A COMPUTATIONAL APPROACH TO REGULATORY COMPLIANCE

Dr. Andrew Marsh
Welsh School of Architecture, Cardiff University, Cardiff, UK
& Square One *research*, Australia
www.squ1.com andrew@squ1.com

ABSTRACT

The impact of building regulations on the final form of a design can be quite significant. At the same time, increasingly stringent and more performance-based regulations are leading to a greater reliance on simulation and analysis as a fundamental part of the design process. As a result, the traditional design-validate-redesign approach is becoming less viable.

This paper argues that an alternate approach based on the generative potential of building regulations is more effective. It shows that many aspects of compliance checking can be fully automated and that these same functions can be used to provide vital formative information even at the earliest stages of the design process. This is illustrated with both right-to-light and energy code examples.

INTRODUCTION

Regulations governing the energy performance of buildings are becoming increasingly stringent, particularly in Europe where new EU Directives are driving fundamental changes in the way that buildings are designed (EU Directive, 2003). Additionally, right-to-light and solar access issues in increasingly dense urban environments can place very specific limitations on the geometry of a building right from the very outset.

This paper argues that there are computational solutions to many of these regulations that, given a simulation model, can either automatically test a proposed design for compliance or use iterative optimisation techniques to generate fully compliant geometries. The aim here is *not* to propose such generative solutions as in any way final. Instead, by pursuing the generative potential of different regulations as they apply to each site, the aim is to provide the designer with additional insight and information to aid the early design process. Moreover, the aim is also to show just how generative of form such building regulations can be.

Two examples of this generative potential are presented. The first discusses in detail the iterative generation of a fully compliant right-to-light design envelope for a site in central London, surrounded by more than four hundred affected windows. The second deals with energy performance regulations, discussing the development of automatic compliance checking routines and, more particularly, the iterative use of these routines to generate fully compliant notional designs from base development models.

GENERATIVE POTENTIAL

The focus of most building regulation is to provide some sensible limitations on different parameters within a building in order to ensure that acceptable levels of performance are met. As not all building designs are subjected to intensive computational simulation, most regulations are necessarily prescriptive - setting out in detail an acceptable range for many design parameters. This is relatively easy for both designers and building control organisations to work with, but relies heavily on the ability of regulators to have foreseen all possible performance ramifications of the application of these parameters.

However, some more recent regulations take a different approach and lay out instead desired overall performance levels - relying on the building designer to choose the right parameters to achieve them in practice. This makes compliance checking a matter of simply taking measurements or recordings directly from the completed building. However, it makes the process of actually designing the building more complex. This is mainly because there is a risk that time and effort will be wasted pursuing design alternatives with parameters that are later found not to meet the required performance criteria.

Computational simulation and analysis is often the only way to reliably validate the energy and lighting performance of more complex design proposals. Traditionally the tools for doing this are quite specialised and require detailed input data, much of which may not be available early in the design process or require significant time and effort to collect. At the most formative stages of design there are often hundreds of other performance criteria vying for the designer's attention, most of which have to be all but solved before a viable proposal can be sufficiently resolved for thermal or lighting simulation. This means that these considerations are often addressed late in the design process and result in less than optimal solutions.

Rather than adding to these problems, the existence of performance-based thermal and lighting regulations actually make it *easier* to consider these issues *earlier* in the design process. Used correctly, they provide essential design targets that can be just as influential on building form as site layout and space provision.

The key is the ability to reverse the traditional design-validate-redesign process and instead use the regulations to actually generate ‘ideal’ solutions as and when required. This involves an iterative method where the results of a series of consecutive analysis are compared with the requirements of the regulations, with incremental changes made each time to the model in order to correct any deficiencies. This method requires some initial geometry to establish the constraints within which to work and a set of decision-making criteria to guide each geometric modification.

Both the initial model and the decision-making criteria can vary in complexity depending on the requirements of different application. However, even at its simplest, this approach means that designers can quickly answer questions such as: “given this simple plan form, how high can it be before it infringes right-to-light regulations ?”; or “how big can the windows be in these rooms and still be energy compliant – do I need to re-plan the interior in order to gain the required light levels ?”.

RIGHT-TO-LIGHT GUIDELINES

Much of the right-to-light legislation in the UK is based on guidelines produced by the Building Research Establishment (Littlefair, 1991). In these guidelines, compliance is approached through a series of steps, each determining if it is necessary to progress onto the next. In the end, however, it is necessary for any new development to prove that the daylight available to windows in adjacent buildings is either above a prescribed threshold or has not been reduced below 80% of their original value.

As a straightforward statement of performance (and therefore compliance), this allows a test to be set up which can be applied to any design proposal and either passed or failed. This is important as it allows the designer to apply it continuously as the design develops. However, it also means that time and effort has to be expended translating each new design into a model format suitable for its application.

A better solution would be a test that any member of the design team could apply at any time with only minimal effort. This can be done by first analysing the site and then calculating the maximum building envelope that would be compliant with right-to-light requirements. Once generated, this envelope could be stored within the CAD files used to develop each design alternative. Performing a right-to-light check would then involve turning on the layers containing the envelope and looking for any parts of the new design that penetrate beyond it. In this way, because the surrounding site is constant, a complex calculation can be turned into an uncomplicated check that not only gives the designer instant feedback, but provides self-evident proof of compliance.

Of course the main difficulty is the actual generation of this maximally compliant envelope. For a site with only a few affected windows, this can be done manually with only a small number of hand calculations. However, some sites need to consider hundreds of potentially affected windows so a computational solution is required.

Given the relative nature of the test - proving that levels are no less than 80% of their original value - there is no straightforward trigonometric solution. However, it is possible to set up an iterative system of directed trial and error to provide a geometric solution. To explain this in detail, consider as an example the site shown in Figure 1, which involves more than 450 potentially affected windows in adjacent buildings.

Calculating Daylight Availability

To calculate the daylight availability for any adjacent window, the Building Research Establishment’s Vertical Sky Component (VSC) is used (Littlefair, 1991). The VSC can be calculated directly from the shading mask for any object (Marsh, 2005). In this case, shading masks are calculated using spherical ray-tracing from a grid of points distributed over the surface of each window. Figure 2 shows an example shading mask calculated for an east-facing window on the site, with the VSC shown in the bottom-right corner.

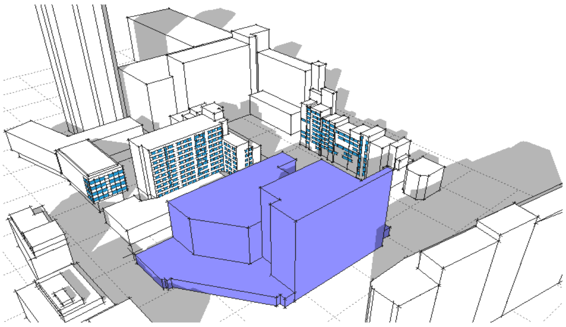
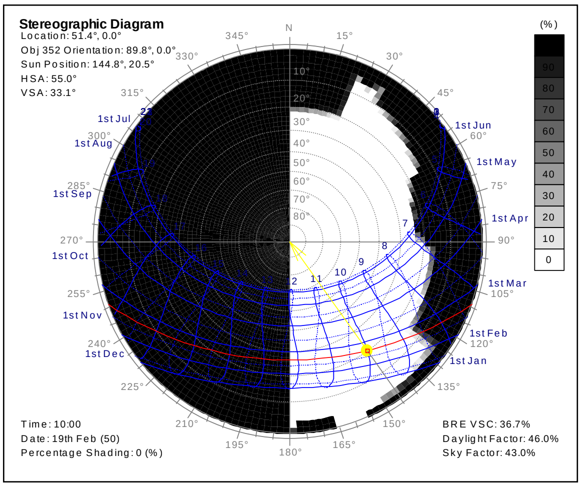


Figure 1 An example development site in which more than 450 windows are potentially affected.



The first step in this method is to calculate and record the VSC for each window based on the original site condition. In the system developed as part of this work, this value is stored as an attribute within each window. This establishes a reference against which the effects of any number of different design proposals can be compared.

Generative Geometry

In order to generate a compliant development envelope, the buildable area of the site is first established. In this particular case, only a part of the site is available for the new building. This area is then mapped out over the site and divided into a series of small grid sections, as shown in Figure 3. The height of each of these sections can then be independently controlled by an analysis script.

At the start of the iteration process, each grid section is assigned a starting height and a positive increment value. On each iteration, the VSC for each window is calculated and compared with its reference value.

If the calculated value falls below 80%, the closest grid section is found based on its geometric distance from the centre point of the window. The height increment for this section is then divided by negative two (-2.0) - this halves the increment of the segment and reverses its direction. This is important as the window has actually fallen below the 80% threshold so the section height must be reduced. If the increment value of the closest grid section is already negative, then the next closest segment with a non-negative increment is used. If, on the next iteration, the calculated value for that window increases beyond 80%, then the closest negative-increment segment is again halved and reversed, but only if the previously calculated value was below 80%.

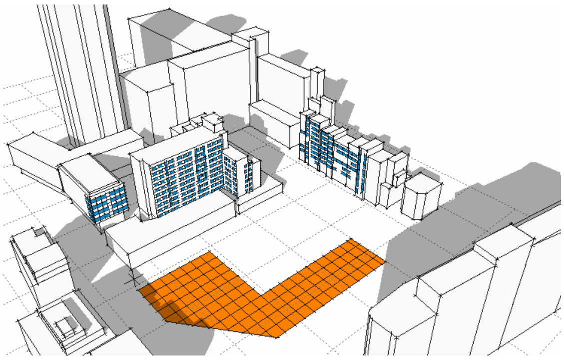


Figure 3 The buildable area is divided into grid sections whose heights can be independently incremented or decremented.

In the initial development of this system it was not uncommon for individual segments to be reversed and then 'forgotten' once the window that caused the reversal regained its 80%. This was because windows could remain below 80% for several iterations, reversing a different grid section each time. Rather than attempt to store all the reversed sections for each window, a limitation of five consecutive iterations with a negative increment was imposed, after which the section reverted to a positive increment. Whilst this increased the total number of iterations required for the resolution of the envelope by approximately 9% in this example, it greatly simplified the scripting.

The process is judged to have been resolved when the increment values of all grid sections fall below a given threshold – in this particular case 100mm. The resulting compliant development envelope is shown in Figure 4.

The system is flexible enough to accommodate any number of grid sections over any site layout with no limitation on the number of potentially affected windows and the complexity of the surrounding site.

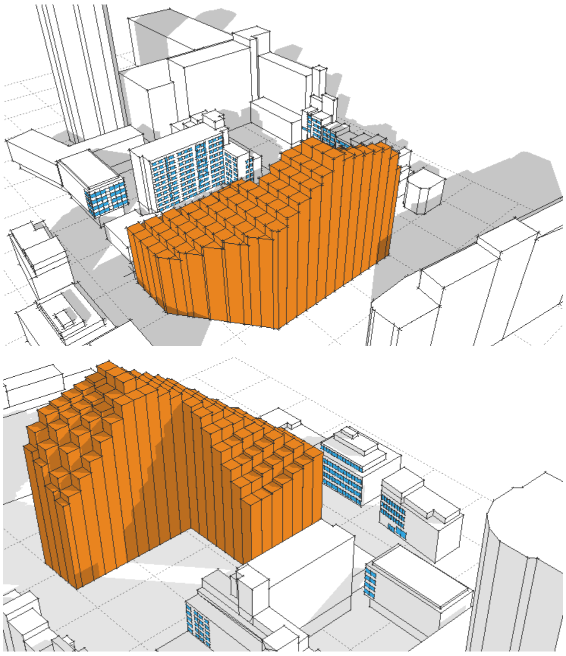


Figure 4 The resulting maximally compliant development envelope on the given site.

It is important to stress here that, at this stage of the research, the generated solution does depend in part on the decision-making system embedded within the analysis script and the order in which grid sections are evaluated at each iteration. The resulting envelope *is* a valid solution, but this may be one of several slightly different envelopes that are all fully compliant. Further research to determine the sensitivity of this method to different starting points and decision-making systems is currently being undertaken.

This example shows that the right-to-light guidelines have significant generative potential – in that they can be used to generate a form that is useful to the designer and can be used as part of the design development process. The resulting shape provides the designer with not only a simple and verifiable compliance check, but also a better understanding of the boundaries within which to work and the opportunity costs of each subsequent building form they propose.

THERMAL ANALYSIS

Part L of the Building Regulations England and Wales (ODPM, 2002) deals with the conservation of fuel and power in buildings. It is part of a broad wave of European legislation which seeks to encourage industry-wide adoption of energy efficient design practices and waste minimisation techniques. This legislation is only in its infancy, however it is already having a significant impact on the building industry.

The regulations offer three alternative methods to demonstrate compliance:

1. *The Elemental Method*: Considers all of the different elemental components of the building and, if they each individually meet the requirements of Part-L, then the building as a whole is deemed to comply.
2. *The Whole Building Method:* Applicable only to certain building types such as schools and offices for which simplified calculation methods are available to predict annual energy consumption and, therefore, carbon emissions.
3. *The Carbon Emissions Calculation Method:* Compliance is demonstrated using thermal and energy simulation software showing that the proposed design produces no more carbon emissions over a typical year than a notional building of exactly the same size and shape, but that fully complies with all aspects of the Elemental Method.

The Elemental Method comprises many simple rules governing the thermal properties of materials in different parts of the building, maximum aperture area ratios and simple solar-gain calculations for each façade. The sheer number of rules and the many qualifications that govern their application make this a laborious process for even mid-sized buildings. However, with an appropriate computer model, this process can be entirely automated.

Beyond CAD Geometry

An understanding of exactly what constitutes an appropriate computer model is quite important. To begin with, the regulations dictate different average thermal conductivity values for different building elements, distinguishing between walls, floors, roofs, windows and doors for example. Further distinctions are made between flat roofs and pitched roofs as well as large and small access doors. Thus, at a minimum a model must allow for the categorisation of objects into these different element types.

The regulations also prescribe maximum window and door areas, given as a percentage of exposed wall area. Similarly, maximum rooflight areas are defined as a percentage of exposed roof area. Both of these are further governed by maximum average solar-induced cooling loads. The regulations provide design values for direct solar gains from different orientations and then describe a process by which individual rooms must be divided into perimeter and interior zones – stating that:

> *"Perimeter zones are those defined by a boundary drawn a maximum of 6m away from the window wall(s). Interior zones are defined by the space between this perimeter boundary and the non-window walls or the perimeter boundary of another perimeter zone. When calculating the average solar cooling load, the contribution from all windows within that zone should be included, plus the area of any rooflight (or part rooflight) that is within the zone boundary. For interior zones, the contribution from all rooflights (or part rooflight) that is within its zone boundary should be included. For each zone within the space, the total solar cooling load should be no greater than 25W/m².*"
> (ODPM, 2003)

This means that the geometric model must be able to be divided into individual rooms (homogeneous volumes within which air is free to mix and convect) and then further subdivided into zones based on the location of each window, as illustrated in Figure 5.

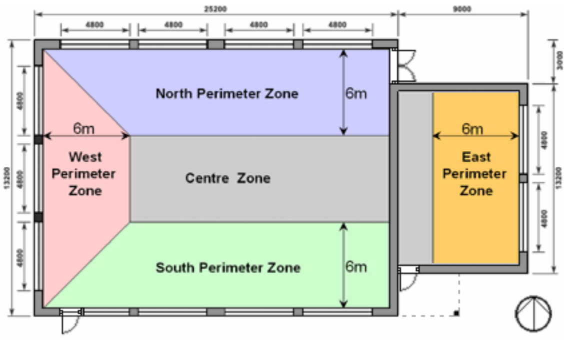


Figure 5 An example of the required zoning of rooms to determine solar loads from windows.

Unfortunately even these two requirements would initially preclude the use of most CAD models for this analysis. Whilst it is possible to embed some of this information using special material or layers names, or even referencing external databases, the process of effectively embedding room and zone information requires a very different approach. A typical 3D CAD model contains a great deal of geometric information but no real spatial information. 'Spaces' exist solely as a by-product of the location of geometry – there is no easy way of referencing a 'space' or even determining which 'space' a geometric element belongs to. Thus, even the calculation of floor area or room volume is very difficult without embedding additional custom information.

This highlights the benefits of using more building-oriented CAD or hybrid design and analysis tools that already include spatial information within the model. It also illustrates the potential future benefits of broader support for Industry Foundation Classes (IAI, 2000) which require this type of information and store it in a more generally accessible form.

A Generative Approach

A full description of all the rules used in the Elemental Method is beyond the scope of this paper. What is important is that window sizes are governed both by the exposed surface areas of the elements in which they sit and by the amount of solar gain falling in a defined 6m zone immediately inside them.

Once the processes of Part L compliance checking have been fully automated, these function can be used as a pass/fail test in much the same way as the right-to-light regulations. They can be applied at any time to the building model as it develops, or used to determine the optimum value of different design parameters. This means, for example, that it is possible to generate maximally compliant window sizes for each room in the model, or determine the complaint shading requirements for fixed window sizes.

It is not suggested here that windows generated in this way represent a 'solution' to the design problem, but rather they serve to inform the designer of potential design conflicts. For example, in the two models shown in Figure 6, there are a number of wall surfaces in which there is a large disparity between the proposed design and what is compliant. This information is vital as early as possible in the design process so that the requirements that led to their proposed size can be resolved against the limitations imposed by the regulations, and internal spaces re-planned where appropriate.

The Notional Building

The same tests used to generate maximally compliant window sizes can also be used to automatically generate the notional building used in the *Carbon Emissions Calculation Method*. This is important as the biggest perceived issue with this method is that it would appear to require the design of two buildings: the actual proposed design and one of the same size and shape but fully elementally complaint. If such a building can be automatically generated directly from the proposed design model, then such an issue is avoided.

A system for doing this has already been implemented within a software package, a demonstration version of which is available for download at http://www.ecotect.com (Marsh, 1996). The examples illustrated in Figure 7 show the result of its application to different building models.

The system works by first deleting all the windows in the model that belong to heated or conditioned rooms and then re-calculating the exposed area for all surfaces bounding each room. For any room with exposed wall surfaces facing only in one orientation, Table 4 of the Part-L regulations (ODPM, 2002) gives the maximum allowable glazed area as a ratio of the room's exposed wall area. For those with walls exposed in multiple orientations, the full solar load calculation must be carried out.

Figure 6 The use of the Element Method rules to generate complaint window sizes.

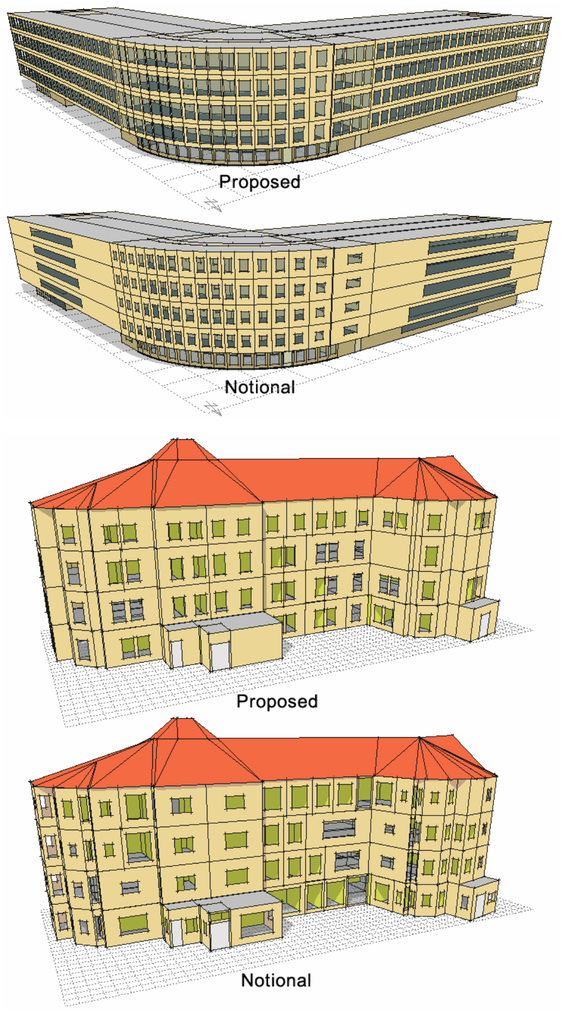


Figure 7 Examples of automatically generated notional building models based on a proposed design.

The 6m perimeter and interior zones discussed previously are calculated by testing many pseudo-random points distributed over the floor surfaces of each room. Each point is tested for proximity to the plane of each exposed wall and roof surface belonging to that room, which are then grouped by the eight orientations for which the regulations give design solar gain values.

The number of different proximate exposed orientations is then determined for each point and a fractional value assigned. If, as an example, a particular point is within 6m of both an east and north facing wall surface, then a value of 0.5 is assigned to each of these orientations. After division by the total number of points tested, the result is the fraction of total room floor area affected by solar radiation from each orientation.

Figure 8 illustrates this process being used to test a particular window configuration. Each orientation is assigned a different colour so it is clear which points are proximate to the planes of different windows.

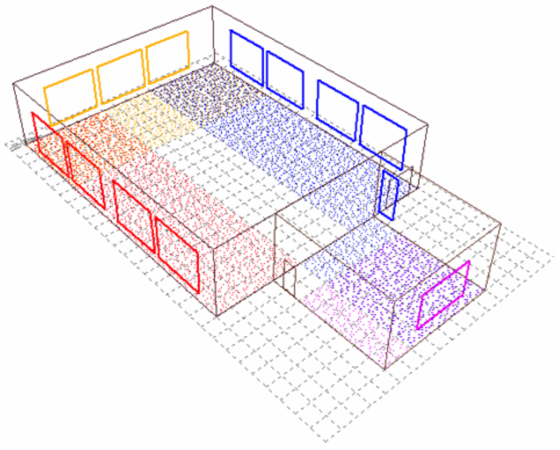


Figure 8 A system of pseudo-random points used to determine the floor areas within 6m of each window wall for distributing solar gains.

Given the floor area, design solar gain and window transmission properties, it is possible to determine the exact window size that would result in a solar load of no more than 25W/m² floor area as specified in Part L. This overall area is then apportioned to each exposed wall/roof in that orientation and a corresponding window added based on the proportions of that surface.

If a particular wall had previously contained multiple windows, the decision to replace these with a single window is important. Research work carried out at the Welsh School of Architecture (Alexakis, 2004) showed that, when wall thickness and edge effects are considered, a large single window allowed through slightly greater solar radiation on average than multiple smaller windows with the same aggregate area. Thus, as the aim of the notional building is to be used for comparison with a proposed design, using the worst-case solution allowable under the regulations is justified.

At the same time as the window generation, the materials used in each heated room, and its occupancy and ventilation parameters, are modified to be compliant with the Elemental Method.

The result is a modified building model that can be used for direct comparison with the original proposed design model. Using both models, this comparison can be performed in a range of external thermal analysis engines including EnergyPlus (Crawley et al. 2004), HTB2 (Alexander & Lannon, 1996) or ESP-r (ESRU, 2002).

CONCLUSION

With government regulations becoming increasingly performance-based, designers are having to embrace simulation and analysis as a fundamental part of their design process. Rather than adding a burdensome extra layer of compliance validation, this paper has shown that adopting a slightly different approach to the application of these regulations can make it is possible for them to aid in the formulation of design proposals.

This different approach applies to both the type of models used and how they are analysed. Future CAD models will need to embed more of the information that building regulations are based on. Industry Foundation Classes represent a positive move in this direction and performance-based energy codes will add pressure for their broader support.

This paper has also shown that, once the right model information and analysis tools are available, much of the work in compliance checking can be fully automated. Moreover, when addressed early enough, issues of compliance can provide vital information to actually drive important parts of the design process.

REFERENCES

Alexakis, A., 2004. Implementation and application of Part L in commercial buildings. Masters Thesis, Welsh School of Architecture, Cardiff University, Wales.

Alexander, D.K., Lannon, S., 1996, HTB2 release 2.01a software and documentation, Welsh School of Architecture, UWCC, , Cardiff University, Wales.

Crawley, D.B., Lawrie, L.K., Pedersen C.O., Winkelmann, F.C., Witte, M.J., Strand, R.K., Liesen, R.J., Buhl, W.F., Huang, Y.J., Henninger, R.H., Glazer, J., Fisher, D.E., Shirey, D.B., III, Griffith, B.T., Ellis, P.G., Gu L., 2004. EnergyPlus: New Capable and Linked, in Proceedings of the SimBuild 2004 Conference, August 2004, Boulder, Colorado, IBPSA-USA.

Energy Systems Research Unit, 2002. The ESP-r System for Building Energy Simulation, User Guide Version 10 Series, October 2002. Glasgow: University of Strathclyde.

EU Directive, 2003, The energy performance of buildings, DIRECTIVE 2002/91/EC, Official Journal of the European Communities, Brussels, Belgium. (http://europa.eu.int/eur-lex/pri/en/oj/dat/2003/l_001/l_00120030104en00650071.pdf)

IAI, 2002. Industry Foundation Classes – Technical Guide, International Alliance for Interoperability, Oakton, Virginia, USA.

Littlefair, P., 1991. Site layout planning for daylight and sunlight: a guide to good practice, Building Research Establishment Report 209.

Marsh, A.J., 1996. Performance Modelling and Conceptual Design, International IBPSA Conference, The University of New South Wales, Sydney, Australia.

Marsh, A.J., 2005. The application of shading masks in building simulation, Proceedings of the Building Simulation 2005 Conference, Montreal, Canada (to be published).

ODPM, 2002. Approved Document L2: conservation of fuel and power, Office of the Deputy Prime Minister, The Stationery Office, London, UK.

Tregenza, P.R., Sharples, S. 1995, IEA Task 21, Subtask C2 - New Daylight Algorithms, (http://eande.lbl.gov/Task21/BRE-ETSU/contents.html).