Design Patterns for Low-Carbon Buildings: a proposal

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Abstract.
Design patterns as introduced by Christopher Alexander and colleagues are proposed in this paper as a means of guiding building designers through the often complex processes of low-carbon building design. The patterns are intended to be integrated into the Building Information Modelling (BIM) environments that are increasingly used in architectural and building engineering design practice, where patterns provide relevant information at appropriate times, carrying out environmental analyses as required, both as selected by the building designer and automatically. The paper provides examples of patterns from some of the various domains and disciplines that encompass low-carbon design of the built environment, as a means of exploring whether patterns could facilitate communication between those domains and disciplines. The focus is on low-carbon building design and building simulation, but patterns used in computer science and interface and interaction design are also discussed as these fit well with the object-oriented environment of contemporary software design and BIM systems.

Keywords: Low-carbon design, low energy buildings, design patterns, BIM.

1 Introduction

There is an ongoing need for reducing carbon and greenhouse gas emissions resulting from the construction, refurbishment and operation of buildings. The processes and interactions of the built environment industries and professions are complex, as are the physical processes resulting in emissions. Legislation sets targets that all actors should follow, and various researchers, organisations and professional bodies publish guidelines and other information on how carbon reductions may be met, some of which may influence the formulation of future legislation and planning laws.

Building designers (architects, engineers, consultants etc.) use their experience and expertise and seek advice and information when needed, to design for lower emissions either to satisfy or surpass regulations. Advice and information are available in a number of forms including checklists and instructions [1], guides to assessment of emissions levels [2], precedents and references [3,4], calculation and assessment methodologies [5,6], rules of thumb for designing low energy buildings, guidebooks, key performance indicators, sophisticated prediction and measurement methods, specialist consultancies etc.

This paper discusses the potential use of design patterns in the complex landscape of low-carbon design. Design patterns potentially provide the designer with reliable and high-quality solutions to commonly encountered problems in the design environment of the domain s/he is working in. A design pattern describes a common problem and its solution in context, describes the forces that have been resolved by the solution [7,8] and suggests link to other patterns. Examples from practice that support and justify the solution given are usually provided, and the pattern is delivered in a format appropriate to the design domain. In architectural design this is typically a blend of text and illustrations [7]. Patterns are generally seen as an effective knowledge transfer method between the expert and the design domains and have not previously been proposed for use in low-carbon building design although have been proposed for use with Building Performance Simulation (BPS) [9,10]. Unlike the existing forms of advice and information mentioned above, design patterns record tacit, contextualized knowledge for transferring between experts and general building designers, facilitating dialogue and decision-making using natural language rather than specific technical representation systems, and are a comprehensive alternative to existing methods.

If the creation of a low-carbon built environment and its parts are taken as an ongoing series of interconnected problems for which designers attempt to find solutions, then design patterns might help to solve these problems. The paper illustrates in outline how patterns might be used across the various domains, by a building designer working in a digital environment. Examples focus on low-carbon building design, and building performance simulation, but also touch on design management, and software development. For the purposes of this paper the term ‘low-carbon’ is taken to encompass related terms such as ‘zero-carbon’ and ‘net zero-carbon’.

2 Design Patterns

2.1 Origin of design patterns

The ideas behind design patterns were developed by Alexander et al. [7,8] as a way of capturing in a transmissible form the best qualities of the built environment, with the intention that others could use to them in their own design processes and thereby incorporate to their work the qualities inherent in and represented by these patterns. A large number of patterns (253) at the scale of towns and cities, buildings, and construction details, were derived from observation of the physical, social and economic elements and interconnections of built environments that appealed to Alexander and colleagues, and which they claimed were ‘timeless’ in their validity as ‘solutions’ to the complex problems of creating high quality spaces and places for human life to unfold.

Combinations of appropriate patterns are supposed to be selected for each project and used together, such that the outcome contains the qualities desired, and provide dynamic and coherent solutions to the problems that originally existed and which the project aimed to address. Design patterns in architecture have had supporters and detractors [11,12,13,14]. However, it is not the intention of this paper to discuss in any depth the qualities of Alexander's patterns but rather to describe how their subsequent use in domains other than architecture might suggest their future use in addressing problems of designing low-carbon environments.

2.2 Design pattern domains

Patterns have been proposed and used in a number of domains including architectural design, computer science and IT, educational pedagogy and others. In computer science design patterns have had great success and much work has been published in this field for over 30 years [15], ranging from object-oriented programming (e.g. [16,17,18]) to machine learning [19], and design patterns published for a number of computer languages. Other fields related to computing in which patterns have been produced are Human-Computer Interaction, Graphical User Interface design and Interaction Design (e.g. [20]). Borchers [21] argued that patterns can express expertise in the different domains of a multi-disciplinary project and therefore act as a 'lingua franca' to the members of the team. This idea is applied here to the field of low-carbon design.

The use of design patterns could promote communication and information sharing in design teams and facilitate the design and construction of low/zero-carbon buildings. To explore this idea, outline design patterns for the building design and software development domains shown in Figure 1 are proposed here. The former is the environment in which the activity of building design takes place and is assumed to consist of design management, low-carbon building design, and building performance analysis. The software development environment is where the software systems that deliver design patterns into the digital environment of building designers are created. The focus of this paper is on the building design environment, but the software development environment is included to emphasise that its creation is part of a multidisciplinary project that could use design patterns throughout.

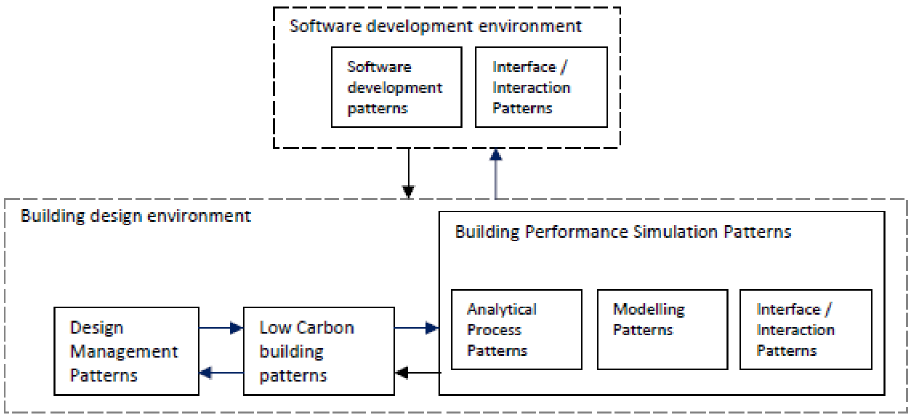

Fig. 1. Building design and software development patterns

The arrows in Figure 1 indicate the two-way interaction between pattern domains. For example ‘low-carbon building patterns’ which describe solutions to making and operating low-carbon buildings lead to the use of specific ‘building performance simulation patterns’ which describe solutions to obtaining numerical data that will inform design decisions (e.g. does design option A produce lower emissions than option B?). When this data has been obtained it will often be the case that another design approach will be considered, hence the arrow back to ‘low-carbon design patterns’. Figure 1 also indicates the nested structures possible with patterns. Within ‘building performance simulation patterns’ are more detailed patterns which describe successful and repeatable analytical procedures, modelling practices, and graphical interface and interaction solutions that enable designers to explore outputs and results.

3 Building design and software development patterns

3.1 Low-carbon design patterns

Expertise concerning low-energy / low-carbon building design can be expressed in design patterns. These patterns could include problem-solution pairing related to carbon emissions in use, embodied carbon, lifecycle carbon etc., providing that definitive knowledge and expertise is available. Such knowledge is available to various degrees of certainty as an outcome of ongoing research and practice-based activities from industry, academia and other organisations. For example, UKGBC [1] outlines the following net zero-carbon strategy which is set out as a series of stages, which if followed will provide ‘solutions’ to the problem of creating zero-carbon buildings.

Table 1. A zero-carbon strategy (summarised from [1])

1	Establish Net Zero-Carbon Scope
2	Reduce Construction Impacts
3	Reduce Operational Energy Use
4	Increase Renewable Energy Supply
5	Offset Any Remaining Carbon

Each stage of Table 1 is supported with associated advice and instructions and could be seen as the solution to a smaller ‘sub problem’ of the larger problem of creating low-carbon buildings. The construction and use of design patterns is illustrated below focusing on stage 3 of Table 1 for reasons of space. This stage is well understood and applies equally to ‘low-energy buildings’ in general. Knowledge of how low-energy buildings work is available in design guides, case studies of best practice etc. (e.g. [3-6]), and if reduced to essentials involves the problems of decreasing heating and cooling loads and using climatic energy flows where appropriate to achieve thermal comfort for the occupants. There are established and well understood ways of solving these problems for different building types and climatic zones, and some of these are shown in Figure 2.

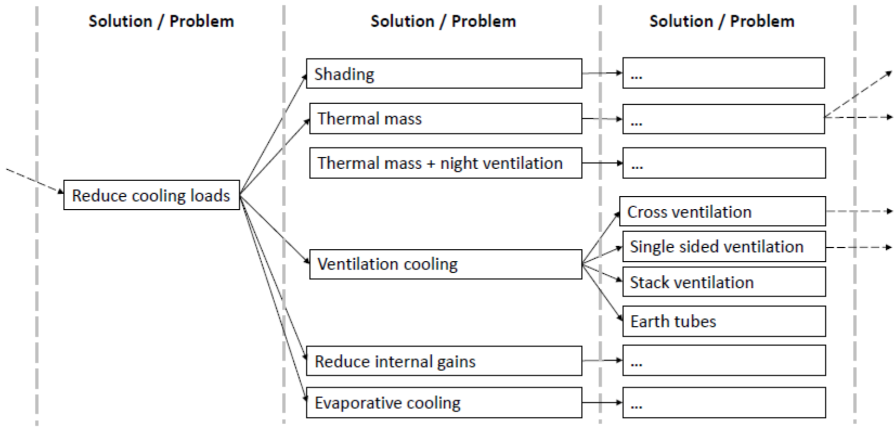

Fig. 2. Some examples of low energy design problems and potential solutions

The elements of Figure 2 are labelled as 'Solution / Problem' because a solution can often be seen also as a further problem (e.g. 'Ventilation cooling is a solution to 'Reduce cooling loads' but can become the problem of 'Implement Ventilation cooling'). Problem-solution pairs are generated by taking a problem and coupling it to a potential solution. Figure 2 shows a small part of the low-carbon design abstract problem-solution space. Note that 'Reduce cooling loads' can itself be seen as a potential solution to the problem of 'Overheating', and 'Cross-ventilation' can be seen as a problem, for example in 'how can cross ventilation be successfully implemented?' or 'will cross ventilation work for the current building proposal?'. In the context of design, at every level of decomposition of a problem the solution will probably at least partly be to 'provide information', and at some point this information will likely be the results of testing a solution. Problem–solution pairs are successively generated in this way until the problem-solution pair does not require further decomposition, because the final problem is to test the solution, at which point another sort of pattern (see section 3.2) is used. Any problem-solution pair can potentially be made into a design pattern with supporting advice and information, to be tested and further refined or discarded considering its relevance and effectiveness in addressing the problem.

The pattern is recorded in an appropriate format. All existing pattern systems have their own consistent format, which describes problem and solution, has a descriptive name, and contains examples and discussion on how the pattern can be used in the wider design context. Table 2 shows a generic pattern template, and a developed example of a Building Performance Simulation pattern is presented in section 3.2.

Table 2. Generic template for a Low-carbon design pattern (modified from [9])

Pattern name	Name should clearly reflect the abstract problem-solution pair and can refer to building typology, specific design actions, design goals to be addressed, climate etc.
Introduction	Situates the pattern in context to larger patterns, connecting it to a network of different but related design decisions.

Problem	A brief outline of the problem addressed by the pattern, including the aims of the design decision(s) to be undertaken.
Context and examples	Situates the use of the pattern in relation to wider aspects of low-carbon design and design practice, explaining the context of the decision(s) to be undertaken by designers and providing examples and information (e.g., on theory or practice) to justify the advice given by the pattern.
Solution	A description of the technique or features of the building that will potentially resolve the problem.
Further patterns	Information on which smaller patterns to move on to, in light of the aims of the designer and the results given by the current pattern.

3.2 Building Performance Simulation patterns

To model building performance and test alternative low energy solutions Building Performance Simulation (BPS) is used. In the BPS domain there are also problem-solution pairs, where a typical problem concerns how to model a scenario in order to obtain the required information, for example concerning heat loads. Previous work by the authors [9,10] has shown how complex simulation scenarios can be broken into steps that can be followed by a simulation user to obtain simulation results that will help in design decision-making. These steps are in the form of design patterns, each of which includes problem, solution, advice, links to similar examples etc. When implemented in a BIM environment they also contain premade building models, analytical procedures, defined inputs and outputs, and methods of interacting with these outputs.

A design pattern to test for ‘Ventilation cooling’ (cross and single sided) is shown in Table 3. BPS patterns include sections (marked *) that specify technical aspects of the simulation procedures to be used, and are supposed to be to be linked with further patterns.

Table 3. Specification for a ‘Ventilation cooling’ pattern

Pattern name	Ventilation cooling (cross / single sided)
Introduction	Previous patterns have shown that cooling is required, which could be achieved using active systems, passive systems or a combination of both. This pattern tests whether ventilation cooling from windows and vents will be sufficient and provides information on building modifications to make to improve the effectiveness of ventilation cooling. Both cross and single sided ventilation are covered.
Problem	*To determine the building performance when ventilation cooling is used.* The building designer needs to know whether ventilation cooling will be sufficient in the current building and needs information on how to modify the building should the current performance need improving.
Context and examples	The effectiveness of ventilation for cooling (both cross and single sided) depends on factors including wind speed and direction, opening size and location, position of internal walls, doors and vents. Links to examples of successful ventilation cooling solutions are provided here. Links to theory (building physics) and simulation methods are provided here.
Solution	A network airflow model is used. The user is prompted to specify opening sizes and schedules (selected if required from drop down list).

Modelling Details*	Building model including all partitions, internal zones and ventilation openings. Annual weather file including hourly wind speed and direction.
Analytical processes*	Network model of airflow is used (or equivalent). Parametric variation of windows & vents between 0% open and 100% open (steps of 25%).
Interface / interaction*	Output; Hourly temperature and air flow rate (line chart); Hours over upper comfort temperature (table); Plan indicating airflow rates between zones, highlighting lowest airflow positions.
Interpretation and Quality Assurance	Advice on airflow rate interpretation.
Further patterns	Reducing cooling loads, Shading, Thermal mass, Thermal mass+night ventilation, Reducing internal gains, Ventilation cooling (earth tubes), Ventilation cooling (stack).

3.3 Analytical process patterns

Analytical process patterns are used within building performance simulation patterns. The advantage of incorporating the analytical process within a pattern rather than simply calling it an algorithm, is that (as in all design pattern construction) this demands that the range of actual problems and contexts that the abstract problem-solution pattern is intended to solve must be thought about carefully. Pattern development in this case acts as a tool to more thoroughly explore the space of problem-solution pairs, a process that leads to development of further patterns, modification of existing patterns and deletion of patterns when a better one is found. Examples are shown in Table 4.

Table 4. Examples of analysis problem-solution pairs

Problem	**Solution**
Determining the effect on performance of a modification(s)	Compare the results of the modified model(s) with the base model
Determining whether a building proposal meets a performance target	Compare the result with the target
Determining the sensitivity of parameters X…n in relation to a target(s)?	Sensitivity test (i.e. parametric variation of the relevant parameters)
Determining optimum values of user defined parameters X ... n for best performance	Optimisation routine

3.4 Modelling patterns

Modelling patterns describe commonly used modeling techniques and practices needed to simulate the type of performance being examined and the building and construction elements and attributes to be modelled that are coherent with the analytical process set up to undertake the investigation. Libraries of modeling patterns can be created related to for example ‘base-case’ or ‘free-running’ models.

3.5 Interface / Interaction patterns

Tidwell [20] authored interface design patterns including patterns on user behaviour, structuring of information, navigation, layout, actions and commands, interaction with users, information graphics, style and aesthetics and others. These patterns aim at increasing ‘useability’ of complex digital environments and have proven to be very popular. Such patterns can be used to instruct and facilitate navigation of BPS results in an interactive way, so that designers can query simulation outputs at different level of temporal and spatial detail. They could also be used in the development of the software development environment to facilitate the connection between BIM and BPS.

3.6 Design management patterns

It is likely that some ways of managing a low-carbon project will be more appropriate than others. For instance, Integrated Design Processes (IDP) and Integrated Project Delivery (IPD) focus on enabling close collaboration among the different specialists involved in a design team, so that integrated solutions addressing social, economic, ecological and sustainable goals are achieved. Interoperable data exchange protocols are recommended by the literature together with documentation on the level of information, detail, tolerances, and purpose of model etc., to feature in contracts [22]. However, the collection and transformation of this information in the form of project management patterns are the subject of future work.

3.7 Software development patterns and Building Information Management

Design patterns are closely linked to object-oriented programming which has made much use of them (e.g. [16,17,18]). Design patterns can be coded as objects and/or classes of object, and those described above could be integrated into an object-oriented software environment. A well-known example of patterns in computer science are the object-oriented software development patterns of Gamma et al. [16]. These include creational patterns used to create classes and objects, structural patterns that describe how objects and classes are related to larger structures, and behavioral patterns that describe how classes and objects behave with respect to each other. Examples of their use in a BPS context are shown in Table 5.

Table 5. Object-oriented pattern type [16] and use in BPS context

Pattern type	Example in BPS context
Creational Patterns	Automatic generation of a pattern instance based on the outputs of another pattern (e.g. a pattern who’s output identifies cooling loads generates an instance of a shading pattern)
Structural Patterns	Specifies how a BPS pattern is related to a low-carbon design pattern
Behavioral Patterns	Specifies how a ‘sensitivity test’ pattern is applied to building parameter objects

Software development activity should consider the potential links with BIM systems. BIM is an object-based manufacturing-centered approach to coordinating design information amongst the design team and contractors [23], and some work has been done on using patterns to facilitate BIM information sharing [24]. Since design patterns are objects that hold information for the purposes of transferring knowledge ‘on demand’ to building designers, they could be integrated into the BIM environment to connect federate models with simulation routines. More specifically, ‘design pattern’ objects that embody knowledge on low-carbon design, building performance simulation etc. could be added to the main BIM objects of ‘construction entities’, ‘built spaces’, and ‘construction elements’. For example, the ventilation cooling pattern (table 3) and all other patterns would be made available through the BIM system, and if used in a project would be attached to the building model just as construction elements of the building are attached. This would facilitate the integration of BPS to BIM systems, as it would enable information about the building, BPS assumptions and results to be recorded in a single environment, facilitating data transfer, coordination and auditing as well as project query and specification at different levels of detail. Current experiments of integrating BIM with BPS (e.g. Autocad Revit Insight [25]) do not provide such an environment.

4 Discussion

Whereas it can be argued that the topics of low-carbon design and building performance modelling and simulations can be and are learnt in theory (see [26] for new development in the latter), most knowledge transfer and application are heavily based on ‘learning by doing’ supported by standard design guides, checklists and similar in different knowledge domains (architecture, civil and mechanical engineering). Since in low-carbon design the assessment of how well a technology, technique or building works is vital, low-carbon design patterns linked to BPS patterns offer a promising future, not only to connect both the theory and the ‘doing’ but to connect different disciplinary domains in a single environment. This approach is coherent, transparent, and easy to upgrade and modify, in synchrony with ongoing development in contemporary object-oriented computer systems. The use of patterns in linking various domains needs further research and development, but the example given here of linking low-carbon patterns to BPS patterns is promising. A limitation of the paper is that the computational methods of implementing a patterns-based system linked to BIM have not yet been addressed and require further work.

5 Conclusions

This paper has outlined how design patterns could be used as a ‘lingua franca’ [21] in the complex processes of producing a low-carbon built environment. Although the idea behind design patterns is over 40 years old, their close links with object-oriented programming and the increasingly ubiquitous use of digital design environments, coupled with the need for accurate building performance modelling, suggest that patterns could become a relevant methodology in low-carbon design. Almost all critics and researchers of design patterns agree that well written patterns possess a powerful educational value. Understanding how to meet the challenges of creating a low-carbon built environment could be made easier through use of a consistent and transparent systematic approach inspired by Alexander’s proposal.

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