

# Open Research Online

---

The Open University's repository of research publications and other research outputs

## Zero and low carbon buildings: A driver for change in working practices and the use of computer modelling and visualization

Conference or Workshop Item

How to cite:

Hetherington, Robina; Laney, Robin and Peake, Stephen (2010). Zero and low carbon buildings: A driver for change in working practices and the use of computer modelling and visualization. In: 14th International Conference on Information Visualisation, 27-29 Jul 2010, London South Bank University, London, UK.

For guidance on citations see [FAQs](#).

© 2010 IEEE

Version: Accepted Manuscript

Link(s) to article on publisher's website:  
<http://www.graphicslink.co.uk/IV10/>

---

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data [policy](#) on reuse of materials please consult the policies page.

---

[oro.open.ac.uk](http://oro.open.ac.uk)

# Zero and Low Carbon Buildings: A Driver for Change in Working Practices and the Use of Computer Modelling and Visualization

Robina Hetherington, Robin Laney, Stephen Peake

The Open University

r.e.hetherington@open.ac.uk, r.c.laney@open.ac.uk, s.r.peake@open.ac.uk

## Abstract

*Buildings account for significant carbon dioxide emissions, both in construction and operation. Governments around the world are setting targets and legislating to reduce the carbon emissions related to the built environment. Challenges presented by increasingly rigorous standards for construction projects will mean a paradigm shift in how new buildings are designed and managed. This will lead to the need for computational modelling and visualization of buildings and their energy performance throughout the life-cycle of the building.*

*This paper briefly outline how the UK government is planning to reduce carbon emissions for new buildings. It discusses the challenges faced by the architectural, construction and building management professions in adjusting to the proposed requirements for low or zero carbon buildings. It then outlines how software tools, including the use of visualization tools, could develop to support the designer, contractor and user.*

**Keywords---** Visualization, Sustainable, BIM, Building Modelling, Zero Carbon

## 1 Context - Climate change

The threat of climate change is forcing us to contemplate a total re-design of our built environment and of all the products and services that we consume. This paper does not seek to challenge or add to the debate regarding the urgency or severity of the predicted changes. Nor does it debate the numbers or question government policy. Climate change is thought to happen primarily because of increased anthropogenic emissions of green house gases. One of the major greenhouse gases is carbon dioxide. In the UK the Government is taking the issue extremely seriously. The Climate Change Act of 2008 sets legally binding targets to reduce the emission of carbon dioxide by 80% from 1990 levels by 2050 [1]. As buildings account for almost 50% of UK carbon dioxide emissions the alteration of practices related to the construction and use of buildings will have a significant role in achieving these targets [2].

Proposed legislation in the UK is driving the requirement for all new buildings to be 'carbon neutral' or 'zero carbon'. The aim of this paper is to explore how

software could assist the visualization, design, construction and management of low and zero carbon buildings.

### 1.1 The built environment and climate change

The human race needs buildings, yet they make significant demands upon the earth. In 2009, it was estimated that buildings use 45-50% of global energy, most of which is associated with the burning of fossil fuels which result in carbon dioxide emissions [3]. In addition, energy produced by burning fossil fuels is consumed in the manufacture and transport of materials to site in order to construct the buildings. When the buildings are in use people then move between them to work, for education and relaxation, again using energy. The EU Energy Performance of Building Directive (2002/91/EC) identifies construction as the sector with the greatest potential to achieve energy efficiency [3].

### 1.2 Government legislation

In 2007 the UK Government announced the intention that all new houses would be carbon neutral by 2016 in the "Building a Greener Future: policy statement". This is to be achieved by progressive tightening of Building Regulations legislation over a number of years [2]. Consultations are currently taking place on the practicalities of legislating for public sector buildings and all new non-domestic buildings to be carbon neutral by 2018 and 2019 respectively [4]. The Welsh Assembly Government has announced its intention of implementing legislation at a much faster rate [5].

This rate of change in the Building Regulations is unprecedented, 2002 and 2006 saw tightening of the existing regulations, and the new low and zero carbon standards will require even more changes with proposals for revisions in 2010, 2013 and 2016 for new domestic buildings. There will be a necessity for an equal or greater level of legislative changes for non-domestic buildings. Existing buildings will not be exempt; they will have to comply with the CRC Energy Efficiency Scheme (CRC), formerly the carbon reduction commitment, which comes into effect in April 2010 [6].

### 1.3 Grand challenge in computing research and software development

Software has an important role in tackling climate change. It is “a critical enabling technology” [7]. The UKCRC [UK Computing Research Committee] has chosen climate change as one of four major societal grand challenges for 2010 and beyond.

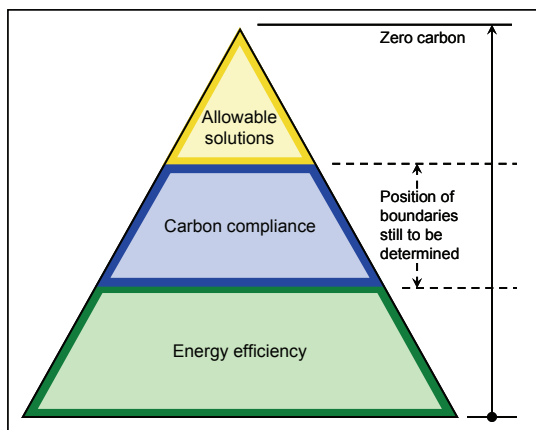
The changes in praxis facing the construction industry in the next 20-30 years are profound [8]. This paper proposes a number of ways in which software could be developed to support the designer, contractor and user in creating and using low or zero carbon buildings. It outlines what LZC [*Low and Zero Carbon*] and sustainability mean, how architects have traditionally worked, the available software and how it is used. It discusses the challenges faced by building designers in achieving zero carbon buildings, describes the available types of software and then outlines how software tools might develop to meet not only the zero carbon challenge but also take the concept further to help design sustainable buildings.

## 2 Background

This section gives the background to the concepts involved in climate change and working practices in the construction industry.

### 2.1 Low and zero carbon

The Government set out a definition for ‘zero carbon homes’; they must have zero net emissions from all energy use in the home over the course of a year. [2]. Consultation to add further detail on the definition of zero carbon and to extend it to non-domestic buildings was initiated at the beginning of 2010 [9]. A three-tiered approach for reaching net zero emissions is proposed by the Government, shown as a hierarchical triangle in Figure 1.



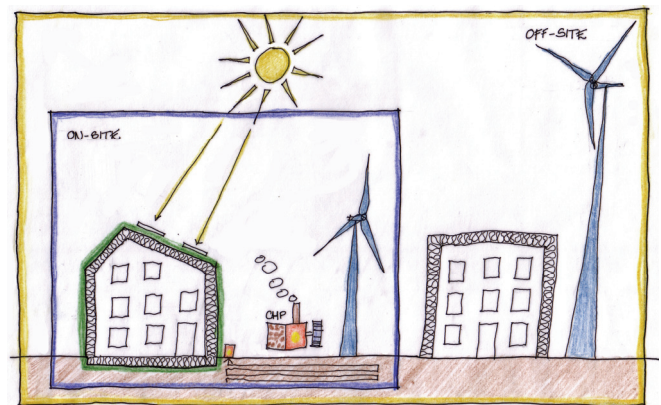
**Figure 1 Hierarchy of permissible methods to achieve zero carbon developments [9]**

The priority, represented by the bottom tier of the triangle in Figure 1 is to construct building envelopes to very high standards of ‘energy efficiency’, so that little

or no energy is required to heat or cool the building. This includes very high levels of insulation of the building fabric (U-values), the control of thermal bridging, significantly reducing air permeability, incorporating thermal mass and utilizing incidental gains, such as metabolic, lighting, solar and appliances. These are expected to be robust methods, entailing lower life-cycle costs than other, possibly higher maintenance, low or zero technologies which constitute the other two tiers.

There are limitations to the effect of fabric and energy efficiency measures. ‘Carbon compliance’, the middle band of the triangle, covers a number of measures including generation technologies, such as solar panels incorporated into the fabric, ground source heat pumps and combined heat and power plants located within, or closely connected, to the development.

To achieve net zero carbon emissions through energy efficiency and onsite ‘carbon compliance’ measures may not be technically possible for many building types. In order to meet the proposed standard there may be a need to apply (predominantly) off-site measures, or ‘allowable solutions’. Off-site solutions considered within the consultation are local energy schemes, credits for paying for local energy infrastructures, upgrading existing local buildings, etc., as illustrated in Figure 2. Other allowable solutions may include equipment within the building such as energy efficient appliances, for instance ultra low energy IT equipment, or advanced heating/cooling/lighting control systems.



**Figure 2 On-site and off-site compliance**

The position of the boundaries between the areas of the triangle, that is for example, the percentage allocated for ‘Allowable solutions’, are still being discussed. See *Building a Greener Future: Towards Zero Carbon Development – Consultation* for further information [9].

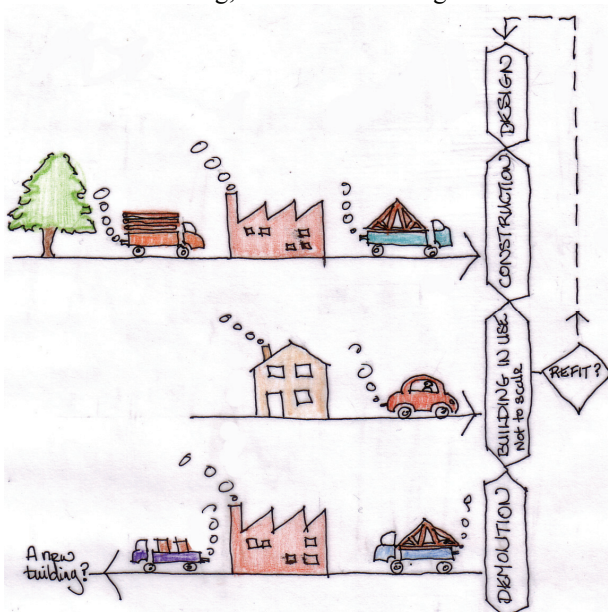
### 2.2 Sustainability

The zero carbon legislation does not specifically mention sustainability. It is, however, included in the *BREEAM* [BRE Environmental Assessment Method] assessments and the *Code for Sustainable Homes*, which whilst not a legal requirement, can be a condition of public funding.



Sustainability is concerned with many more issues in addition to the reduction of fossil fuels. The Brundtland definition of sustainability is “meeting the needs of the present without compromising the ability of future generations to meet their own needs” [10]. This is now considered over simplistic. The triple bottom line of economic, ecological and social sustainability is considered better criteria for measuring organizational (and societal) success [11]. The BRE [Building research Establishment] further describes it as “a complex web of systems and cycles in science, economics, politics, ethics and engineering” [12].

In addition to the energy required to light, heat or cool, and run appliances within a building there is energy to construct, refit and demolish it. This energy is embodied within the building. A sustainable approach, ‘cradle to cradle’, would have the building reprocessed into another building, as illustrated in Figure 3.



**Figure 3 Sustainable building life cycle**

Energy use is one important consideration of sustainable construction; there are many other life cycle considerations such as water resources, pollution, biodiversity, habitat, ecosystems. Whilst this paper deals with zero carbon legislation as a driver for change, the larger picture should be borne in mind.

### 2.3 How buildings are designed

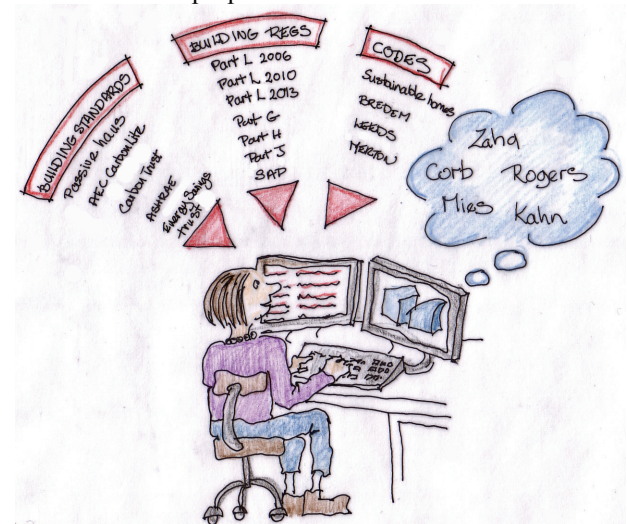
A and B:	Appraisal and Design Brief
C	Concept, the client signs off the brief
D	Design development and detailed planning permission
E	Technical design includes the required details, choice of materials and standards of ‘workmanship’
F	Production information
G and H	Tender process

**Table 1 Stages of a building project [13]**

The design of buildings is a complex process. When designing a building the architect will consider aesthetics, technology, sociology, geography, history, philosophy, law and psychology. Hellman visualizes the architect as trying to control two wild horses labeled **Art** and **Science** [14]. There is always a balance between the two. Traditionally Art (or design) has lead the process with the Science (or technology) following. This approach has been followed for a very long time and is implicit in the stages of a project as set out by the RIBA [Royal Institute of British Architects], currently used in the UK, as set out in Table 1 [13].

### 2.4 Paradigm shift in the design process

It can be seen from Table 1 that the technical design is scheduled to occur after the client has “signed off” the design and planning permission has been granted for the project. Historically, energy intensive technological solutions would then be used to “solve” problems arising from lack of environmental considerations at the design stage, for instance over/under heating or lack of day lighting. In the future the consideration of significant technical consideration and detail will be required at a very early stage to overcome these energy penalties. The design of zero carbon buildings will require an unprecedented paradigm shift in how new buildings are procured and designed. Software will have a significant part to play in how designers assimilate, handle, visualize and design with the extra information necessary to achieve these proposed standards.



**Figure 4 Laws, Codes and Guidelines**

The architectural and construction professions are becoming subject to ever-increasing legislation, stringent building codes and guidelines relating to energy use and sustainability. To achieve zero carbon the building designer will need to implement a significant amount of technical data at very early design stages, see Figure 4. The move to sustainable design requires collaboration between all stakeholders, again software has a role to play in facilitating team work between construction professionals, regulatory bodies and end-users.

## 2.5 Current design and analysis software

Architecture has gone through significant changes since the 1980s when CAD [Computer Aided Draughting/Design] was introduced. The use of software has significantly altered working practices and enabled imaginative and inspiring designs, sometimes using complex geometries, only achieved through the use of advanced modelling and engineering computational techniques. However, advances in digital design media have created a complex web of multiple types of software, interfaces, scripting languages and complex data models [15]. The types of software used by architects can be grouped into four main categories:

**CAD** software that can be used to generate 2D or 3D visualizations of buildings. This type of software evolved from engineering and draughting practices, using command line techniques to input geometries. This software is mainly aimed at imitating paper based practices, with designs printed to either paper or pdf.

**Visualization** software, generally used in the early design stages for massing studies and generating high quality renderings of the project. This type of software is often used in the gaming and movie industries.

**Analysis** software, used to perform calculations such as heat loss, solar gains, lighting, noise, etc.

**BIM** [Building Information Modelling] software has been a significant development in the last few years. BIM software contains not only the building geometry and spatial relationship of building elements in 3D; it can also hold geographic information, quantities and properties of building components. Each component is an 'object' that is recorded in a backend database. The software can be used to facilitate team working with consultants and manage building data during its life cycle. Building models are key to the calculations now required to support zero carbon designs. Working in 3D reduces errors in buildings by reducing the conflicts in building structures and components and thus significantly reducing wasted effort and materials on site [16]. However, significant numbers of designers are still working in 2D and the take-up of BIM is still low [17].

CAD, BIM, energy analysis and visualization software is extremely expensive. More than one package may be used in any one project. The software requires top end workstations and multiple display devices to be used efficiently. The architectural profession includes a number of large architectural practices with excellent IT resources and their own in house energy analysts who can afford a wide range and selection of software. However, there are a significant number of smaller firms in the profession. A recent survey showed that 11% of the profession work as sole practitioners [18]. It is estimated that 55% of all architects work in practices with less than 10 employees [19]. These small practices will struggle with both the knowledge and data demands of designing to zero carbon standards. In addition CAD, BIM, energy analysis and visualization software requires a significant amount of time, to learn and to achieve proficiency [16].

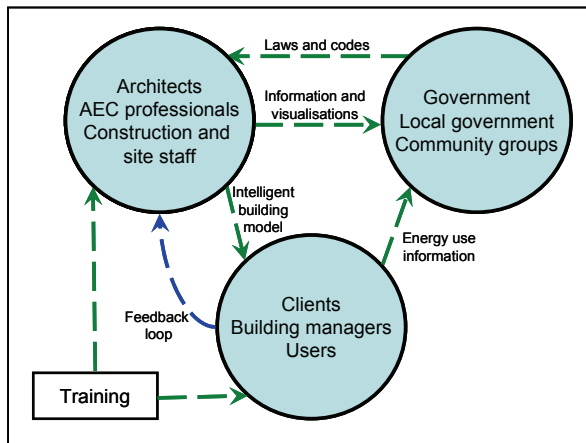
There is a plethora of tools available to designers to design and assess proposals. However, these tools are not easy to use and the environmental data they produce is difficult to interpret. Nor are the different software packages well integrated with each other. At present there is an iterative process, with geometric meshes and data transferred between the design package and the various analysis tools. Specifically, the geometry of meshes requires manipulation for movement into the analysis software from the modelling environment and data such as material properties needs to be re-entered, with a significant penalty in time and possible loss or corruption of data [20][21]. Interoperable standards such as the ifcXML [Industry Foundation Classes eXtensible Markup Language] specification and gbXML [Green Building eXtensible Markup Language] enable this movement of models between various types of software.

The ifcXML specification, developed by the IAI [Industrial Alliance for Interoperability], was designed to facilitate the movement of information from and between BIM software. It was designed in a "relational" manner, as a result of the BIM database concept. Accordingly there is concern about the potential file size and complexity of the standard arising from the XML format and the amount of data it can contain [22] [23]. Also, the seamless interoperability it is intended to support has proved to be elusive. Take up has been slow and incomplete with software companies not always supportive [24]. The language designed specifically for interchange of data between design modelling environments and energy analysis packages is gbXML. In comparison with ifcXML it is considerably simpler and easier to understand, but therefore is lacking in detail [25]. The limitations are apparent in the geometric detail contained in the file which inhibits the transfer back to the design package [26].

CAD, BIM, energy analysis and visualization software packages are almost all developed in the USA by large and well-resourced companies with the associated bias towards American procedures. In the UK the BRE [Building Research Establishment] has been at the forefront of the development of assessment and building code checking software, but this is not part of the early design process [16][27].

## 3 The software challenge

The following section suggests how software could be developed to help and support the various stakeholders in any project. The software discussed is primarily aimed at the supporting SME [Small to Medium-sized Enterprises] mentioned in the previous section, who along with their clients, may not have the financial freedom to employ engineers to analyze and advise on zero carbon design. Figure 5 shows how we have chosen to group the stakeholders and the type of information flow between them. These groupings then make up the following sections. Some software types will sit or span between the groups.



**Figure 5 Software user groupings**

### 3.1 Software to assist the design process

Visualization is key to all software discussed below. Modern modelling methods give the designer the ability to create and visualize the building virtually before it is created physically. Building environments can be simulated and tested. However, energy analysis produces copious amounts of data, this data will require presentation in a meaningful way to enable it to be understood and the building model manipulated.

#### 3.1.1 Quality of software to design and visualize zero carbon buildings

There is a need for high quality software that will encourage designers to work in 3D and BIM and allow for better visualization and integration of energy data. Although there have been significant improvements since the early days of Computer-Aided Draughting, opportunities still exist to make better software that is simpler, easier to use, quicker to learn with interfaces that are more intuitive. The rapid take-up and popularity of *SketchUp* [28] demonstrates that the opportunity is there to radically re-think the modelling process, user interface and visualization.

Software should be designed to allow for country-specific adaptation, integrating local building products, national building codes and legislation. This data could then be used to support early design decisions that would support effective sustainable solutions, as opposed to retrospective design validation such as BREEAM [27].

Software should be developed that supports a more sensible approach to design, with the software supporting and facilitating optimization of the building model as the design progresses. The ability to test and evaluate design options in real-time would be of enormous benefit. An example would be the ability to visualize the effect of altering areas of glazing on the quality of the space and at the same time see how this affects the thermal and lighting performance. Again, this represents a paradigm shift away from retrospective code compliance checking, leading to a streamlined and efficient building design process.

At present, there is no software that “does everything”; that is an environment where design and environmental analysis can take place concurrently. Models need to be moved between analysis and modelling software packages. There is a significant time penalty for designers to prepare the geometry for analysis and data needs to be added in the separate tools leading to possible loss or corruption of data [20][21]. Whilst there are opportunities for creating one piece of software incorporating building information modelling and analysis we suggest a different approach. This solution would be a suite of modular software, based on open source principles, well integrated to enable the transfer of data. Key to this are standards for interoperability of data. This would enable smaller software companies to penetrate the CAD and BIM market with the benefit of more competition and the development of country specific software.

#### 3.1.2 Training and advisory systems for zero carbon building design

The major challenge for the designer is understanding the key issues and learning how to set up a model and the parameters for running a simulation that produce results on which practitioners (and consequently clients) can rely. The “Zero Carbon Homes Programme Delivery Timeline” states that it is critical that 75 % of all architects are trained in low and zero carbon homes concepts between 2010 and 2013 [29]. A report published by Revelation Research showed that the percentage of designers using BIM software was small compared to 2D draughting [17]. Opportunities exist to provide digital training material both to learn how to use and better understand BIM and energy analysis concepts and the new skills/knowledge required by designers to interpret and use the energy data. The skills will include the ability to carry out the analysis required by the proposed legislation. Designers and construction professionals will need training in detailing and implementing highly insulated and air-tight constructions. Designers will need to understand and be able to specify devices such as solar panels, ground source heat pumps, biomass boilers, CHP [combined heat and power plants] and wind turbines.

Consultation carried out by the Department of Communities and Local Government showed that there was demand for sustainable practices which go beyond zero carbon buildings [30]. In the future architects will be required to handle new and demanding knowledge pertaining to designing sustainable and zero carbon buildings. Opportunities exist to create advisory systems, integrated into BIM software, which would provide timely, appropriate, relevant and understandable data to the architect to support design decision making. We propose that this data should be more than online text, it should be an interactive multimedia experience, including pictures, building details, 3 D models, graphs, animations, etc.



### 3.2 Software to assist regulatory bodies and communities to understand the proposals

Visualization is key to understanding buildings and their environmental credentials; making this data available and understandable to decision makers and communities constitutes another software engineering challenge.

The Web has transformed the availability of information relating to planning decisions. However, most information is simply in the form of a pdf of traditional architectural drawings, which lay people can often struggle to understand. The developments in the display of 3D models over the web that are happening currently offer new opportunities for the display of consultative information. The development of HTML 5 may mean that browsers will not require 3D plugins to display augmented virtual models and thus lead to more extensive use of 3D models [31].

New developments, such as tangible devices which allow a user to interact with digital information through the physical environment, enable new and interesting methods of interaction with building models [32].

### 3.3 Software to assist the management and use of buildings

Software is needed to deal with the complete life cycle of buildings, where one data set is used from inception through construction, management, refurbishment and eventual re-cycling of the building fabric.

#### 3.3.1 More energy efficient building usage

The way in which occupants use and manage a building can have significant impact on the energy consumption. There are opportunities for the development of ubiquitous devices and management systems both to control and educate building usage. For instance, rather than the static graph of energy use now required in public buildings, there could be interactive, real-time displays of energy usage. The data could be used to actively manage and educate users. The efficacy of these devices will rely on the quality of visualization of the data and warnings. Tightening of legislation will require regular review of building energy usage.

#### 3.3.2 Post-occupancy feedback loop

There are significant problems of obtaining adequate data for effective life-cycle analysis of buildings [8]. Post occupancy evaluation shows that there can be significant differences between design predictions on energy usage and the actual fuel used [33]. Lessons need to be learnt on how a building performs and how people use it to enable a feedback loop to inform future designs. Again, software has an important enabling role, the building information model needs to record energy used, along with comfort and satisfaction with the building.

## Conclusion

Buildings are major contributors to carbon emissions, yet unlike other industries/technologies, workable solutions are available to achieve a significant reduction. All of the five plans for Britain to be sustainable in energy by 2050 outlined by MacKay are based on the assumption that all new buildings will require no space heating from 2010 [34], not 2019 as proposed by the UK government. Legislation is being used to force change on the construction industry; many buildings currently considered as exemplar could not be built under the proposed regulations.

This paper has dealt with very complex issues, with the aim of giving an overview of how software could be designed to help with a multifaceted set of problems. It has not challenged either the feasibility or reach of UK government policy in being primarily concerned with the reduction of the operating energy requirements for a building rather than total embodied energy. Nor has it chosen to query the details of achieving zero carbon through both 'Carbon Compliance' and 'Allowable Solutions' and the probable use of mechanical systems and renewables this will entail. It has focused instead on how software can support designers.

There is also another significant limitation; the government proposals concerning new buildings will not meet the targets set for reducing carbon used by all buildings. There are approximately 26 million existing domestic buildings plus an estimated 2 million non-domestic buildings in the UK [35]. Hence, new buildings form only a small part of the problem, upgrading existing stock present even greater, and arguably, more urgent challenges.

This paper has outlined how software could be designed to help and support the various stakeholders in any building project. The proposed changes in legislation have the possibility of leading to 'safe', but arguably dull, buildings. We advocate that software has an important role to play to support architects in decision-making, enabling them to create imaginative and beautiful, yet sustainable, designs. It has drawn upon the buildings codes and legislative drivers that exist or are proposed in the UK and uses them to formulate a set of proposals. These are relevant, irrespective of a country's legislation, to the development of quality enabling software.

## References

- [1] Great Britain, *Climate Change Act of 2008*, 2008.
- [2] Department for Communities and Local Government, "Building a Greener Future: policy statement," Jul. 2007.
- [3] B. Edwards, *Rough guide to sustainability*, London: RIBA, 2009.
- [4] Zero Carbon Hub, "Consultation on Zero Carbon Non-Domestic Buildings" [http://www.zerocarbonhub.org/events\\_details.aspx?event=3](http://www.zerocarbonhub.org/events_details.aspx?event=3) [Accessed January 28, 2010].
- [5] Welsh Assembly Government, "Welsh Assembly

Government | Programme of action to tackle climate change,” *Welsh Assembly Government | Programme of action to tackle climate change*

<http://wales.gov.uk/news/archivepress/environmentpress/2007/1420889/?lang=en> [Accessed May 6, 2010].

- [6] Y. Baker, “NetRegs - CRC Energy Efficiency Scheme (CRC),” *CRC Energy Efficiency Scheme (CRC)* <http://www.netregs.gov.uk/netregs/legislation/future/97515.aspx> [Accessed February 25, 2010].
- [7] S.M. Easterbrook, “First international workshop on software research and climate change,” *Proceeding of the 24th ACM SIGPLAN conference companion on Object oriented programming systems languages and applications - OOPSLA '09*, Orlando, Florida, USA: 2009, p. 1057.
- [8] T. Oreszczyn and R. Lowe, “Challenges for energy and buildings research: objectives, methods and funding mechanisms,” *Building Research & Information*, vol. 38, 2010, pp. 107-122.
- [9] Great Britain., *Definition of zero carbon homes and non-domestic buildings : consultation.*, London: Department for Communities and Local Government, 2008.
- [10] World Commission on Environment and Development., *Our common future*, Oxford; New York: Oxford University Press, 1987.
- [11] J. Elkington, *Cannibals with forks: the triple bottom line of 21st century business*, Gabriola Island BC; Stony Creek CT: New Society Publishers, 1998.
- [12] C. Atkinson, *Sustainability in the built environment : an introduction to its definition and measurement*, Bracknell England: IHS BRE Press, 2009.
- [13] Royal Institute of British Architects., *Architect's job book.*, London: RIBA, 2008.
- [14] L. Hellman, *Architecture A to Z : a rough guide*, Chichester West Sussex: Wiley-Academy, 2001.
- [15] R. Oxman, “Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium,” *Design Studies*, vol. 29, 2008, pp. 99-120.
- [16] E. Krygiel and B. Nies, *Green BIM : successful sustainable design with building information modeling*, Indianapolis Ind.: Wiley Pub., 2008.
- [17] Revelation Research LLP, *2008 Architectural CAD User Survey Summary Report*, Revelation Research LLP, 2009.
- [18] The Fees Bureau, *Architects' Earnings. How do you compare?*, Mirza & Nacey Research Ltd, .
- [19] D. Chappell, *The architect in practice*, Oxford ;Malden MA: Blackwell Pub., 2005.
- [20] I. Pritchard and E. Willars, *Climate Change Toolkit, 05 Low Carbon Design Tools*, RIBA, 2007.
- [21] A. Lawton and D. Driver, “Autodesk Sustainable Design Curriculum 2010 – Lesson 1,” 2010.
- [22] V. Bazjanac, “Building energy performance simulation as part of interoperable software environments,” *Building and Environment*, vol. 39, 2004, pp. 879-883.
- [23] R. Howard and B. Bjork, “Building information modelling – Experts’ views on standardisation and industry deployment,” *Advanced Engineering Informatics*, vol. 22, 2008, pp. 271-280.
- [24] R. Jardim-Goncalves and A. Grilo, “Building information modeling and interoperability,” *Automation in Construction*, 2009.
- [25] B. Dong, K. Lam, Y. Huang, and G. Dobbs, “A comparative study of the IFC and gbXML informational infrastructures for data exchange in computational design support environments,” *Tenth International IBPSA Conference*, Beijing: IBPSA China: 2007.
- [26] N. Hamza and M. Horne, “Building Information Modelling: Empowering Energy Conscious Design,” *3rd Int'l ASCAAD Conference on Em'body'ing Virtual Architecture*, Alexandria, Egypt: .
- [27] BRE Group, “BRE Group: BREEAM,” *BRE* <http://www.bre.co.uk/page.jsp?id=829> [Accessed February 28, 2010].
- [28] Google, “Google SketchUp” <http://sketchup.google.com/> [Accessed February 25, 2010].
- [29] D. Adams, *Zero Carbon Homes Programme Delivery Timeline*, Zero Carbon Hub, 2009.
- [30] Department for Communities and Local Government, *Building a Greener Future: Towards Zero Carbon Development - Analysis Report of Consultation Responses*, 2007.
- [31] J.A. Stewart, “X3D a write once, render anywhere, anytime 3D graphics format for HTML 5,” Dec. 2009.
- [32] H. Ishii, “The tangible user interface and its evolution,” *Communications of the ACM*, vol. 51, 2008, p. 32.
- [33] W. Bordass, R. Cohen, and J. Field, “Energy efficiency in non-domestic buildings: closing the credibility gap,” *Proceedings of the International Conference on Improving Energy Efficiency in Commercial Buildings*, Frankfurt, Germany: 2004.
- [34] D. MacKay, *Sustainable energy--without the hot air*, Cambridge England: UIT, 2009.
- [35] I. Pritchard and E. Willars, *Climate Change Toolkit, 01 Climate Change Briefing*, RIBA, 2007.