004; Clarke, Johnstone, Kelly, Strachan, & Tuohy, 2008; De Wilde, Augenbroe, & Van Der Voorden, 2002). Mahdavi and Suter (1998) argue that the use of building performance simulation may be inhibited by routine design and construction practices. The challenges in the incorporation of building performance simulation in the design process suggest a gap in the practical use of simulation by designers (MacDonald, McElroy, Hand, & Clarke, 2005). Incorporating building performance simulation in the design process is challenging because the design thinking and problem-solving paradigms of designers and simulationists differ in terms of knowledge and praxis (Bleil de Souza, 2012). Several studies have advocated for further research with designers in the workplace to gain a better understanding of their design problem-solving activities. Such

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understanding is likely to inform the development of tools (De Wilde & Van Der Voorden, 2004; Mahdavi, 2011); to identify how tools fit in the process and its data flows (Augenbroe & Winkelmann, 1991); and to identify the relationship between the characteristics of the design tools and the nature of the design process (Mahdavi & Suter, 1998). There is a growing interest in considering the practical use of simulation by the building industry, for example, in terms of: communication and visualisation of results (Bleil de Souza & Tucker, 2015; Hamza & DeWilde, 2014); architects' perspectives as potential users of building performance simulation (Alsaadani & Bleil de Souza, 2012); the role of simulation in the communication between architects and simulationists (Reinhart, Dogan, Ibarra, & Samuelson, 2012), to cite few. However, the use of building performance simulation by designers during real-time design remains underexplored.

Design literature and phenomenological accounts of technology offer insights into how designers engage in problem-solving and invoke the tools during design development. This work applied design science and phenomenology propositions to investigate the methods used for low-energy building design, with focus on building performance simulation. The study included a variety of methods that contributed to low-energy design, from experiential knowledge to simulation tools. The relevance of the topic is justified by the urgency to reduce the carbon emissions in the building sector. Existing approaches to offer support for low-energy design tend to overemphasise the provision of computational support for design problem-solving. Thus, these perspectives tend to assume the straightforward application of robust simulation techniques by designers while ignoring the designers' problem-solving preferences and the context of the design process. This work investigated how tools and methods for low-energy building design were used during the design process, based on the observations of five case studies. The article starts by discussing literature on design problem-solving and phenomenological approaches that address the relationship between tools and their context of use. The next section outlines the methodology. Then the field data are presented, followed by the discussion and conclusions.

Design problem-solving

Design science acknowledges that architecture design problem-solving is exploratory. Rowe (1987) suggests that the design process has an 'episodic structure' due to the ill-defined nature of design problems. Designers are unlikely to define the problems rigorously because design is exploratory (Cross, 2001). Schön (1983) argues that architecture designers engage in reflective conversations with the design problems. The dialogue leads to an incremental understanding, helping to reframe the constraints and the design goals as the solutions are envisaged. The design conversations by architects tend to look for a general understanding of the problem in order to explore acceptable solutions. Architects are prone to propose the design solutions on the basis of experiential knowledge (Cross, 2007; Lawson, 2004; Schön, 1983) and naive representations (Akin, 2001). Lawson (1997) argues that 'designers need to have some feel for meaning behind the numbers rather than precise methods to calculate them ... strategic decision rather than careful calculation'. A key characteristic of architecture problem-solving that differs from the traditional rational methodology of science (Simon, 1969) is that architecture designers adopt an explorative perspective to relate the problem and the solution in an open-ended semi-structured enquiry.

In the context of design team work, design is considered a process of negotiation where defined goals are rarely fixed at the beginning of the problem-solving activities. Bucciarelli (1994), for example, compares the design process to the negotiation of worldviews between design team members. The design negotiation facilitates the construction of a common understanding and helps different design team members to reach agreements. Similarly, Cross (1982, 1999) argues that design has a social dimension besides being a technical process and a cognitive activity.

In summary, design literature suggests that architecture design problem-solving has some key characteristics: (1) architects are unlikely to rigorously frame the design problem; (2) architecture designers opt for an intuitive understanding of the design problem that enables flexibility in

finding the solution and (3) in the context of design team work, the design process has a social dimension that facilitates the construction of collective understanding and the negotiation of the solution with the input of different design team members. Those characteristics define the context where the design support tools, including simulation tools, are introduced.

Tools in the context of use

Phenomenological approaches to the human-technology relation draw attention to aspects that affect the use of tools. The environmental psychologist James Gibson introduces the concept of affordance to refer to the potential of an object to enable action (Gibson, 1979). The affordances of a tool are relative to its inherent characteristics and to the users' perception about the potential of the tool. Tools provide a framework for action (intended use defined by the developer); however, the use of a tool is also defined by the intentions and preferences of the users (Ihde, 2004). Ihde's argument does not negate the technical properties of a tool; it simply highlights that the properties of a tool are part of the relativity of the human-technology relationship. Technologies become part of the pre-existing network of human interactions; therefore, tool developers need to understand the complexities of human thinking to avoid erroneous interpretations about the role of computers in the context of human practice (Winograd & Flores, 1987). In architectural and engineering research, a number of studies have considered the relationship between users and technology, suggesting that tools could be potentially disruptive. For example, Berente, Baxter, and Lyytinen (2010) point out that new tools are introduced to old systems and routines, leading to new configurations of practice while Coyne, Park, and Wiszniewski (2002) use the 'evolutionary metaphor' to highlight the dynamic nature of tools. Chastain, Kalay, and Peri (2002) argue that the properties of tools are inferred from the tool developers' assumptions of praxis so when a new technology is adopted, a dysfunctional relationship might emerge between tools and tasks. Tool developers embed assumptions and constraints about the intended users which could affect their use in practice (Harty, 2008). On the other side, in the context of team work, Bucciarelli (1994) argues that tools are part of the worldview negotiation between the members of groups, influencing communication and learning. Boundary objects mediate the interaction in multidisciplinary teams, bridging the communication between the team members (Carlile, 2002). Boundary objects allow different communities to work together (Wenger, 1998). Boundary objects are multidimensional and become part of the negotiation in multidisciplinary teams. In a similar vein, Brown and Duguid (1994) suggest that 'different communities use objects differently'. Suchman (1987) argues that unique circumstances and situated practices affect the use of objects. The authors, therefore, consider that the tools for low-energy design are in essence objects that become part of the context, mediating the communication and negotiation between the design team members.

In summary, two main propositions are inferred from the literature: (1) the nature of design problem-solving (preference for intuitive understanding, worldview negotiation between design team members) and (2) the relativity of the user-technology relationship due to pre-existing practices – tools are not used in a vacuum; they are incorporated in a complex context. Different design team members may hold distinctive perceptions and expectations about the process and the role and contribution of different tools for low-energy design.

Methodology

This study adopted ethnographic methods to investigate the design process in action. Ethnographic research enables the study of experience and behaviours within the context of practice (Angrosino, 2007; Bryman, 2008; Gobo, 2008; Silverman, 2005). It allows the detailed exploration of action, meanings and processes that develop over time within their setting of occurrence (Delamont, 2012; Hammersley & Atkinson, 1995). Ethnography has been widely applied on the study of design and construction processes (Ball & Ormerod, 2000; Bucciarelli, 1988, 1994; Button, 2000; Lloyd &

Deasley, 1998; Pink, Tutt, Dainty, & Gibb, 2010). It comprises a combination of methods (observation, interviews and document analysis) applicable to exploratory studies to identify what people engaged in practice do. In this study, we have investigated the routine design process, looking at the designers' acceptance and barriers to the integration of building performance simulation.

The main research participants were architects from four large architecture firms with experience in sustainable design.¹ Large sustainable architectural firms were chosen due to their prior experience and interest in low-energy design and their willingness to participate in the research. In other words, the inclusion of sustainable firms with some different degrees of experience was intended to give an indication of different degrees of 'robust application' of processes, best practices and methods for low-energy design, including building simulation. Under the umbrella of 'sustainable architecture firms', firms with different profiles were recruited to enable a variety of observations about the design process and the ways that designers inform the low-energy building design. The main differences between the architecture firms were the types of partnership arrangements between the architects and other design team members, in-house expertise and the type of learning organisation as per Communities of Practice principles.² Table 1 outlines the sampling criteria of the architecture firms and Table 2 illustrates their profile.

Other design team members such as building services engineers, BREEAM assessors, energy consultants and simulationists were included in the research so as to consider the design process in relation to the wider design team. Five case studies of new non-domestic low-energy buildings located in England and Wales were investigated during conceptual and/or detailed design (Table 3). The energy performance targets of the case studies are summarised in Table 4. The Royal Institute of British Architects (RIBA) Plan of Work (RIBA, 2013) has been used as a reference to the design process timeline. For the purposes of this work, conceptual design corresponds to RIBA Workstages 0–3 (strategic definition to developed design) and detailed design corresponds to RIBA Workstages 4 and 5 (technical design and construction). RIBA Workstages 6 'Handover and close out' and 7 'In use' were not included in the study.






Table 1. Sampling criteria parameters.

Criterion	Description		Categories per criterion
Firm's identity in relation to sustainable and low-energy design	Sustainable experience and credentials advertised as main expertise of the firm	Strong	Experience in sustainability and low-energy design, variety of awards and recognitions, portfolio of projects advertised with emphasis on their sustainability credentials
		Medium	Some sustainability experience, mixed portfolio of projects, some highlighting sustainable credentials, others emphasising on other types of design expertise that is, renovation, urban planning
In-house expertise	Dedicated team of energy or environmental specialists in the firm as indicator of existing expertise and knowledge in sustainability and low-energy design	Yes/no	
Type of learning organisation	Denotes the existing arrangements in the company to nurture and disseminate the knowledge that circulates among employees as per definition of Communities of Practice (Wenger, McDermontt, & Snyder, 2002, pp. 65–112)	Strong	Existing methods for knowledge management encourage social practices to foster knowledge and learning at organisational level. Formal methods help to disseminate information that is, seminars, notice boards, intranet blogs, discussion groups across offices
		Medium	Incipient or novel methods are in the process of being implemented to disseminate knowledge and learning. Few mechanisms in place to disseminate information about sustainability and low-energy design

Table 2. Profile of architecture firms as per sampling criteria.

Arch. firm	Identity as sustainable firm	Energy in-house expertise	Learning organisation	Profile of the company	Awards
1	Strong	Yes	Strong	Architecture firm with in-house expertise in engineering, sustainability, lighting, acoustics	Sustainable designer/consultant of the year, sustainable building of the year, several RIBA awards, CIBSE Building performance awards
2	Strong	Yes	Strong	Architecture firm with in-house expertise in landscape, urban design, interior and environmental design	CEW 2010 Project of the year, awards and shortlistings, nominations for sustainable architect, champion of the year
3	Strong	No	Medium	Architectural firm with in-house expertise in town planning, urban design and interior design	Shortlisted FX awards, BCSE
4	Medium	No	Medium	Architectural firm with in-house expertise in urban, landscape, interior design and conservation work	Shortlisted and winner of AJ 100 awards, Building awards

Table 3. Case studies: stage investigated, data collection timeline and description of team.

	Conceptual design (RIBA Workstages 0–3)	Detailed design (RIBA Workstages 4–5)	Duration of data collection (months)	Arch. firm	Partnership Arch. and design team members
Case 1			21	1	Building services engineer, acoustics and lighting consultant in-house
Case 2			12	2	No partnership with consultants
Case 3 ^a			14	3	Previous work with building services engineer and sustainability consultants
Case 4			13		No partnership with consultants
Case 5 ^a			13	4	Previous work with building services engineer and sustainability consultants

^aCase Studies 3 and 5 were studied in conceptual design only.

■ Stages studied in the investigation.

Table 4. Design targets per case study.

Case study	1	2	3	4	5
Building type	Educational	Educational	Educational	Educational	Educational
Location	South Wales	England	South Wales	England	South Wales
EPC	40	31	19	40	40
% LZC tech	20	10	30	15	15
BREEAM Credits	81.70	71.85	89.00	64.00	73.00
BREEAM Rating	Excellent	Excellent	Outstanding	V Good	Excellent
U-value roof (W/m ² K)	0.18	0.15	0.18	0.15	0.15
U-value walls (W/m ² K)	0.26	0.15	0.26	0.18	0.16
U-value glazing (W/m ² K)	1.60	1.20	1.60	1.60	1.60
U-value floors (W/m ² K)	0.32		0.19	0.21	
Airtightness (m ³ /m ² @50Pa)	1	3	3	5	5

Table 5. Data collection methods and aspects investigated.

Method	Aspects investigated
Interviews	Self-accounts of practices to design low-energy buildings, methods to design low-energy buildings. Semi-structured and opportunistic ethnographic interviews throughout the course of the data collection period. Perceptions about the role of simulation tools and other methods to inform the low-energy design development, challenges and benefits in using simulation in the process
Non-participant observation	Analysis of the design process in action and the methods used by designers for as-designed performance estimations. The activities included shadowing of work, observation of design and delivery team meetings
Document analysis	Analysis of the information produced during the design process, with focus on methods to inform energy performance and energy performance targets. The data sources included standards, guidance, project deliverables, drawings, reports, energy studies, design and access statements, BREEAM documentation, sketches, tender documents, Part L documentation, interim deliverables, companies' databases

The data collection was conducted for 12–21 months per architecture firm, with approximately 25 visits per firm. The data collection methods comprised non-participant observation (shadowing architects' work, observation of design and delivery team meetings), semi-structured and opportunistic interviews and document analysis. Table 5 summarises the data collection methods and the aspects explored on the investigation.

A thematic coding approach was adopted using a qualitative software package, *Atlas t.i.* (2010) to sort, code and analyse the field data. Design literature and phenomenology of technology informed the development of the theoretical framework and the data analysis. This article reports the findings related to two main themes: (1) the methods used by designers to inform low-energy design, including building performance simulation, and (2) the integration of simulation tools during the design process in action.

Field data: methods for low-energy design

It has been inferred from the field studies that the architects engaged in problem-solving used rules of thumb and experiential knowledge³ when making energy performance appraisals, before invoking simulation tools.

Experiential knowledge

In all of the case studies, rules of thumb and experience-based knowledge were used pervasively by architects and building services engineers to inform the low-energy targets, the selection of low-energy strategies and the as-designed performance estimations. The architects in the case studies did not use any quantification method to estimate the energy performance. The architects invoked experience-based advice from the building services engineers.

The building energy services used rules of thumb and in-house simplified calculation methods for quick energy performance estimations during conceptual design. The performance estimation in conceptual design did not explicitly seek an accurate result but rather an indication of the potential performance to advance the design development:

BUILDING SERVICES ENGINEER3: We sort of start talking about the low carbon strategies quite early with the architects without any calculation so it is quite experience-based in a way. We look at the orientation, the form, the massing, the things that you could do without the calculations, the things that you know that will work. It is done in that way, it is more qualitative than quantitative ...

Rules of thumb and experiential knowledge were reported to inform the selection of passive design strategies according to site features (weather analysis); to estimate heating loads, power usage, ventilation rates, airtightness; to consider spatial requirements for equipment, systems and low zero carbon technologies; to select design strategies related to natural ventilation and daylighting (i.e.

window/wall/floor ratio); to inform the specification and sizing of mechanical ventilation ducts; to define the thermal performance of the envelope (U-values); to estimate the capital cost of low zero carbon technologies and operational savings during occupation; and to anticipate the users' practices that have a bearing on the energy consumption during occupation.

Use of building performance simulation

The simulation tools were likely to be invoked in preparation to planning application and building control. Planning application was submitted around RIBA Workstage 3. The building control documents were generally submitted around RIBA Workstages 4 and 5.

In the light of planning application, design teams used simulation tools to estimate the energy performance in quantifiable terms (i.e. EPC, Kg of CO₂), with a level of certainty that rules of thumb and experiential knowledge were not perceived to afford:

BUILDING SERVICES ENGINEER4: Simulation results have usually come after planning. If they are available before, we [the design team] could identify rooms that overheat and so on ... we could make arrangements before planning submission. It's positive because the team can assess things; check if it's feasible to achieve what's offered by the design. Once the simulation results have been issued, we'll be in a position to know what the [energy performance] targets are ...

The proprietary simulation tools observed in the case studies were Integrated Environmental Solutions (IES) and Thermal Analysis Simulation Software (TAS). IES was invoked to analyse the geometry of the building, orientation, shading and ventilation strategies in Case Studies 1 and 3 from RIBA Workstage 2. The simulation tool was used to inform the design development and to produce evidence for planning application and for building control. Case Study 1 used the simulation results to evaluate the energy implications of value engineering changes proposed in the light of construction. The design team in Case Study 5 used TAS after the decisions about geometry and orientation had been made, before planning application (RIBA Workstage 3). Case Study 2 used SBEM⁴ to verify the compliance to energy standards prior to planning submission (RIBA Workstage 3) and IES for building control purposes (RIBA Workstage 5). However, no simulation tool was used continuously in Case Study 2 to inform the design development. Seemingly, compliance reasons triggered the use of simulation in Case Study 2. Table 6 presents the tools observed in the case studies.

Despite the different tools used by designers to quantify energy performance, there were some commonalities in the way that experiential knowledge and simulation tools were invoked. A simplified schema⁵ has been used to illustrate the key features observed in the field (Table 7). In RIBA Workstage 2, the designers predominantly sought a general understanding of the relationship between building and site and the potential of different low-energy strategies to meet or exceed the energy benchmarks outlined by regulatory standards. The intuitive understanding of performance and previous experience helped designers to understand the potential performance of the building. Around planning application (RIBA Workstages 3–4), the quantitative analysis of energy performance indicators was estimated by simulation tools. The performance evaluation focused on achieving

Table 6. Tools for low-energy design observed in the case studies: purpose (what for) and when in the process (as per RIBA Workstages).

What for	Which tool and when				
	CS 1	CS 2	CS 3 ^a	CS 4 ^b	CS 5 ^a
To evaluate orientation, passive design	IES, RIBA 2	Ecotect, RIBA 2	Ecotect, RIBA 2		
To compare façade design options	IES, RIBA 3		IES, RIBA 2-3		
To quantify performance for planning application	IES, RIBA 3	SBEM, RIBA 3	IES, RIBA 3		TAS, RIBA 3
To assess changes for value engineering	IES, RIBA 4			IES, RIBA 4	
To quantify performance for building control	IES, RIBA 4	IES, RIBA 5		IES, RIBA 4-5	

^aCase Studies 3 and 5 were analysed until RIBA Workstage 3 only.

^bCase Study 4 was analysed from RIBA Workstage 4.

Table 7. Schema of the performance understanding throughout the design process.

	Conceptual design (RIBA Workstages 0–2)	Transition between conceptual and detailed design (RIBA Workstages 3–4)	Detailed design in the light of construction work (RIBA Workstages 4–5)
Purpose of the performance estimation	Understanding of the relation-building site, benchmarking against statutory requirements and use of previous experience	Performance analysis switches from intuitive understanding to quantification by calculation tools. The initial performance estimation focuses on compliance by the end of conceptual design	Analysis seeking an acceptable compromise between the energy aspirations and cost, site concerns, workmanship, tolerances
Preference in terms of tools	Intuitive understanding, experiential knowledge, heuristics and in-house simplified tools for quick estimation	Intuitive understanding and calculation tools	Experiential knowledge. Simulation is invoked for compliance but unlikely to be used for the analysis of the impact of design changes on site on the expected performance
Criteria analysed	Passive strategies, potential of low zero carbon technologies, climate analysis	Implications of the performance on the project drivers: cost, payback cost of low zero carbon technologies, maintenance, use, minimum regulatory requirements (benchmarks)	Evaluation of energy performance intentions in the light of cost and time onsite
Indicators commonly used	Architects focus on the U-values and the mechanical engineers assess the heat gain, thermal conditions, overheating risk, feasibility of low zero carbon technologies	Energy consumption per use (heating, cooling, lighting, etc.), indoor thermal conditions, heat gains, temperature variations, thermal comfort indexes, overheating risk, TER/BER, percentage of low zero carbon energy supply, cost/savings during operation	Compliance driven, production of Part L evidence Pass/fail – Part L and BREEAM (policy requirements)
How the indicators are presented	Visual outputs linked to numerical data, diagrams, solar diagram, graphical analysis of the sun path	Time-series tables, graphs, EPC report, BRUKL document (Part L 5 criteria)	Part L report, EPC
Backdrops	Uncertainty in the assumptions that are based on heuristics; misunderstanding of performance implications when the output of the analysis is a graphic representation ('pretty pictures')	Computational effort, domain expertise needed, difficulties in relating the results to parameters for design improvement, simulation distrust and lack of integration, compromise between accuracy and quick estimation of performance of different design strategies	As-designed model/estimation is not informed by performance achieved during construction. The experience gained on site is unlikely to inform the design assumptions and modelling scenarios that is, safety factors, tolerances on site, etc.

specific energy performance targets and compared the as-designed performance and the regulatory targets. From RIBA Workstage 4 'Technical Design', the analysis sought to find an acceptable compromise between the energy performance metrics intended by the design team and other project requirements: cost, buildability aspects (workmanship on site, construction tolerances).

Simulation in routine building design-perceived challenges

Timing the use of simulation

In general terms, the research participants perceived that it was difficult to identify the time to start using simulation tools in the design process:

BUILDING SERVICES ENGINEER1: There is certainly no wish to trying modelling [the building] before it is quite reasonably fixed, but of course, the point at which that will happen is a bit transient; it is a bit fluid. If you model it too early and there are still changes to the walls and the glazing, we have to do a big update. If the design changes massively, then we have to scrap the whole model and start it again. Building up [a simulation model] for the ground up and populating all the information ... that's a hell of a process.

The Building Services Engineer in Case Study 1 reported that IES was invoked from RIBA Workstage 2 'Conceptual design', earlier in the design process than compared to previous projects. In the past, IES had been invoked around the development of technical design or later (from RIBA Workstage 4), after the general design decisions had been made.

Simulation results are theoretical

The research participants perceived that the simulation results were theoretical. Despite the simulation software enabling the quantification of performance, the as-designed estimations were unlikely to be related to as-built and in-use factors. This undermined the credibility of the simulation results to indicate the potential building performance:

ARCHITECT4: The building services engineering did the calculation and produced the figures. The key point that they made is that those figures were academic. They were just numbers. We'll never reach the [energy] target; it's some kind of false target really. It's uncontrollable, because you can't control people. You can control lights to a degree; you can obviously control heating and ventilation. But on the modeling we've managed to reach the target and that's completely right if no one is going to switch a plug.

The architect in Case Study 1 recognised that the as-designed simulation scenarios could be improved based on the feedback from the operational phase. The feedback could help to inform the assumptions embedded in simulation models and increase the designers' knowledge about building performance:

ARCHITECT1: We need the feedback [from the building occupants] ... We need to get that information back to design. On a computer model, this amazing ventilation system [is supposed to] work this way but in reality it did not work ... It's easy for the designers to stop at the drawing, they have the EPC, but we need to go back and see how it works ...

Given the perception that simulation results were 'theoretical', the designers in Case Studies 1 and 4 used experiential knowledge to inform the modelling scenarios embedded in simulation models. The energy performance metrics obtained by simulation were related to experiential knowledge on as-built and in-use factors. For example, with regards to in-use performance, the architects and the building services engineers in Case Studies 1 and 4 worked with the users and clients to identify the occupation patterns and preferences so as to customise the occupation profiles in the simulation models. In Case Study 1 the occupancy patterns were identified in workshops with the users. The design team had discussions with the client throughout the design process to outline the prospective operation of the building. Questionnaires were included in the reports during the design development for the client to clarify the potential occupancy patterns. The questionnaires in Case Study 1 addressed the hours of use throughout the year; schedule of use of classrooms, cafeteria and

kitchen; users' control of radiators and windows; set point adjustments and building services; schedule of use of louvers; manual overrides of automatic lighting, heating and ventilation systems with automatic BMS reset; use of seasonal commissioning; IT equipment strategy for classrooms and offices. In Case Study 4, the simulation model used the CIBSE typical practice guidance and monitored data⁶ of the consumption of appliances, electricity and gas consumption to customise the occupation profiles.

Integration of simulation in the context of design

This section illustrates how the simulation tools were used in the design process, based on the observations of Case Studies 1 and 2. This section brings attention to the role of the simulation tools as boundary objects that become part of the 'worldview negotiation' and knowledge exchange between design team members. The characteristics of the context are highlighted as a preamble to explain the differences observed in the use of simulation. Case Study 1 was developed by a design team with architects and building services engineers based in the same architecture firm. The client's brief encouraged the application of sustainability principles and outlined energy performance aspirations for the building. Sustainability and energy performance aspect were drivers of the design process. By contrast, Case Study 2 was developed by a design team with architects and building services based in different companies. The main client's requirement was to design and construct the building in 15 months. The reduction of capital cost and speed of construction were main drivers of the context of the design process. The characteristics of the design are summarised in Table 8.

Case Study 1: Simulation, a support tool for the design team

In Case Study 1, IES was invoked from RIBA Workstage 2 'Concept design' in combination with rules of thumb and experiential knowledge by the building services engineer. The design development tasks led by the architect were continuously informed by the simulation results. The same team of building

Table 8. Characteristics of the design context in Case Studies 1 and 2.

Characteristics	Case Study 1	Case Study 2
Team arrangement	Same architects and building services engineers worked as the core design team during the whole design process. All the simulation models and energy advice were produced by the same building services engineers during the design process	Same architects worked with the same building services engineer for the entire design process. However, an in-house environmental consultant advised the architects about passive and low-energy design strategies until RIBA 2. An external energy consultant was appointed to develop the detailed simulation model for building control in RIBA 5
Explicit client requirements	Client's brief outlines of the sustainability and energy targets. Targets are set to exceed the minimum energy standards	Client's brief refers to energy and sustainability aspirations; however, there is no explicit aspiration to exceed the minimum energy standards
Project drivers	Energy performance and sustainability	Capital cost reduction and speed of construction on site
Project length	Approximately 36 months for project completion (including design stage)	Approximately 15 months for project completion (including design stage)
Knowledge sharing and communication	Knowledge-sharing mechanisms in place, immediate exchange of information, quick feedback for ongoing design development, informal meetings and discussions to exchange advice- dialogue facilitated by architects and building services engineers working in the same firm	Fragmented communication; formal design team meetings are the main forum to exchange advice and feedback – compressed design process timeline urges the design team to quickly progress the design development to meet the project completion deadline, limited time to consolidate the partnership between different design team members
Negotiation dynamics	Collaboration	Conflict

Table 9. Simulation tools in the design process in Case Studies 1 and 2.

		Case Study 1	Case Study 2
Early design decisions	What tool	In-house U-value calculator and IES	Ecotect
	Who deployed it	Building services engineer (design team member)	In-house environmental consultant
	When	RIBA 2	RIBA 2
	What for	Passive design and low-energy strategies	Passive design and low-energy strategies
In the light of planning application	What tool	IES	SBEM
	Who deployed it	Building services engineer (design team member)	Building services engineer (design team member)
	When	RIBA 2-3	RIBA 3
	What for	Passive design, low-energy strategies and evidence for planning application	Evidence for planning application
In the light of building control (Part L)	What tool	IES	IES
	Who deployed it	Building services engineer	External energy consultant (not a design team member)
	When	RIBA 4	RIBA 5
	What for	Evidence for building control, to evaluate the energy implications of value engineering proposals	Evidence for building control

services engineers produced the simulation model that informed the design decisions, calculated the EPC for planning application submission (RIBA Workstage 3) and estimated the building performance for building control (around RIBA Workstages 4–5). The simulation tools used in the process are outlined in Table 9. During different stages of the design process, the architect and the building services engineer worked together and engaged in co-design and knowledge-sharing activities, supported by the simulation results. During co-design sessions, the low-energy design strategies were discussed collectively by the design team members and decisions were supported by simulation results. The conversations between different design team members informed the as-designed modelling assumptions embedded in the simulation model. Co-design activities also contributed to the consideration of the low-energy design strategies in relation to other project requirements such as acoustics, lighting, fire safety, structural safety, cost, buildability and users' preferences:

ARCHITECT1: We have quite thorough investigations within our design team. The building services engineer is doing the thermal studies to make sure that we are providing enough ventilation and the ventilation strategies are coordinated with the lighting and acoustic teams as well ... When we talk to them, we have awareness and; as we develop the details, it becomes more precise, that's where our conversations and coordination become more intense ... but it is a two-way dialogue: the building services engineer will say something and we will challenge it: I'm sure you could come up with a way of doing this ...

It is not surprising that designers have co-design sessions during problem-solving. However, a few observations should be highlighted in Case Study 1. The simulation results informed the design development and were used as evidence for compliance. The simulation results supported the design conversations between the energy experts and the rest of the design team. The design team members provided experiential knowledge about as-built and in-use performance to inform the simulation modelling scenarios. The input from non-energy experts was valued to inform the simulation scenarios and the selection of low-energy design strategies. The simulation modelling scenarios were understood by the non-energy specialists and the simulation results were trusted by the design team. The simulation tool, as a boundary object linked to specific energy expertise, contributed to the worldview negotiation (agreements between design team members and collective problem-solving) and helped to share knowledge about performance (conversations about energy performance in the light of the wider project requirements).

Case Study 2: Simulation, a tool that aggravates conflicts

In Case Study 2, Ecotect was invoked for site analysis and evaluation of passive design strategies in RIBA Workstage 2. As the design process progressed, the design decisions were based on rules of thumb and experiential knowledge. SBEM was used by the building services engineer to estimate the energy performance for planning application submission around RIBA Workstage 3. The SBEM results suggested that the energy performance of the building was likely to meet criterion 1 of Part L, the calculated CO₂ emission rate of the building. Around RIBA Workstage 5, a dynamic thermal model in IES was commissioned to an external energy consultant to analyse the risk of overheating. The simulation model followed the climate change provisions outlined by CIBSE Technical Memoranda 36 (CIBSE, 2005). The simulation results suggested that the design would only satisfy one of three requirements of Part L criterion 3, limiting solar gains.⁷ The simulation results were questioned by the design team members:

ARCHITECT2: According to the [simulation] report, only one ARCHITECT2 criterion is met. The report's wording is rather negative, it seems like they are blaming the design but the ventilation rates are not design factors. I talked to our environmental team to check the simulation, they analysed the assumptions and it seemed a reasonable scenario ...

A dynamic thermal model was invoked in RIBA Workstage 5 after the start of the construction work. This model was a more accurate estimation of the energy performance compared to the use of SBEM in RIBA Workstage 3. It enabled the assessment of the wide range of criteria to be met for building control purposes, including reduction of carbon emission (Criterion 1 Part L) and overheating risk (Criterion 3 Part L). It identified potential risk of overheating and suggested design strategies to mitigate the risk. However, since the simulation model was produced after the start of the construction work, the architect considered that it was difficult to implement the recommendations:

ARCHITECT2: The simulation has just been issued. If we had it before, we could have changed something but it's too late now. It's designed and on site, we could do something but not huge changes ...

The simulation model was developed by an external energy consultant who was not part of the design team in Case Study 2. The model did not consider the specific users' routines identified by the design team during workshops with the client; for example, the IT equipment and lighting use; possibly due to the lack of communication between the design team and the external consultant.

Different estimation methods were developed by different consultants in Case Study 2: Ecotect by in-house environmental consultant (RIBA Workstage 2), SBEM by building services engineer in the design team (RIBA Workstage 3) and IES by the external energy consultant who was not a design team member (RIBA Workstage 5); as illustrated in Table 9. SBEM was invoked as planning application evidence and IES for building control purposes. Although simulation tools were available in Case Study 2 from RIBA Workstage 2, the simulation results were not part of the design conversations and did not inform directly the design strategies. The field observations did not suggest significant episodes of collective problem-solving or co-design sessions supported by simulation results in Case Study 2. The design team did not have thorough co-design sessions with the consultants who produced the simulation models. The simulation results were not linked to the design development. The as-designed performance estimation was triggered by compliance requirements (Planning application and Building control). The simulation tool, as a boundary object, aggravated the conflicts that arise during the design process. It was not observed to support the worldview negotiation or the knowledge-sharing process between the design team members in Case Study 2.

Comparison between the use of simulation in Case Studies 1 and 2

Co-design sessions in Case Study 1 were supported by building performance simulation and helped the design team to collectively understand the design performance targets and strategies, aligning different visions and expectations, the 'worldview negotiation'. By considering the energy performance metrics in relation to different requirements, the design team members shared knowledge to

Table 10. Roles and perceptions of simulation tools in the design process in Case Studies 1 and 2.

	Case Study 1	Case Study 2
Level of integration of the simulation tool	With continuous use of simulation tools in the process, simulation results supported design conversations and codesign sessions, simulation results produced evidence for compliance (planning and building control) and to evaluate implications of changes in the design strategies (i.e. evaluation of value engineering proposals)	Simulation tools were used mainly to produce evidence for compliance (planning and building control). Simulation results did not directly inform design decisions
Perception of simulation results	Trusted, informed the design development	Lack of trust, theoretical results
Simulation tool as boundary object	Facilitator of the worldview negotiation and knowledge sharing between design team members	Barrier that obscured the communication and aggravated the conflicts between design team members
Value of input of non-energy experts	Input from non-energy experts valued to inform the simulation scenarios	Input from non-energy experts is not fully considered to inform the simulation scenarios, probably due to poor communication

define the as-designed performance targets, propose together low-energy strategies and connect different design requirements (i.e. regulatory compliance, cost and buildability aspects). In other words, the design conversations supported by simulation helped the design team in Case Study 1 to discern together the rationale of the design strategies and inform the as-designed estimation models based on experiential knowledge on as-built and in-use performance. Co-design sessions supported by simulation and informed by experiential knowledge enabled the design team in Case Study 1 to collectively discuss the simulation assumptions, modelling scenarios and the as-designed estimation scenarios produced by the simulationist; legitimising the role and credibility of simulation as a design support tool.

In contrast, in Case Study 2 the simulation tools were invoked due to regulatory requirements and did not inform the design conversations. Different as-designed estimation models were produced by different consultants. They had limited influence to inform the design development and to support the co-design and knowledge-sharing activities between design team members. In the light of discrepancies, the credibility of the simulation results was questioned by the design team members. The aspects observed in Case Studies 1 and 2 are compared in Table 10.

Discussion

Conventional approaches to energy-efficiency design tend to focus on the provision of computational support to designers via building performance simulation to explore, inform and validate their decisions. The provision of user-friendly tools for conceptual design and sophisticated building performance simulation tools for detailed design is presupposed to be the panacea to low-energy building design. However, the field data question the tool-centric approaches to low-energy design that assumes that designers rely heavily on building performance simulation for problem-solving and decision-making. The insights of this study bring attention to few aspects that affect the robust use of simulation tools in routine building design:

- (1) the predominant use of experiential knowledge to advance the design development;
- (2) designers' conflicting views about simulation tools and the challenges to incorporate simulation tools in the design process;
- (3) the status of simulation tools as boundary objects in the design process which affects their integration in the design process.

Rules of thumb and experiential knowledge are prevalent methods to inform design problem-solving. They enabled quick performance appraisals to advance the design development in situations

where building performance simulation did not offer immediate results. Rules of thumb and experiential knowledge were also invoked to inform the assumptions embedded in simulation tools and the as-designed estimation models.

The field data suggest that design teams struggle to decide the time to invoke simulation. Designers perceive that simulation results are theoretical. Yet, designers are interested in considering the as-built and in-use performance information to improve the as-designed estimation models.

The research participants had contradictory views about simulation tools. While designers thought that simulation tools helped to quantify performance with more certainty than rules, they also perceived that simulation results were theoretical. The as-designed performance estimation was considered to be an uncertain representation of the designers' intentions and the simulationist's assumptions about the building. This perception seems to undermine the credibility and trust in simulation results by the design team members who are not energy specialists.

In relation to the integration of simulation tools in the design process, the study has presented different levels of integration based on the notions of boundary object and worldview negotiation. The potential of simulation tools to support co-design and knowledge-sharing activities could be affected by the context of the design process: partnership and relationship between design team members, client expectations, drivers of the process and the perceived value of the contribution of different design team members.

In the context of routine design problem-solving, these data contest the view that simulation tools fit smoothly in the design process. In relation to user-friendly tools for early design, the data bring attention to the architects' preference for rules of thumb and heuristics for quick decision-making. In relation to advanced simulation tools for detailed design, the data suggest that the simulation tools used by the energy specialists need to be part of the design dialogue and support the co-design activities of the whole design team. The simulation results are more effectively integrated in the design process if they are a consistent part of the design dialogue at different points of the process: to share knowledge, to outline the assumptions embedded in the simulation models, to negotiate the design strategies, to estimate the as-designed performance. The involvement of the non-energy experts to inform the as-designed estimation scenarios seemed to increase the credibility and legitimization of the simulation results among the non-energy experts.

Although this study engaged with architecture firms experienced in low-energy design, the data question the assumption that simulation tools are used in a robust and rigorous manner to support routine low-energy building design. This is of concern because the study suggests that even architecture firms with some experience, expertise and motivation to design low-energy buildings are struggling to integrate simulation tools in the design process. Different levels of integration of simulation were observed in the design process. In Case Study 1 a simulation tool was deployed from RIBA 2 to 5 to inform the design development and support the co-design sessions. Conversely, in Case Study 2 a simulation tool was used intermittently, mainly to respond to the compliance requirements outlined by planning application and building control. While different simulation models were available in Case Study 2 the results had limited influence in the design development, potentially due to a number of factors such as team arrangements, clients' expectations, drivers of the process, perceived value of the expertise of different team members.

The simulation tools have the potential to support the design conversations between the energy and non-energy experts and increase the knowledge about energy performance among the design team members. However, in situations where the simulation results were not part of the design teams' dialogue, the simulation results created conflicts and aggravated the controversies among design team members. If a simulation tool was invoked for compliance purposes only, it could interfere with the way that knowledge about low-energy aspects is shared between the design team members.

Conclusion

This work has been informed by propositions of design science literature and phenomenology of technology to investigate the role of tools in low-energy design, with a focus on simulation tools. The field data have highlighted some of the challenges to incorporate simulation tools in the design process. It has been observed that experiential knowledge and heuristics were pervasively used before invoking simulation. In routine low-energy design, simulation tools were used to confirm the intuition of designers rather than to explore the design options. A fruitful area of work is to determine how to enhance the informal and experience-based methods that designers rely on; for example, providing robust methods to support quick design decisions in situations where simulation tools are computationally expensive or time consuming.

In relation to team work, the concepts of 'worldview negotiation' (Bucciarelli, 2002) and 'boundary object' (Carlile, 2002) have provided the conceptual ground to study the use of simulation tools in the design process in action. The field data illustrate episodes where the simulation tool becomes part of the dialogue and co-design activities of design team members, supporting the knowledge-sharing process. However, depending on the characteristics of the context (arrangements, drivers and team dynamics), the worldview negotiation could be deterred by the opportunistic and intermittent deployment of simulation tools. While there are opportunities for simulation tools to support co-design and knowledge sharing in a routine design process, it is important to consider how the simulation tools enable communication of the energy performance aspects to the non-energy experts, at different points of the process. The use of experiential knowledge, as-built and in-use data offer promising avenues to support the legitimisation of simulation results and to improve the as-design modelling scenarios and assumptions embedded in the simulation models. This aspect highlights the urgent need to consider how as-built and in-use performance information could be 'brought back' to designers to close the feedback loop of the building process.

Due to the small number of case studies and the qualitative nature of this work, there are some limitations to be acknowledged. The study engaged with a small number of architecture firms with similar profiles in terms of sustainable expertise. Therefore, the findings only reflect the characteristics and circumstances found in the case studies. No claims for generalisation or representativeness are made. Yet, the insights have illustrated some of the challenges that design teams faced when using simulation tools and designing low-energy buildings. The observations are likely to have a global relevance to suggest how tools are used in the context of the design process. This work is relevant to opening up a critical debate about the ways to support designers in the pathway to low-energy built environments.

Notes

1. The architecture firms have offices in the UK and overseas. Their experience in sustainable buildings was demonstrated by their portfolio, the green certifications awarded to their projects (BREEAM, PassivHaus) and the recognitions achieved by the firms (Royal Institute of British Architects and Chartered Institute of Building Services Engineers Awards).
2. Communities of practice is a social theory of learning that argues that knowledge is the competence gained through social participation in an enterprise. The key postulate of Communities of Practice theory is that knowledge is socially created and enhanced by the members of a community and their interaction. Knowledge is located 'in the relations between practitioners, their practice, the artefacts and the social organisation' (Wenger, 1998).
3. For the purposes of this discussion, experiential knowledge refers to embodied and practical knowledge gained through experience. Experiential knowledge[3] tends to be loosely articulated as intuitive understanding.
4. SBEM is the Simplified Building Energy Model, a tool for the calculation of the building energy consumption that is aligned to the UK National Calculation Method for the Energy Performance of Buildings Directive. Further information: <http://www.uk-ncm.org.uk/>.
5. The schema follows the notion of 'ideal type' by Hammersley and Atkinson (1995). The ideal type schema does not intend to represent every detail of all observed case studies; it rather presents the main characteristics and the underlying structure found across the case studies.

6. Monitored consumption data were available from the users and would be relocated from an existing building to the new building being designed.
7. For the assessment of overheating risk in school, Part L refers to the Building Bulletin 101 (2006) Ventilation of school buildings. A dynamic thermal model is to be used to demonstrate that at least two of three criteria are satisfied. For more information refer to Part L2A document (H. M. Government, 2010) and the Building Bulletin 101.

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