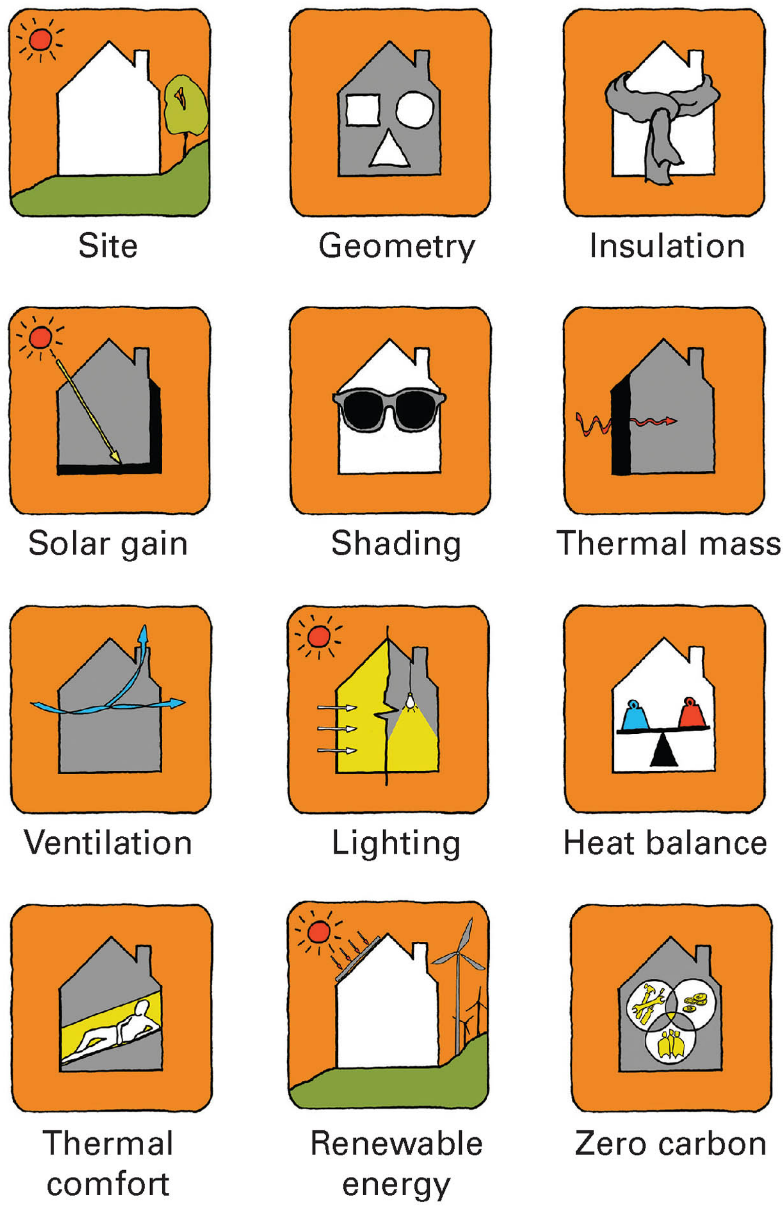
Designing ZERO Carbon Buildings Using Dynamic Simulation Methods

SECOND EDITION



Ljubomir Jankovic

Routledge

DESIGNING ZERO CARBON BUILDINGS USING DYNAMIC SIMULATION METHODS

In addition to the application of fundamental principles that lead to a structured method for the zero carbon design of buildings, this considerably expanded second edition includes new advanced topics on multi-objective optimisation; reverse modelling; reduction of the simulation performance gap; predictive control; nature-inspired emergent simulation leading to sketches that become 'alive'; and on an alternative economics for achieving the sustainability paradigm. The book features student design work from a Master's programme run by the author, and their design speculation for a human settlement on Mars. Tasks for simple simulation experiments are available for the majority of topics, providing the material for classroom exercise and giving the reader an easy introduction into the field. Extended new case studies of zero carbon buildings are featured in the book, including schemes from Japan, China, Germany, Denmark and the UK, and provide the reader with an enhanced design toolbox to stimulate their own design thinking.

Ljubomir Jankovic is Professor of Zero Carbon Design at Birmingham City University, UK. He conducts multidisciplinary research in the field of zero carbon design of buildings, and has established a research group called Zero Carbon Lab. He has worked on instrumental monitoring, dynamic simulation and environmental design of buildings over a career spanning three decades. He is Programme Director for a Master's course on Zero Carbon Architecture and Retrofit Design. He holds a BSc (Mech. Eng.) from the University of Belgrade and a PhD from the University of Birmingham, and is a Chartered Engineer, a Member of CIBSE, a Member of ASHRAE, and a Fellow of the Institution of Analysts and Programmers.

‘A clear and well researched user-orientated perspective on the latest zero carbon building design practice and software tools, this engaging book guides the reader through the basics before discussing current best practice techniques. High points are a structured application of the latest multi-objective design optimisation tools and a vision of how some promising new building materials and analysis techniques are likely to be applied in the future. Look out for advice not seen elsewhere, such as interoperability between energy modelling tools.’

Dr Andy Tindale, Managing Director, DesignBuilder Software

DESIGNING ZERO CARBON BUILDINGS

USING DYNAMIC SIMULATION METHODS

Second Edition

Ljubomir Jankovic

Routledge
Taylor & Francis Group
LONDON AND NEW YORK

Second edition published 2017
by Routledge
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

and by Routledge
711 Third Avenue, New York, NY 10017

Routledge is an imprint of the Taylor & Francis Group, an informa business

First edition published by Routledge 2012

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging in Publication Data
Names: Jankovic, Ljubomir, author.
Title: Designing zero carbon buildings using dynamic simulation methods /
Ljubomir Jankovic.
Description: Second edition. | New York : Routledge, 2017. | Includes
bibliographical references and index.
Identifiers: LCCN 2016038440| ISBN 9781138658301 (hb : alk. paper) | ISBN
9781138658318 (pb : alk. paper) | ISBN 9781315620909 (ebook)
Subjects: LCSH: Sustainable buildings--Design and construction. |
Buildings--Performance--Computer simulation. | Carbon dioxide mitigation.
Classification: LCC TH880 .J36 2017 | DDC 720/.47--dc23
LC record available at https://lccn.loc.gov/2016038440

ISBN: 978-1-138-65830-1 (hbk)
ISBN: 978-1-138-65831-8 (pbk)
ISBN: 978-1-315-62090-9 (ebk)

Typeset in Gill Sans Std
by Saxon Graphics Ltd, Derby

To my family

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ACKNOWLEDGEMENTS

A number of people helped generously in the preparation of this book, and I wish to thank them all, in no particular order. I wish to thank Birmingham City University for partial release from teaching while working on this book. Thanks also go to Emission Zero Engineering Architecture Ltd for access to their project material. Special thanks go to Greenpower Education Trust and Fordingbridge plc for their collaboration on the Greenpower Centre; to the Bournville Village Trust (BVT) for financial assistance related to the Rowheath Solar Village project and to Alan Shrimpton of the BVT and to Dr Leslie Jesch, my former PhD supervisor and good friend who sadly passed away in June, for their collaboration on the Rowheath Solar Village; to the Bioeconomy Consultants–NNFCC, to Mrs Cathie Eberlin of Leading Energy, to Ian Pritchett of Greencore Construction Ltd, Hab Oakus LLP and Linford C-Zero Ltd for their collaboration on hemp–lime related projects; and to Innovate UK, to Ron and Isabel Beattie of Beattie Passive Retrofit Ltd, and to Paul McGrath of Birmingham City Council for collaboration on RetrofitPlus project. Birmingham architect John Christophers helped generously with essential information, photographs and access for instrumental monitoring of his unique Zero Carbon House on which I have written a case study in one of the chapters. Photographer Martine Hamilton Knight provided high-quality photographs of John's house which stand out in comparison with my own photographs. I am grateful to Associated Architects of Birmingham; Cardiff University; Construction Industry Council of Hong Kong; Diocese of Worcester, UK; Koizumi Atelier of Yokohama; Rolf Disch Solar Architecture, Freiburg, Germany; Samuel Ashfield Photography; Tokyo Metropolitan University; University of Copenhagen; and VELUX, for providing material for case studies of zero carbon projects featured in the book. Special thanks go to Dr Andrew Tindale, David Cocking and Dr Yi Zhang for proofreading the material on multi-objective optimisation and making useful suggestions. I am also grateful to my current and former students Raquel Fachini, and Khan Prigboonchan for providing their design project material to be featured in the book; to Purvesh Bharadwaj, who in addition to providing his design project material featured in the book also assisted with Ataitiya Bana in preparation of models in RetrofitPlus project; to Roba Alnatour for providing a conceptual model for design on Mars; and to Michael Burnett for collaboration on complementary currencies research. My former student Holly Doron prepared wonderful hand illustrations for the cover, and she and Oliver Mould prepared illustrations for figures which improved the book's graphical appearance. Thanks also go to my numerous other former students who approached their coursework on scale model experiments with a lot more enthusiasm when they knew that some of their material may be used in this book, and whose scale models are acknowledged where they are referred to in the book. My daughters Katarina and Sofia, both recent graduates, proofread the manuscript and suggested useful style improvements. My family, who have been very tolerant of my long working hours and late nights, have given their unconditional support. The people concerned helped generously, without any obligation to do so, and I am very grateful to all of them.

All photographs, images and illustrations generously provided by others have been acknowledged accordingly, next to where they occur in the book. The screen images of software tools are acknowledged as follows: DesignBuilder, by permission of DesignBuilder Software Limited, www.designbuilder.co.uk; EnergyPlus™ Copyright © 2011, The Regents of the University of California, through Lawrence Berkeley National Laboratory (subject to receipts of any required approvals from the US Department of Energy). All rights reserved. Used by permission. EnergyPlus™ was developed with support from the US Department of Energy; IES Virtual Environment, by permission of Integrated Environmental Solutions Ltd, www.iesve.com; JEPlus/JEPlus+EA, by permission of Energy Simulation Solutions Limited, cms.ensims.com; and TAS Building Designer, by permission of Environmental Design Solutions Limited, www.edsl.net. Microsoft® Excel® for Mac 2011 is copyright © 2010 by Microsoft Corporation.

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Ljubomir Jankovic
Birmingham, 28 July 2016

DISCLAIMER

PART 1

INTRODUCTION

CHAPTER 1 **INTRODUCTION**

Why we need zero carbon buildings
Why we need this book
The place of this book in the context of other literature
Rationale for the second edition

CHAPTER 2 **DESIGN METHODS AND DESIGN TOOLS**

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CHAPTER 1

INTRODUCTION

A zero carbon building is a building that generates as much energy as it uses over a year and will therefore have net emissions of carbon dioxide resulting from energy consumption equal to zero.

There has been a growing sense that climate change is a hard, almost impossible problem to solve; that our targets for zero carbon are far in the future; and that our targets are hard to achieve. In this book I develop methodology for zero carbon design and demonstrate that it is perfectly possible to design new or retrofit zero carbon buildings today. By following this methodology we will be able to design buildings that are comfortable, economically viable and carbon-negative. We will learn that the use of dynamic simulation will be a prerequisite for the level of analysis and optimisation that will be needed in order to achieve zero carbon design.

I will show that zero carbon design also reaps financial return. In economic terms I will demonstrate that there are higher rates of return from a zero carbon investment than from any other financial investment, based on a detailed case study of a zero carbon retrofit building presented in this book. However, I will also show that not all zero carbon designs are economically viable, emphasising the need for economic analysis as an integral part of design methodology.

One of the key goals of the method for zero carbon design is to achieve thermal comfort. I will argue that zero carbon living is not about a considerable change of behaviour and use of woolly pullovers, but that it is about design that works with the climate rather than against it, that uses predominantly passive rather than active means for achieving thermal comfort, and that is well tested, integrated and optimised using dynamic simulation methods. My detailed analysis of an existing zero carbon home will show that high levels of thermal comfort have been achieved without use of extensive heating or cooling systems.

This book will therefore make a case for change: a change of the perception that climate change is an impossible problem to solve, a change of our financial investment models, and a change of attitude towards zero carbon design and zero carbon living.

And what will happen if the lights go off before we get there, before the change to zero carbon living takes place on a large scale? I will demonstrate that the world has enough energy for our needs. This energy comes from the sun, but whilst there have been significant developments in harnessing solar energy, most of it literally goes over our heads. I will discuss a need for a step change of technological development and a response on the scale of the planet that will be required to tap into this vast resource. I believe that the method developed in this book will be one of the humble steps forward in that direction.

Learning from the past, where some societies burdened themselves with unnecessary energy-intensive activities that held them back, such as the society of Easter Island discussed in Chapter 3, this book calls for a re-examination of what we globally do today, and for a careful targeting of effort that will move the world forward. We are at the dawn of a new revolution that can potentially be far greater than anything else that has happened before, but it will not happen automatically. I will argue that education, research, development and a change of economic models are the key to unlocking the potential of the future opportunities that lie before us.

WHY WE NEED ZERO CARBON BUILDINGS

As we start to come to terms with climate change and its long-term consequences that will affect the next few generations, the demand for zero carbon design of buildings is influenced both by legislation and by the increased awareness of building owners and users.

Climate change is caused by greenhouse gases, such as carbon dioxide, methane, nitrous oxide and others. Carbon dioxide is the most significant contributor, produced by burning fossil fuels. Energy used in buildings contributes to 40% of carbon dioxide emissions. As the earth receives heat from the sun, greenhouse gases prevent heat loss into space, making the earth a heat trap.

How did we get here?

Historically, there are two major revolutions that have governed the current state of use of global resources: the agricultural and industrial revolutions.

The agricultural revolution occurred around 6,000 years ago, when food production was established and food surpluses were generated that enabled people to specialise in non-food production activities. That led to the development of complex societies and political systems (Diamond, 2005).

The industrial revolution occurred around 250 years ago, where the transition to new manufacturing processes led to rapid development of technology and was made possible by abundant reserves of coal. The industrial revolution has been very successful in supporting a much larger global population, more than 600 times larger than the population that existed before the agricultural revolution. However, it has had a major impact on the global use of resources.

Buildings leading up to the industrial revolution had a strong relationship with the local site and climate. Natural materials were used from the close proximity of the site, and design was responsive to the structural and environmental properties of these materials and the local climate (Weber and Yannas, 2014). However, industrial revolution has created machines that made it possible to bring building materials from far away, and to create internal conditions that work independently from the local climate. Buildings have become intensively serviced machines, and no longer have a strong relationship with the climate and site, and thus have become internationalised, all made possible by the extensive use of fossil fuel resources.

Additionally, industrial revolution has brought about the notion of growth economy. Today, economic growth is considered to be one of the measures of the health of our economy, implying that it can grow indefinitely. But infinite growth cannot be sustained on a finite planet, meaning that an alternative non-growth imperative has started receiving interest (Zovanyi, 2013).

In 1972 a study about the future of our planet was conducted by a group of scientists at the Massachusetts Institute of Technology. The research was based on computer modelling of a number of scenarios in which the world could develop. The study modelled five variables: population, industrialisation, pollution, food production and resource depletion. Although the computer model used a great deal of aggregation and was not as detailed and sophisticated as those of today, the results of the study were of great concern to many people. It demonstrated that most scenarios led to an overshoot by going beyond the limits of global resources, followed by a collapse of global society in the second half of the twenty-first century. This research was published in a book *The Limits to Growth* (Meadows *et al.*, 1974), which reached 12 million readers in 37 languages.

Stark reminders of the state of the world's resources that corroborated this study followed in the form of the 1973 oil crisis and 1979 energy crisis. As there was an increasing awareness about the world's climate, the first World Climate Conference was held the same year. In the years that followed, this increasing awareness underpinned by research led to the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988. With more scientific evidence emerging from the IPCC studies, the United Nations Framework Convention on Climate Change was adopted at the Rio Earth Summit in 1992, and the countries that ratified the Convention were named 'Parties to the Convention'. The main objective of the Convention was 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system' (United Nations, 1992, p. 9).

The Kyoto Protocol, a treaty ratified in 1997, gave the Convention an operational status, by establishing legally binding targets for the reduction of greenhouse gases. To enforce it, the European Parliament and Council ratified a Directive 2002/91/EC, known as the Energy Performance of Buildings Directive (EPBD), resulting in national changes of building regulations and long-term commitments of European governments towards carbon dioxide reduction.

In response to the EPBD, the UK Parliament published the world's first Climate Change Bill in 2007, setting out CO_2 reduction targets of 32% by 2020, and 60% by 2050, in comparison with 1990 levels (House of Lords, 2007). This target was subsequently amended to 80% by 2050.

The Convention is now ratified by 195 countries, and regular UN Climate Change Conferences, named Convention of the Parties or COP have been held since 1995. The COP21 meeting in Paris in 2015 brought together the countries that ratified the Convention. A consensus was reached about the urgency for a global agreement and the importance for achieving net zero emissions during the second half of the century.

The challenges arising from climate change, no matter how hard they seem, can also be seen as great opportunities for change and improvement. We are living at a time of great change, comparable to the time of great inventions such as that of the motor car for instance, when new products and services emerged and old products and services disappeared. Kauffman (2010) in his book *Reinventing the Sacred* remarks that the invention of the motor car has resulted in 'creative destruction', making horse-based goods and services such as carts and saddles obsolete, and causing the collapse of the whole range of industries that created them. At the same time, new products, services and ways of living emerged: oil, roads, fuel stations, motels, suburbia and many other products and associated industries.

The change from the world of fossil fuels to a world of non-fossil fuels is likely to be much larger in scale than the change resulting from the invention of the motor car. Bearing in mind the lessons learnt from the past, we can look at these forthcoming changes with excitement, and embrace them fully as they open up new unseen possibilities. This is the time for great creativity and innovation in which we can work on changing the world like it has never been changed before.

WHY WE NEED THIS BOOK

As commitments for CO_2 emission reductions increase through global awareness and legislative pressures, there is an apparent lack of textbooks on the method for the zero carbon design of buildings. Dynamic modelling and simulation of buildings are the only means of testing designs before construction but the material published in this area is reduced to very basic user manuals of corresponding software tools. This book fills the gap as it develops a structured design method underpinned by dynamic simulation.

I hope to convince you that designing zero carbon buildings is not something that will only be possible in the distant future. We already have the necessary knowledge and tools, and I hope that you will agree after reading this book that designing zero carbon buildings is something that can be done on a regular basis already, today.

The 2015 United Nations Climate Change Conference COP21 reached a consensus about the importance for achieving net zero emissions during the second half of the century, but no global agreement was reached about *how* this will be achieved.

These challenging targets and the absence of a global plan require a new consolidation and integration of design methods. The book aims to facilitate this through a structured design process using dynamic simulation as a design and performance evaluation tool, drawing on my experience of teaching, research and practical design work.

At the time of writing this text, the implementation of the Paris agreement was still some years away and without a global plan, with the national policies of some countries still to be aligned with it. In the absence of a global plan, this book contributes to answering the *how* question. It makes a small but important contribution towards one of the most important solutions for humanity.

THE PLACE OF THIS BOOK IN THE CONTEXT OF OTHER LITERATURE

I will now highlight similarities and differences between this book and existing literature.

This is a 'how to' book focused on dynamic simulation methods for zero carbon design. It is intended to provide detailed guidance to the reader about converting principles of building physics into zero carbon design using detailed dynamic simulation methods. The material is provided in a way that enables the reader to repeat the design simulation steps and thus carry out his or her own design independently.

CIBSE AM11: Building Performance Modelling (Awbi, 2015) provides guidance on a range of different aspects of modelling, including modelling of energy, thermal environment, ventilation, lighting, plant and renewable systems, and modelling for compliance with regulations. It provides a detailed expert overview of building modelling in these areas and guidance on quality assurance in modelling. Although it contains references to zero carbon buildings, it does not focus on their design. It is highly complementary to my book and I strongly encourage the reader to consult it as background material.

The Passivhaus Designer's Manual: A Technical Guide to Low and Zero Energy Buildings by Hopfe and McLeod (2015) gives an in-depth account of principles that underpin a Passivhaus building and describes initiatives for near zero energy and energy plus projects. However, it does not go into details of how to integrate these principles into an overall design. Additionally, Passivhaus buildings are designed using PHPP (Passive House Institute, 2015b), a spreadsheet-based calculation tool that uses 12 sets of monthly inputs per year for design calculations. In contrast, my book uses dynamic heat transfer calculations in hourly time steps, hence 8,760 sets of inputs per year, and it provides detailed guidance on how to integrate the principles of building physics into holistic designs of zero carbon buildings.

Sustainable Architectural Design: An Overview by Iyengar (2015) is a high-level ideas book about sustainable design, which examines the subject in broad terms; however, it does not go into details of how to actually carry out the design.

Sustainable Building Design: Learning from Nineteenth Century Innovations by Lerum (2015) is an overview of the application of technological innovations and first principles that determined best performing buildings until the present time. Being based almost entirely on case studies, it provides useful complementary information for this book.

Introduction to Architectural Science: The Basis of Sustainable Design by Steven Szokolay (2014) deals with physics principles of heat, light and sound in buildings, but does not have an ambition to guide the reader towards zero carbon design. In clear contrast, the main objective of my book is to integrate various principles of physics, analysis and application methods into a zero or low carbon design.

A holistic companion for this book is another 'how to' book entitled *Integrated Sustainable Design of Buildings* by Paul Appleby (2011), which looks into a wide range of sustainable design issues and their design integration.

The Environments of Architecture: Environmental Design in Context by Randall Thomas and Trevor Garnham (2008) goes some way towards describing the subject of environmental design. However, it covers only a limited number of issues and is therefore short of a coherent method for zero carbon design.

The ZEDbook: Solutions for a Shrinking World by Bill Dunster and co-workers (Dunster *et al.*, 2008) deals with the same subject. However, it does not appear to give practical guidance to the designer, as it primarily focuses on the description rather than on the method. My book is focused on the method, and is expected to be used by designers and students alike, both as a textbook and as a handbook.

Paola Sassi (2006), in *Strategies for Sustainable Architecture*, deals with a range of subjects such as community, health and well-being, materials, energy, water and land use. These issues are complementary to my book, as they look into a wider aspect of architecture, instead of the method for zero carbon design. Sassi's book would therefore be a good companion for this book.

The Green Studio Handbook: Environmental Strategies for Schematic Design, by Alison Kwok and Walter Grondzik (2006) contains elements of the design method; however, it does not follow it through in a logical manner, as it alternates between building energy efficiency and renewable energy systems (i.e. between architecture and machinery). The Kwok and Grondzik book also does not demonstrate an ambition for zero carbon design. However, it follows the design method consistently, leading towards a holistic conclusion of integrated passive design and renewable energy systems.

The HOK Guidebook to Sustainable Design by Sandra Mendler and co-workers (Mendler *et al.*, 2005) gives design process guidance in the form of checklists. It then moves on to building types, and concludes with case studies. Although the book deals with the design process and has extensive case studies, it does not develop the method and there is no ambition for zero carbon design.

Green Buildings Pay by Brian Edwards (2003) looks at a number of ways in which environmentally sound buildings can give financial returns. It makes a case for designing a green building and then focuses on a range of detailed case studies which illustrate the main point, which makes it complementary to this book.

Of course I do not mean to say that this book is superior to all of the above published material. It merely covers a specific angle of the subject that differentiates it from other books; however, these other books will cover certain aspects of the broader subject area in more detail. I would therefore encourage the reader to consult this other material as background reading.

RATIONALE FOR THE SECOND EDITION

Whilst the fundamental principles of building physics have remained the same, a few important things have changed since the first edition.

One of the most significant changes has been the development of optimisation methods that work with dynamic simulation. Instead of considering a small number of design possibilities and seeking the best solution amongst these, we can now consider several million possibilities for a single design, and use genetics-inspired computation methods to seek optimum solutions. This edition will introduce these new methods as a new extension to the structured method for zero carbon design.

There were only a few examples of zero carbon buildings at the time of writing the first edition, but the number of examples have now increased considerably, indicating that zero carbon projects are becoming less of an exception and more of a norm. This edition will capture a range of case studies of these recently emerged zero carbon projects.

Since the first edition was published, I have developed a new Master's programme on Zero Carbon Architecture and Retrofit Design, and this has led to interesting explorations and designs by my students. This edition features a selection of results from this Master's programme, introducing zero carbon designs in the different parts of the world that the individual students came from.

This edition responds to structured and constructive feedback received by the publisher from the readership of the first edition. In response to this feedback, most chapters now include tasks for simple simulation experiments that can be either carried out in groups as part of teaching or in students' own time, thus expanding the teaching scope of this second edition, and helping students focus on experimentation and exploration.

Since the time of the first edition I have also organised an international conference on Zero Carbon Buildings Today and in the Future, which has now become a conference series. This created an interesting sample of the worldwide activity in the field, reflected in this edition.

One of the suggestions received as part of the feedback was to introduce an overview of 'where the cutting-edge research currently sits in this area'. As a result, I have written a new chapter on research, in which I have introduced the most recent developments in advanced methods.

I was once asked whether much research goes into writing a book. I am not sure about other books, but in the case of this one numerous computational experiments had to be carried out repeatedly until clear methodology emerged, before there was something to write about. This edition brings the results of such research to the reader in an easy-to-use form, with an aim to help scale up the application of this methodology for the benefit of all of us and of the world that we will leave to our children and grandchildren.

CHAPTER 2

DESIGN METHODS AND DESIGN TOOLS

Before a simulation of building performance can be carried out, a computer model of the building needs to be developed. The term *modelling* is defined as making a logic machine which represents the material properties of the building and physics processes in it. *Simulation* is then defined as numerical experimentation with the model so as to investigate its response to changing conditions inside and outside the building. Models which are based on first principles and are capable of replicating dynamic heat transfer in a building in response to external and internal influences on the timescale of one hour or less are called *dynamic simulation models* (DSMs).

Modelling involves a certain degree of abstraction. A simulation model is not a detailed representation of all geometry and all processes in a building but just of those aspects of geometry and processes that are important for objectives of our analysis. According to John Holland, one of the early pioneers and giants of computer science, 'the art of model building turns on selecting a level of detail' (Holland, 2000, p, 46). In the creation of a dynamic simulation model, the importance of abstraction through setting a level of detail is comparable with the process of making architectural scale models. It 'means taking away any unnecessary components or detail that will not aid the understanding of the design being communicated' (Dunn, 2010, p. 28).

Computer modelling is, however, different from architectural modelling as it changes with time. Generally it involves capturing a definition of a real world system (in our case a building) at time 't' through observation and measurement, applying abstraction and transferring this definition into model domain at time 't', running the model for one time step till time 't+1', and transferring the results into real world domain and interpreting their meaning at time 't+1' (Holland, 2000). Abstraction and interpretation are therefore two critical aspects of dynamic simulation modelling.

DESIGN APPROACH

The main design principle that will be adopted in this book will be that of experimentation with a DSM. In order to design a zero carbon building, we first need to reduce energy demand by improving building energy efficiency. After the energy efficiency has been maximised, we then need to consider the efficiency of various systems and various renewable energy options that are suitable and feasible for the building we are designing. Energy efficiency and carbon emissions analysis, together with economic analysis and comfort analysis, are essential ingredients of this method, which ensure the overall success of a design. Details of this design approach will be presented throughout this book. A simple example of improving energy efficiency using multiple simulations is described in the optimisation section later in this chapter.

DESIGN VARIABLES

The variables that we will be able to affect by design are:

- response to climate context: climatic conditions for a particular location, taking into account predicted climate change

- response to site context: solar radiation, building orientation, prevailing winds, site configuration, overshadowing by the land configuration or existing objects
- building geometry
- thermal insulation
- airtightness
- passive solar gain
- thermal mass
- natural ventilation
- natural daylight
- electrical lighting
- renewable energy systems
- internal heat gains
- additional heating or cooling.

These variables will be discussed in detail in corresponding chapters in this book.

DESIGN TOOLS AND EVALUATION TOOLS: DSM VERSUS SAP, SBEM AND PHPP

We need to differentiate very clearly between what is and what is not a design tool. As we can see from the introductory part of this chapter, DSMs are based on first principles, running on timescales of one hour or less, and are for that reason capable of replicating dynamic performance of the building that is close to the performance of its real world equivalent – a building constructed on the basis of DSM design. Therefore, using a DSM, a designer can establish relative merits of different design options. This makes DSM a *design tool*.

Methods that are used to investigate building performance in response to much larger timescales of monthly changing conditions or on the basis of one calculation per year are not DSM and cannot be used as design tools. These methods, which we consider merely as performance *evaluation tools*, such as SAP – Standard Assessment Procedure (BRE, 2012), SBEM – Simplified Building Energy Model (DCLG, 2015), and PHPP – Passive House Planning Package (Passive House Institute, 2015b) are outside of the scope of this book.

It is important to understand that information content offered by evaluation tools is not sufficient to fully evaluate building performance. I experienced this first-hand when running a DSM model and an evaluation tool of the same building. The DSM model revealed a significant overheating problem in the building, but no overheating was reported by the evaluation tool. This is easily understood when considering the difference in resolution between evaluation tools and DSM tools. The former use 12 sets of numbers if they are based on monthly average calculations, and the latter use at least 8,760 sets of numbers equal to the number of hours in the year, taking even sub-hourly time steps for more detailed calculations, and applying dynamic heat transfer principles. If we are given a choice of two computer screen resolution of 12 pixels and 8,760 pixels it is intuitive that we will get much more information from the higher resolution than from the lower resolution screen. Taking this analogy back into the domain of building performance calculation, it is apparent that most of the information generated by DSM will not even be on the 'radar' of the evaluation tools – it will simply not be visible there.

CREATING A DYNAMIC SIMULATION MODEL

The creation of a dynamic simulation model may appear to be a complicated process; however, it can be considerably simplified by breaking it down into several major subtasks. First, the user needs to define the geometry of the building in three dimensions. Second, the site location needs to be specified together with the associated weather data file. Third, building construction types need to be defined, including all building components such as walls, floors, ceilings, windows and doors, and these need to be assigned to the corresponding building geometry. Fourth, building use patterns need to be defined, including room conditions, internal gains, and infiltration and ventilation air exchange. Fifth and finally, heating and cooling systems need to be defined and associated with corresponding parts of the building.

Within these five tasks, other subtasks need to be performed, depending on specific requirements related to individual buildings. We will address these subtasks in the context of individual subject areas in the chapters of this book.

Commercial DSMs contain ready-made generic models of buildings. Modelling therefore involves filling in the blanks of the generic model, to make it specific for the analysed building. However, any remaining blanks filled in by the software as default parameters can considerably affect the results.

Despite the simplified process of the creation of a DSM described here, and in the context of the default parameters used by some models, the complexity of modelling should not be underestimated. Dynamic simulation is to some extent comparable to playing the violin: one needs to practise a lot, learn a lot, and use all of one's skills to perform well. This book is intended to point the reader some way towards achieving this capability.

PLANNING AND RUNNING SIMULATIONS

Before running any simulations, we must first define the design objectives, and then define design variables and their values which will be investigated in order to achieve these objectives. Depending on the number of simulation cases to be investigated and the approach to this investigation, we can either carry out a single simulation, or a series of parametric simulations, or optimisation that takes into account a large number of simulation cases.

SINGLE SIMULATIONS AND PARAMETRIC SIMULATIONS

One of the best ways to plan simulations is to list all design variables that need to be investigated during the simulation into a table. These variables are assigned discrete values within a specified range during the simulation. These discrete values effectively represent what-if scenarios, and assigning a single value to a single variable at a time will enable us to find out the effect of that variable on building performance. An example of a plan for a simple simulation analysis from a real-life project is shown in Table 1.

A *single simulation* run is carried out with a single set of design variables and single values for these design variables. This is useful if no comparison between different design options is required, although this is very rarely the case.

Multiple simulation runs are carried out when a comparison between design options is required. In such cases, each value assigned to each design variable, as in Table 1 for instance, is considered to be a parameter, and combinations of all these parameters through several single simulations is called *parametric simulation*.

Here is an example of investigation of energy performance of four building types at the design stage, with an objective to select the best building type and related parameters. The results of the simulations were then interpreted and supplied to a design team. Subsequently an estate of houses was designed and built on this basis.

TABLE 1 SIMULATION TABLE – EACH CASE FROM EACH ROW IS SIMULATED WITH EACH OTHER CASE FROM EACH OTHER ROW					
Design variable	**Values assigned to design variable**				**No. of cases**
Building type	Datum type: masonry, cavity wall, insulation as per building regulations	Heavy weight type: all masonry, super-insulated	Light weight type: timber frame, masonry core, super-insulated	Hybrid type: masonry core, timber-frame skin, super-insulated	4
South glazing increase by (%)	50	100	150	200	4
Density of masonry (kg/m^3)	650	1,300	2,000	–	3
Mechanical ventilation (m^3/day)	11,000 no heat recovery	27,000 no heat recovery	27,000 plus heat recovery	–	3
Total number of cases (product of the above) =					144

Figure 1 shows a simulation analysis of four different construction types. One type needs to be chosen to build an estate of houses. The simulations of each construction type were conducted using an annual weather data set for the location in which the houses were to be built, and with a number of assumptions, as set out in Table 1. From the results of this analysis (Figure 1), the advice given to the design team was to use the hybrid construction type.

Another simulation analysis taken from Table 1 had the objective to establish the optimum size of the south-facing windows (Figure 2). When the surface area of the windows is too small, the building does not receive enough solar energy, and therefore the annual heating energy consumption is higher than the optimum. If the window sizes are increased in small steps, the building will be receiving more solar energy than the amount of heat losses through the windows, and the conventional heating energy consumption will be decreasing. After the optimum window size is reached, increasing the surface area of windows will make the heat losses through windows greater than the heat gains from solar radiation, and the conventional heating energy consumption will be greater. From the results in Figure 2 it appears that the optimum window size is 150% of the original size, and therefore the advice given to the design team was to increase the window size by 50%.

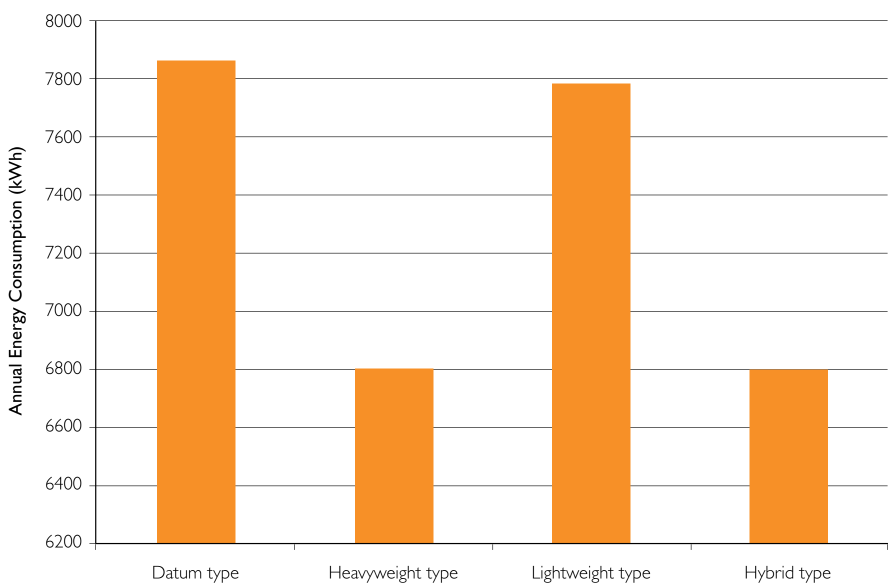


Figure 1 Simulation analysis of four construction types

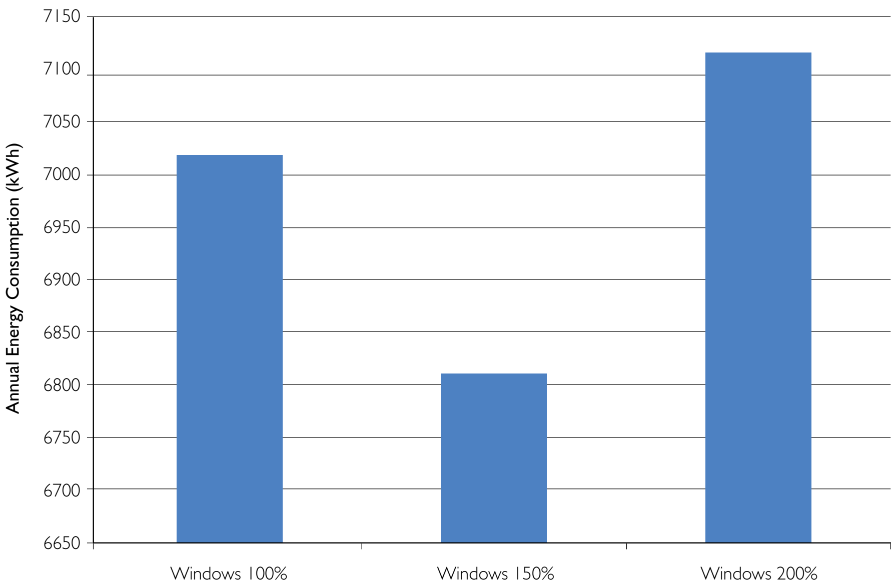


Figure 2 Simulation analysis of south-facing window sizes

SINGLE-OBJECTIVE AND MULTI-OBJECTIVE OPTIMISATION

Depending on the number of combinations of different parameters, parametric simulations can produce a very large number of single simulation outputs, and searching through these outputs manually may become very time-consuming and in many cases an impossible task. This is where optimisation search methods become very useful. There are two types of optimisation: single-objective and multi-objective optimisation, where the objective is a function that needs to be optimised.

Optimisation is a process of finding either a minimum or a maximum of a function, by finding values of independent variables for which the objective function reaches its maximum or minimum value. In the context of building simulation, the independent variables are design variables. Optimisation always seeks a global minimum ($y = y_{min, G}$) or maximum, as opposed to a local minimum ($y = y_{min, L}$) or maximum that represents a suboptimum, in other words 'not so good' performance (Figure 3). The simplest case of optimisation is a single-objective optimisation in which the objective function has only one independent variable. For instance, Figure 2 shows the process of finding the best solution for energy consumption of a building, depending on the south-facing window size. The best solution in that particular case, the minimum energy consumption, is achieved for a south-facing window size that is halfway between the initial window size and the window size that is doubled. In that example, the single-objective function is the annual energy consumption, and the independent variable is the window size. The result of the single-objective optimisation, which is carried out manually in that example, is the value of the independent variable, the window size that achieves the optimum, in that case the minimum energy consumption.

Single-objective optimisation with a single independent variable is relatively straightforward. Unless there are any local minima where the optimisation process could get locked into (Figure 3), it will quickly proceed to finding the best solution.

Multi-objective optimisation will be typically looking at two or more objective functions, such as energy consumption and cost, and each of these objective functions will have its own or shared independent variables. These multiple objectives and corresponding independent variables will create a multidimensional solution space, in which optimisation is far from trivial.

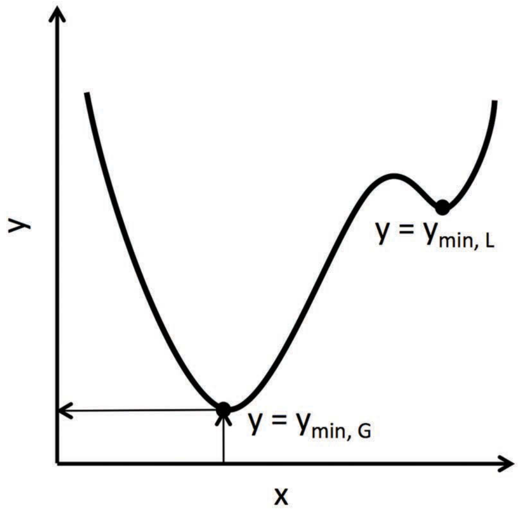


Figure 3   Local and global minimum of a function with one independent variable

As different combinations of design variables can amplify each other (for instance volume to surface ratio and glazing surface area) or oppose each other (for instance thermal insulation and glazing surface area), optimisation will analyse their combined effect, thus giving an insight into building performance that cannot be achieved by single individual simulations.

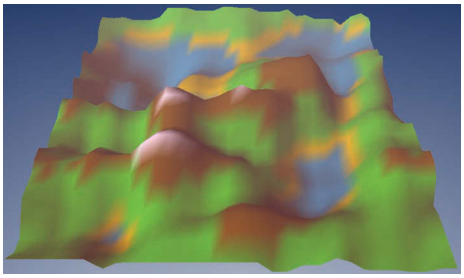
Multidimensional solution space: 'God's view' and 'pedestrian's view'

Let us consider two objective functions: (1) to minimise operational carbon emissions; and (2) to minimise discomfort. The independent variables shared between these two objectives could include those shown in Table 2.

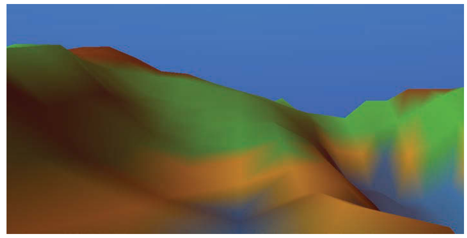
This large solution space containing over 8 million variations of a single design will be optimised using evolutionary computation methods that search such large spaces quickly, in order to achieve minimum CO_2 emissions and minimum life-cycle cost normalised to the present value.

TABLE 2   AN EXAMPLE OF DESIGN VARIABLES INVESTIGATED IN MULTI-OBJECTIVE OPTIMISATION

Design variables and values assigned to these	No. of cases
Site orientation (clockwise declination from north): min = 140°, max = 220°, step = 10°	9
External wall construction: U-value (W/m^2.K): 0.26, 0.18, 0.10	3
Roof construction: green roof U-value (W/m^2.K): 0.10, 0.16, 0.25	3
Thermal mass: insulated ground-floor concrete slab U-value 0.10, 0.16, 0.22; internal slab: timber floor, 100 concrete, 150 mm concrete	6
Airtightness (m^3/h/m^2): min = 0.5, max = 4, step = 0.5	8
Glazing: double, triple, quadruple	3
Electrical lighting power density (W/m^2/100 lux): 3, 2, 1 uncontrolled, plus 3, 2, 1 linear dimming control (daylight following)	6
Window-to-wall ratio (%): min = 20, max = 80, step = 20	4
External window opening (%): min = 0, max = 80, step = 20	5
PV array: six different sizes to facilitate optimisation	6
Total number of cases (product of the above) =	8,398,080



(a) 'God's view'



(b) 'pedestrian's view'

Figure 4 Conceptual multidimensional solution space

As there are ten independent variables in this example, the solution space therefore becomes ten-dimensional. In order to visually illustrate the problem, and as it is difficult to visualise the ten-dimensional space, a three-dimensional analogy will be used for explanation. In this analogy, the solution space consists of hills and valleys (Figure 4) and the highest hill or the deepest valley will be the best solution. If we had 'God's view' (Figure 4a), it would be easy to see where the highest hill or the deepest valley is.

However, when starting from the surface of the solution space, we in fact have a 'pedestrian's view' (Figure 4b), and the horizon might look the same in all directions, so that we will not know where to go to find the highest hill or the deepest valley. Following an initially promising path, our search for the optimum solution might lock into a local minimum, and result in model parameters that give suboptimum performance.

There are many well-established numerical methods for dealing with this kind of problem of multidimensional optimisation, and one of the most efficient of these methods is based on evolutionary computation, namely on genetic algorithms. Building simulation tools with multi-objective optimisation capabilities primarily use a method by Deb *et al.* (2002) named 'NSGA-II: A fast and elitist multiobjective genetic algorithm'. This method will give us 'God's view' that we need in order to find the optimum solution in the multidimensional solution space.

In typical practice, designers only consider a small number of variations of design parameters, and carry out a small number of single simulations, perhaps not more than half a dozen or so, and a single-objective function, potentially leading to suboptimum building performance and significant missed opportunities. In contrast, the above approach that potentially considers over 8 million possibilities for a single design will give a range of solutions and an opportunity for trade-off choices between cost and CO_2 emissions, whilst ensuring minimum discomfort levels.

TOOLS FOR PARAMETRIC SIMULATION AND MULTI-OBJECTIVE OPTIMISATION

The need to run building simulation with different values of design variables and to find optimum building performance from a combination of a number of alternative values of parameters has created a new range of tools, or new functionality within existing simulation tools. Thus DesignBuilder, JEPlus/JEPlus+EA, TRNSYS and others now have capabilities for parametric simulation and multi-objective optimisation.

VALIDITY OF SIMULATION RESULTS FOR DESIGN DECISION MAKING

Until simulation models are experimentally validated, building simulations cannot give absolute answers. The results can be 100% wrong, as a number of default parameters in the simulation model may have not been set by the user. So why simulate? Because simulation has great value as a comparative analysis tool. It is easy to tell from simulation analysis which design option is better, when compared with other design options from the same simulation model. What is not easy to tell is how good these individual options are in absolute terms. In this way the design team can be advised on the relative significance of design parameters, and use the simulation results as a decision-making tool for trade-offs between various design options.

Model calibration

Calibration is a process of increasing the accuracy of a simulation model by comparing its output with measured data and adjusting its parameters in order to reduce the discrepancy between the two. The existence of 'measured data' suggests that this process applies to existing buildings, which either have energy bills, or are monitored in regular time intervals with instruments.

Calibration can be described as a process analogous to bracketing in artillery fire (Figure 5), so that the error 'bracket' is reduced by changing parameters of the model until desired accuracy is achieved.

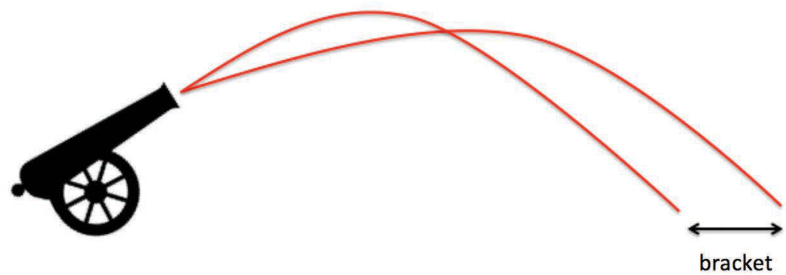


Figure 5 Calibration as analogous process to bracketing in artillery fire

The simplest way of calibrating the simulation model is to use measured annual energy consumption figures and adjust the model to produce outputs that closely match these figures. In the absence of any detailed performance monitoring, these measured figures can come from energy bills.

Whilst this type of calibration guarantees annual performance accuracy, it does not guarantee the accuracy of dynamic response of the simulation model to time-dependent inputs. In order to overcome this limitation, a second calibration is required, in which hourly outputs are compared with hourly data from instrumental monitoring, and root mean squared error between the two is minimised over the entire simulation period.

However, in cases of calibration of time-dependent simulation outputs, such as hourly room air temperatures, it is no good using library weather data files. Instead, the weather data file needs to be synthesised using hourly data from monitoring. In other words, actual weather data that created the building response needs to be used to drive the simulation model during the calibration process from within the weather data file used by the simulation tool.

EnergyPlus Weather (EPW) data files are suitable for this process, as they are well documented (Crawley *et al.*, 1999), available for numerous locations around the world, and available in plain text format. The process of synthesising the weather data file takes the following steps.

1. Convert <weather_file_name>.EPW for the location of the simulated building into <weather_file_name>.CSV, where extension CSV means 'comma separated values'. The file then becomes readable and editable by spreadsheet programs. Open the CSV file in a spreadsheet program.
2. Referring to weather data specification developed by Crawley *et al.* (1999), locate the columns in the weather data file to be replaced by data from monitoring. In the case of dry-bulb temperature and relative humidity, the replacements are straightforward. However, in the case of certain other parameters, such as dew point temperature, direct normal radiation and others, these need to be calculated from available monitored data before the replacement, and that will require relevant expertise.

3 After all intended replacements of data columns are completed, save the file as <modified_weather_file_name>.CSV, rename it into <modified_weather_file_name>.EPW, and place the file in the directory of weather data files for the corresponding simulation tool.

This makes the weather data file ready for the purpose of calibration of the simulation model with reference to hourly time-dependent building performance parameters.

SIMULATION PERFORMANCE GAP AND HOW TO DEAL WITH IT

Differences between theoretical values and user assumptions in the simulation model on the one hand and actual properties of the building and the conditions in and around it on the other hand cause a discrepancy called performance gap.

The performance gap in existing buildings can be eliminated by a process of calibration of the simulation model using actual performance data. However, as simulations are predominantly conducted for design purposes, when the building does not yet exist, the calibration is not possible.

Findings by Menezes *et al.* (2012) suggest that some of the reasons for performance gap are shortcomings of simulation tools and poor assumptions made and implemented by their users. Studies by Carbon Trust, RIBA, and CIBSE (Carbon Trust, 2011; RIBA/CIBSE, 2010), divide the causes of performance gap into regulated energy (from fixed building services), unregulated energy (from plug loads, lifts etc.), poor commissioning, maintenance and control.

As one of the possible ways of reducing the performance gap, Menezes *et al.* (2012) suggested a development of realistic building energy performance benchmarks on the basis of post-occupancy monitoring data. However, this approach would only provide information for the calibration of simulation models using single annual figures for heating and electricity energy consumptions. As explained in the previous section, that would help with improving accuracy of annual performance of simulation models, but it would not help with improving dynamic response to time-dependent inputs on an hourly basis.

I worked on an alternative approach, which creates a relationship between the simulated and monitored building performance of an existing building on an annual basis in the form of a 'digital filter'. After the filter has been created, its application to a non-existing building of a similar type morphs the output of the simulation model into values that are equivalent to the results from the monitoring of that non-existing building (Jankovic, 2013), something that sounds intuitively impossible. This approach offers opportunities for development of dynamic benchmarks in the form of digital filters applicable on an hourly basis throughout the simulation year. As performance gap is particularly significant in the cases of buildings made from photosynthetic materials, such as hemp–lime biocomposite, there is experimental evidence that this approach can lead to significant improvements of accuracy of design analysis, leading to significant capital and operational savings in buildings (Jankovic, 2016a).

PHYSICAL SCALE MODELS VERSUS DYNAMIC SIMULATION MODELS

Physical scale models (Figure 6) are suitable for the investigation of certain aspects of building behaviour. Because of a difference in dimensions between the actual building and the scale model, physical models are less suitable for investigation of thermal comfort. To scale a building down ten times (a scale of 1:10) to the size of a physical model, thicknesses of all materials need to be scaled down proportionally. We will show throughout this book how scale models can be used to investigate certain aspects of building performance, such as thermal insulation, thermal mass, natural ventilation and natural daylight.

Figure 6 Physical scale models of various aspects of building performance created by my students

However, scale models need to be built using real materials; instrumentation systems are required to monitor their behaviour; and we cannot put people into them to tell us how they feel. DSMs overcome these disadvantages and have a much wider application scope than physical scale models. Whereas we can use a physical scale model to investigate a particular aspect of building behaviour, a simulation model can be used to investigate multiple aspects of behaviour simultaneously.

OVERVIEW OF DYNAMIC SIMULATION TOOLS

BEST ('Building Energy Software Tools' Directory[1]) contains information about more than 100 software tools. Some of these tools are suitable for whole-building analysis, and some are specialised for: demonstrating compliance with codes and standards; lighting; ventilation; HVAC components and systems; and other various aspects of building energy performance.

It is clearly not practical to review all of these software tools in this book. Instead, I will focus on the tools that I have used in this book, in alphabetical order.

DesignBuilder

DesignBuilder (DBS, 2016) is an advanced modelling tool. A dashboard user interface contains the majority of controls available from a single screen, which is reconfigured according to the type of editing operation being carried out.

In addition to energy simulation, DesignBuilder can carry out heating and cooling design calculations, computational fluid dynamics (CFD) simulation, daylighting simulation, and it can calculate construction cost and embodied carbon.

A particularly useful and well-developed aspect of energy simulation in DesignBuilder is multi-objective optimisation, which is becoming one of the major directions in which the building simulation field is developing. Optimisation will be discussed in detail elsewhere in this book, and will be used as one of the main methods for zero carbon design in Chapter 17.

A simulation model is created in 'Edit' mode (Figure 7). The user first needs to create a site, and define its layout, location and region, where the simulation weather data file is also selected.

DesignBuilder uses EPW data files in native format, as EnergyPlus is its main simulation engine. After setting the site parameters, the user needs to create a building and can define:

- layout: creation of building geometry;
- activity: specification of activity templates, internal heat gains, environmental control settings etc.;
- construction: specification of wall/floor/roof constructions, airtightness and costs, and including material choices from conventional to PCM;
- openings: specification of windows, doors and vents;
- lighting: specification of electrical lighting power density, lighting controls and costs;
- HVAC: specification of heating, cooling, DHW, natural and mechanical ventilation, earth tubes, and costs.

In addition to the above settings which are necessary for energy simulation, the following optional settings are also available:

- generation: renewable energy generation settings if applicable;
- outputs: heating and cooling design and simulation output options, if non-default outputs are required;
- CFD: applicable only if computational fluid dynamics analysis is carried out.

Building geometry is specified under 'Layout' editing, either created using 3D solid modelling tools, or imported from a BIM model in gbXML (Green Building XML) format. Geometry of simulation models have an architectural look and feel (Figures 7 and 8).

All dialogues give comprehensive written and visual access to various controls. For instance, setting a construction type opens a dialogue box with several different tabs, which enable the user to select construction layers and choose materials and their properties (Figure 9a). Another tab then gives the corresponding U-value calculation (Figure 9b), reminding the user that this steady state value is not used in dynamic simulation. This will be elaborated upon in Chapter 6, where it will be explained which construction parameters are used in dynamic simulation. The same dialogue for setting the

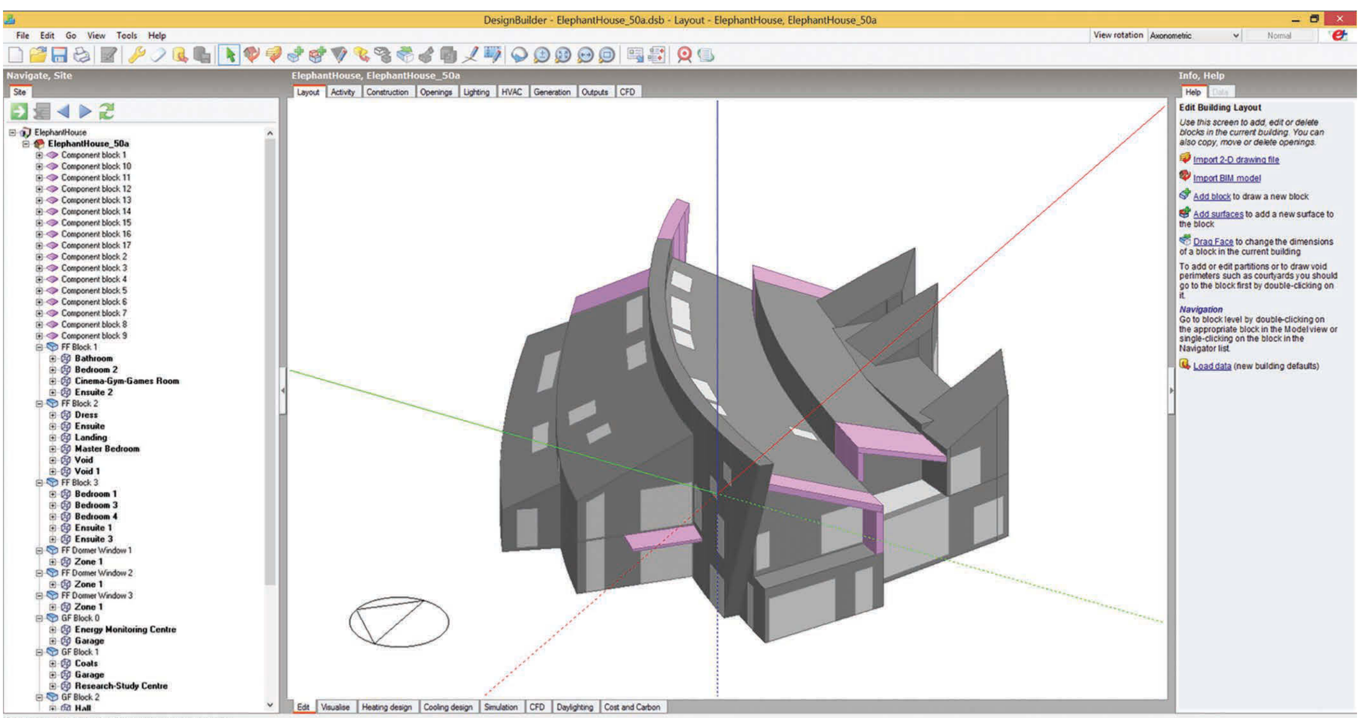


Figure 7 DesignBuilder 'Edit' dashboard (model based on design of Elephant House by Vivid Architects Ltd)

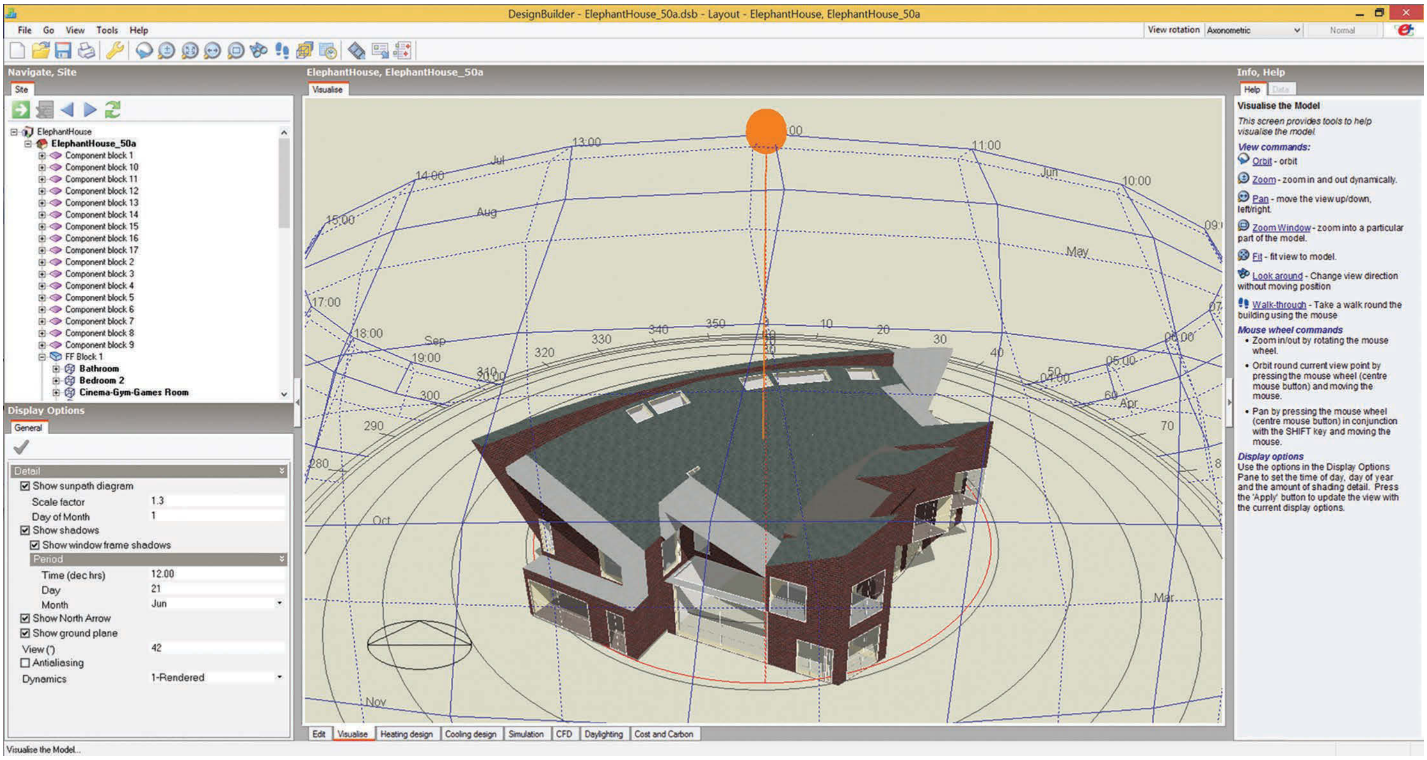
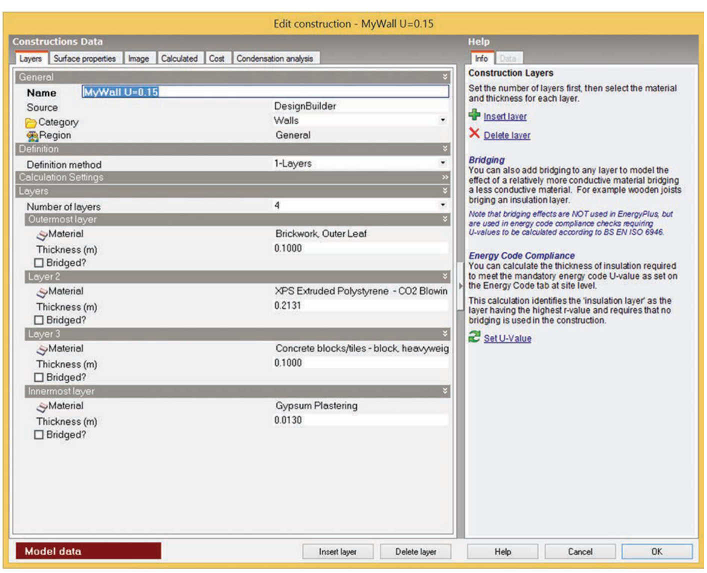


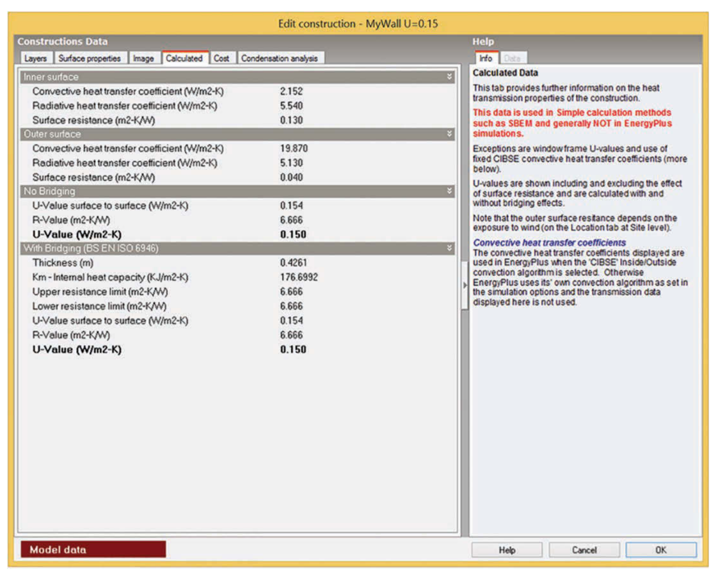
Figure 8   DesignBuilder rendered geometry (model based on design of Elephant House by Vivid Architects Ltd)

construction layers enables the user to choose if any of the layers are thermally bridged, and by which material and percentage (Figure 9c). This enables the user to quickly evaluate the effect of a thermal bridge, as shown in Figure 9d. As it can be seen from Figure 9c, thermal bridging of the insulation layer with 1% of steel doubles the U-value of the entire construction in Figure 9d. Constructions are also represented visually (Figure 9e), and condensation analysis is carried out for each construction (Figure 9f).

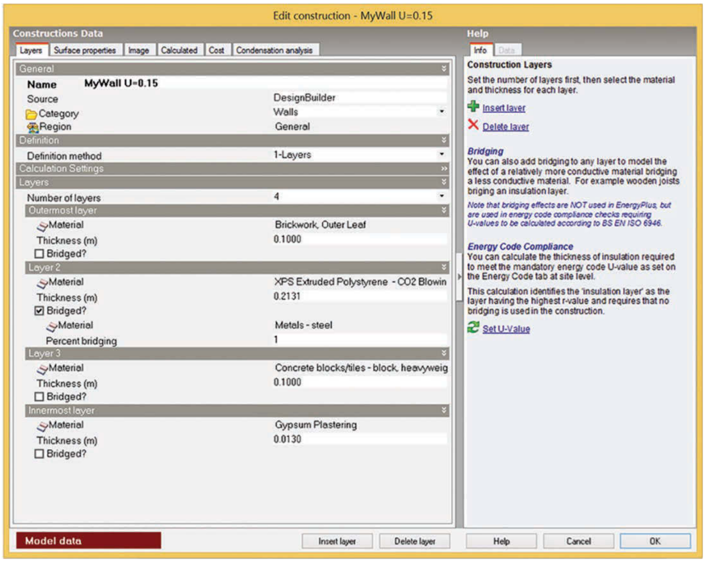
Other features include a capability to set a target U-value (Figures 9a and 9c) and choose which layer to vary (changing its thickness) in order to achieve the target. All constructions have a cost per square metre setting, which enables overall construction cost calculation.



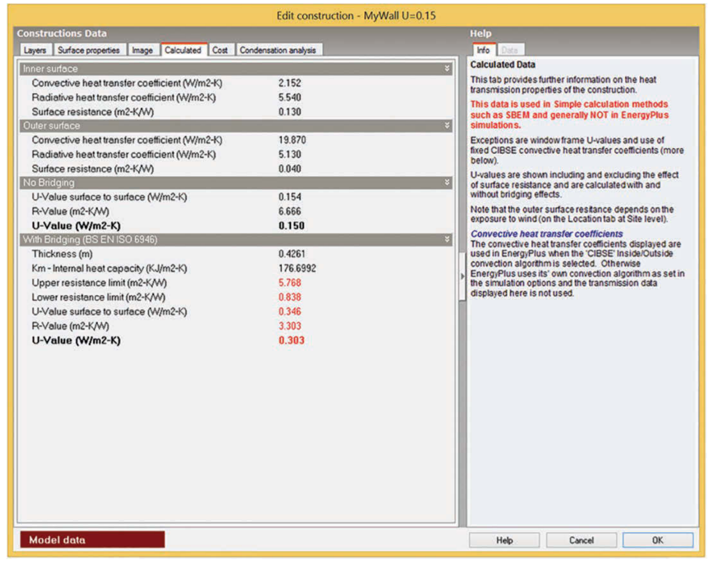
(a)   construction layers with no thermal bridging



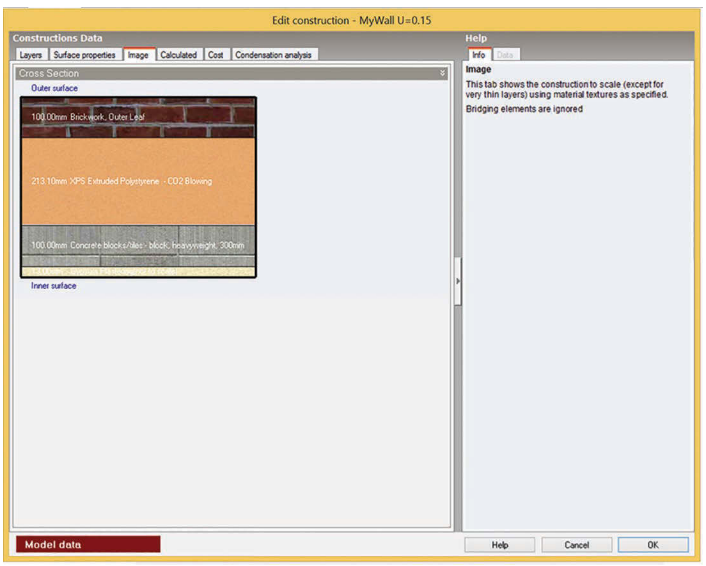
(b)   corresponding U-value calculations with no thermal bridging



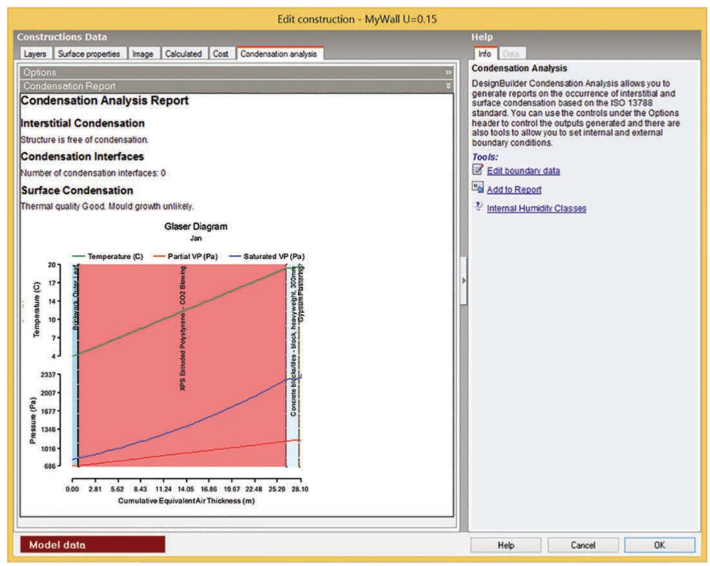
(c) construction layers with 1% thermal bridging



(d) corresponding U-value calculation with thermal bridging



(e) visual representation of a construction



(f) condensation analysis for a construction

Figure 9 DesignBuilder constructions setting

Simulations are run in the 'Simulation' tab, which opens a simulation setting dialogue box to enable the user to set the simulation period, time step resolution of outputs, output details and an optional use of an external simulation manager (Figure 10). The latter feature is particularly useful in 'Optimisation' mode, accessible from the 'Simulation' tab, where numerous simulations are sent to an external simulation server and thus do not use CPU time of the local machine.

Simulation results are all on one page within the same dashboard (Figure 11), from where different types of outputs (graphical or tabular) and different variables can be selected.

After a single annual simulation is completed, the user can proceed to the 'Parametric' tab to carry out multiple parametric simulations, or to the 'Optimisation' tab to carry out multi-objective optimisation (Figure 11).