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

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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.

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
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 Lyttinen (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 multi-disciplinary 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. 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. 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.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Description</th>
<th>Categories per criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firm’s identity in relation to sustainable and low-energy design</td>
<td>Sustainable experience and credentials advertised as main expertise of the firm</td>
<td>Strong</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td>In-house expertise</td>
<td>Dedicated team of energy or environmental specialists in the firm as indicator of existing expertise and knowledge in sustainability and low-energy design</td>
<td>Yes/no</td>
</tr>
<tr>
<td>Type of learning organisation</td>
<td>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, McDermott, &amp; Snyder, 2002, pp. 65–112)</td>
<td>Strong</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
</tr>
</tbody>
</table>
### Table 2. Profile of architecture firms as per sampling criteria.

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

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

<table>
<thead>
<tr>
<th>Case study</th>
<th>Conceptual design (RIBA Workstages 0–3)</th>
<th>Detailed design (RIBA Workstages 4–5)</th>
<th>Duration of data collection (months)</th>
<th>Arch. firm</th>
<th>Partnership Arch. and design team members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td></td>
<td></td>
<td>21</td>
<td>1</td>
<td>Building services engineer, acoustics and lighting consultant in-house</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td></td>
<td>12</td>
<td>2</td>
<td>No partnership with consultants</td>
</tr>
<tr>
<td>Case 3b</td>
<td></td>
<td></td>
<td>14</td>
<td>3</td>
<td>Previous work with building services engineer and sustainability consultants</td>
</tr>
<tr>
<td>Case 4</td>
<td></td>
<td></td>
<td>13</td>
<td>4</td>
<td>No partnership with consultants</td>
</tr>
<tr>
<td>Case 5b</td>
<td></td>
<td></td>
<td>13</td>
<td>4</td>
<td>Previous work with building services engineer and sustainability consultants</td>
</tr>
</tbody>
</table>

*Case Studies 3 and 5 were studied in conceptual design only.

Stages studied in the investigation.

### Table 4. Design targets per case study.

<table>
<thead>
<tr>
<th>Case study</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building type</td>
<td>Educational</td>
<td>Educational</td>
<td>Educational</td>
<td>Educational</td>
<td>Educational</td>
</tr>
<tr>
<td>Location</td>
<td>South Wales</td>
<td>England</td>
<td>South Wales</td>
<td>England</td>
<td>South Wales</td>
</tr>
<tr>
<td>EPC</td>
<td>40</td>
<td>31</td>
<td>19</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>% LZC tech</td>
<td>20</td>
<td>10</td>
<td>30</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>BREEAM Credits</td>
<td>81.70</td>
<td>71.85</td>
<td>89.00</td>
<td>64.00</td>
<td>73.00</td>
</tr>
<tr>
<td>BREEAM Rating</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Outstanding</td>
<td>V Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>U-value roof (W/m²K)</td>
<td>0.18</td>
<td>0.15</td>
<td>0.18</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>U-value walls (W/m²K)</td>
<td>0.26</td>
<td>0.15</td>
<td>0.26</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>U-value glazing (W/m²K)</td>
<td>1.60</td>
<td>1.20</td>
<td>1.60</td>
<td>1.60</td>
<td>1.60</td>
</tr>
<tr>
<td>U-value floors (W/m²K)</td>
<td>0.32</td>
<td>0.19</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airtightness (m³/m²@50Pa)</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
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.ti. (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 knowledge 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 docu-
ments 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 CO$_2$), 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 plan-
ing 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 perfor-
mane] targets are …

The proprietary simulation tools observed in the case studies were Integrated Environmental Sol-
sions (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 evi-
dence 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 construc-
tion. 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 SBEM$^4$ 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 simpli-
ﬁed schema$^5$ has been used to illustrate the key features observed in the field (Table 7). In RIBA Work-
stage 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).

<table>
<thead>
<tr>
<th>What for</th>
<th>Which tool and when</th>
</tr>
</thead>
<tbody>
<tr>
<td>To evaluate orientation, passive design</td>
<td>IES, RIBA 2</td>
</tr>
<tr>
<td>To compare facade design options</td>
<td>Ecotect, RIBA 2</td>
</tr>
<tr>
<td>To quantify performance for planning application</td>
<td>Ecotect, RIBA 2</td>
</tr>
<tr>
<td>To assess changes for value engineering</td>
<td>IES, RIBA 3</td>
</tr>
<tr>
<td>To quantify performance for building control</td>
<td>SBEM, RIBA 3</td>
</tr>
<tr>
<td></td>
<td>IES, RIBA 4</td>
</tr>
<tr>
<td></td>
<td>Ecotect, RIBA 5</td>
</tr>
<tr>
<td></td>
<td>IES, RIBA 4-5</td>
</tr>
</tbody>
</table>

$^a$Case Studies 3 and 5 were analysed until RIBA Workstage 3 only.
$^b$Case Study 4 was analysed from RIBA Workstage 4.
Table 7. Schema of the performance understanding throughout the design process.

<table>
<thead>
<tr>
<th>Conceptual design (RIBA Workstages 0–2)</th>
<th>Transition between conceptual and detailed design (RIBA Workstages 3–4)</th>
<th>Detailed design in the light of construction work (RIBA Workstages 4–5)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose of the performance estimation</strong></td>
<td>Understanding of the relation-building site, benchmarking against statutory requirements and use of previous experience</td>
<td>Performance analysis switches from intuitive understanding to quantification by calculation tools. The initial performance estimation focuses on compliance by the end of conceptual design</td>
</tr>
<tr>
<td><strong>Preference in terms of tools</strong></td>
<td>Intuitive understanding, experiential knowledge, heuristics and in-house simplified tools for quick estimation</td>
<td>Intuitive understanding and calculation tools</td>
</tr>
<tr>
<td><strong>Criteria analysed</strong></td>
<td>Passive strategies, potential of low zero carbon technologies, climate analysis</td>
<td>Implications of the performance on the project drivers: cost, payback cost of low zero carbon technologies, maintenance, use, minimum regulatory requirements (benchmarks)</td>
</tr>
<tr>
<td><strong>Indicators commonly used</strong></td>
<td>Architects focus on the U-values and the mechanical engineers assess the heat gain, thermal conditions, overheating risk, feasibility of low zero carbon technologies</td>
<td>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</td>
</tr>
<tr>
<td><strong>How the indicators are presented</strong></td>
<td>Visual outputs linked to numerical data, diagrams, solar diagram, graphical analysis of the sun path</td>
<td>Time-series tables, graphs, EPC report, BRUKL document (Part L 5 criteria)</td>
</tr>
<tr>
<td><strong>Backdrops</strong></td>
<td>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')</td>
<td>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</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compliance driven, production of Part L evidence Pass/fail – Part L and BREEAM (policy requirements)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Part L report, EPC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>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.</td>
</tr>
</tbody>
</table>
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 compro-
mise 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 simu-
lation software enabling the quantification of performance, the as-designed estimations were unli-
kely 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 develop-
ment 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 data 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>
<thead>
<tr>
<th>Characteristics</th>
<th>Case Study 1</th>
<th>Case Study 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Team arrangement</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td>Explicit client requirements</td>
<td>Client’s brief outlines of the sustainability and energy targets. Targets are set to exceed the minimum energy standards.</td>
<td>Client’s brief refers to energy and sustainability aspirations; however, there is no explicit aspiration to exceed the minimum energy standards.</td>
</tr>
<tr>
<td>Project length</td>
<td>Approximately 36 months for project completion (including design stage).</td>
<td>Approximately 15 months for project completion (including design stage).</td>
</tr>
<tr>
<td>Knowledge sharing and communication</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td>Negotiation dynamics</td>
<td>Collaboration</td>
<td>Conflict</td>
</tr>
</tbody>
</table>
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).

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

<table>
<thead>
<tr>
<th>Early design decisions</th>
<th>Case Study 1</th>
<th>Case Study 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>What tool</td>
<td>In-house U-value calculator and IES</td>
<td>Ecotect</td>
</tr>
<tr>
<td>Who deployed it</td>
<td>Building services engineer (design team member)</td>
<td>In-house environmental consultant</td>
</tr>
<tr>
<td>When</td>
<td>RIBA 2</td>
<td>RIBA 2</td>
</tr>
<tr>
<td>What for</td>
<td>Passive design and low-energy strategies</td>
<td>Passive design and low-energy strategies</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>In the light of planning application</th>
<th>Case Study 1</th>
<th>Case Study 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>What tool</td>
<td>IES</td>
<td>Ecotect</td>
</tr>
<tr>
<td>Who deployed it</td>
<td>Building services engineer (design team member)</td>
<td>Building services engineer (design team member)</td>
</tr>
<tr>
<td>When</td>
<td>RIBA 2-3</td>
<td>RIBA 3</td>
</tr>
<tr>
<td>What for</td>
<td>Passive design, low-energy strategies and evidence for planning application</td>
<td>Evidence for planning application</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>In the light of building control (Part L)</th>
<th>Case Study 1</th>
<th>Case Study 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>What tool</td>
<td>IES</td>
<td>Ecotect</td>
</tr>
<tr>
<td>Who deployed it</td>
<td>Building services engineer</td>
<td>External energy consultant (not a design team member)</td>
</tr>
<tr>
<td>When</td>
<td>RIBA 4</td>
<td>RIBA 5</td>
</tr>
<tr>
<td>What for</td>
<td>Evidence for building control, to evaluate the energy implications of value engineering proposals</td>
<td>Evidence for building control</td>
</tr>
</tbody>
</table>
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 CO$_2$ 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. The simulation results were questioned by the design team members:

ARCHITECT2: According to the [simulation] report, only one 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
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 dis-
crepancies, 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.

| 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                  | 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                              | Lack of trust, theoretical results                            |
| Simulation tool as boundary object                            | Facilitator of the worldview negotiation and knowledge sharing between design team members |
| Value of input of non-energy experts                          | Input from non-energy experts is not fully considered to inform the simulation scenarios, probably due to poor communication |

Discussion

Conventional approaches to energy-efficiency design tend to focus on the provision of computa-
tional 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 inte-
gration 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 exper-
iential 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 consid-
ering 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 per-
ceived that simulation results were theoretical. The as-designed performance estimation was con-
sidered 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 effec-
tively 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 perform-
ance. The involvement of the non-energy experts to inform the as-designed estimation scenarios
seemed to increase the credibility and legitimation 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 simu-
lation 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 inter-
fere 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.
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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