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Introduction

Modern society is strongly focussed on performance and efficiency. There is a constant drive to make production processes, machines and human activities better, and concepts like high performance computing, job performance and economic performance are of great interest to the relevant stakeholders. This also applies to the built environment, where building performance has grown to be a key topic across the sector. However, the concept of building performance is a complex one and subject to various interpretations. The dictionary provides two meanings for the word performance. In technical terms, it is 'the action or process of performing a task or function'. It may also mean the 'act of presenting a play, concert, or other form of entertainment' (Oxford Dictionary, 2010). Both interpretations are used in the building discipline; the technical one is prevalent in building engineering, while the other one frequently appears in relation to architecture and buildings as work of art (Kolarevic and Malkawi, 2005: 3). But the issue goes much deeper. As observed by Rahim (2005: 179), 'technical articles of research tend to use the term "performance" but rarely define its meaning'. In the humanities, performance is a concept that implies dynamic, complex processes with changing values, meanings and structures (Kolarevic, 2005b: 205).

Whether approaching building performance from a technological or aesthetic perspective, buildings are complex systems. Typically they consist of a structure, envelope, infill and building services. Many of these are systems in their own right, making a building a 'system of systems'. All of these work together to ensure that the building performs a whole range of functions, like withstanding structural loads caused by people and furniture, protecting the occupants from environmental conditions, allowing safe evacuation in case of emergency, delivering a return on investment or making an architectural statement. Building performance thus is a central concept in ensuring that buildings meet the requirements for which they are built and that they are fit for purpose. Building performance plays a role in all stages of the building life cycle, from developing the building brief[1] to design and engineering, construction, commissioning, operation, renovation and ultimately deconstruction and disposal.

Different disciplines contribute knowledge on specific performance aspects of buildings, such as architectural design, mechanical engineering, structural engineering

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[1] In the United Kingdom the term *briefing* is used, whereas in the United States this is named *architectural programming*.

Building Performance Analysis, First Edition. Pieter de Wilde.

and building science.[2] Other disciplines focus on specific systems, such as building services engineering or facade engineering, or are grounded in a common method, such as building performance simulation or the digital arts; in many cases disciplines overlap. The knowledge of all these disciplines needs to be combined into a building design, a building as a product and ultimately an asset in operation, which adds further complexities of interdisciplinarity, information exchange, management and control.

Building performance is a dynamic concept. The architectural performance depends on the interplay between the observer, building and context. The technical performance relates to how a building responds to an external excitation such as structural loading, the local weather to which the building is exposed and how the building is used. This often introduces uncertainties when predicting performance. Furthermore building performance needs to materialize within the constraints of limited and often diminishing resources such as material, energy and money. Challenges such as the energy crisis of the 1970s, the concern about climate change and the 2008 global financial crisis all contribute to increasingly stringent targets and a drive towards more efficient buildings and a growing interest in building performance.

Within this context, a large body of literature exists on building performance. Underlying principles are provided by generic books like, amongst many others, Clifford *et al.* (2009) in their introduction to mechanical engineering, Incropera *et al.* (2007) on fundamentals of heat and mass transfer, Stroud and Booth (2007) on engineering mathematics, Zeigler *et al.* (2000) on theory of modelling and simulation or Basmadjian (2003) on the mathematical modelling of physical systems. The application of these principles to buildings and to the assessment of building performance can be found in more specialist works such as Clarke (2001) on energy modelling in building design, Underwood and Yik (2004) on energy modelling methods used in simulation, Hensen and Lamberts (2011) on building performance simulation in design and operation and Mumovic and Santamouris (2009) on their integrated approach to energy, health and operational performance. Architectural performance arguably is covered by Kolarevic and Malkawi (2005) in their work on performative architecture. This is complemented by countless articles in peer-reviewed archived journals such as *Building and Environment*, *Automation in Construction*, *Energy and Buildings*, *Advanced Engineering Informatics*, *Architectural Science Review*, the *Journal of Building Performance Simulation*, *Building Research and Information* and *Design Studies*. Building performance is also a day-to-day concern in the construction industry and is of central importance to building legislation.

With the complexity of buildings, the many functions they perform and the multitude of disciplines and sciences involved, there are many different viewpoints and interpretations of performance. The many stakeholders in building, such as architects, contractors, owners and tenants, all view it from a different position. Even in academia, different research interests lead to distinct schools of thought on performance. An example is the work by Preiser and Vischer (2005), who provide a worthwhile contribution on building performance assessment from the point of view of post-occupancy evaluation, yet do not really connect to the aforementioned building performance modelling and

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[2] This discipline is typically named building science in the Anglo-Saxon countries, but *building physics* in continental Europe.

simulation domain. This lack of common understanding is problematic as it hinders the integration that is needed across the disciplines involved. It impedes the use of modelling and simulation in the design process or the learning from measurement and user evaluation in practice, since it makes it hard to sell services in these fields to building clients and occupants. The absence of a common understanding also means that building science and scholarship do not have a strong foundation for further progress and that the design and engineering sectors of the building sector are seen to lack credibility.

The discussion about building performance is further complicated by some intrinsic properties of the building sector. Some may consider building to be a straightforward, simple process that makes use of well-tested products and methods like bricks, timber and concrete that have been around for a long time and where lay people can do work themselves after visiting the local builders market or DIY[3] centre; however this risks overlooking some serious complexity issues. Architectural diversity, responding to individualist culture, renders most buildings to be different from others and makes the number of prototypes or one-off products extremely large in comparison with other sectors such as the automotive, aerospace and ICT industries (Foliente, 2005a: 95). Typically, buildings are not produced in series; almost all buildings are individual, custom-built projects, and even series of homes built to the same specification at best reach a couple of hundred units. This in turn has implications for the design cost per unit, the production process that can only be optimized to a certain extent and, ultimately, building performance. With small series, the construction sector has only limited prospects for the use of prototypes or the use of the typical Plan-Do-Study-Act[4] improvement cycles that are used in other manufacturing industries. Quality control programmes, modularization with standard connectors, construction of components in automated factories and other approaches used in for instance the automotive or electronic system industries are thus not easily transferred to construction as suggested by some authors such as Capehart *et al.* (2004) or Tuohy and Murphy (2015). Buildings are also complex in that they do not have a single dominant technology. While for instance most automobiles employ a metal structure, building structures can be made from in situ cast concrete, prefabricated concrete, timber or steel or a combination of these; similar observations can be made for the building shell, infill and services. Furthermore the construction industry is typically made up of many small companies who collaborate on an ad hoc basis, with continuous changes in team composition and communication patterns, which are all challenges for the dialogue about building performance. Of all products, buildings also are amongst those that undergo the most profound changes throughout their life; while changing the engine of a car normally is not economically viable, it is common practice to replace the heating system in a building, to retrofit the façade or even to redesign the whole building layout, with profound consequences on the building performance (Eastman, 1999: 27–30). Once buildings exhibit performance faults, these are often hard to rectify; there is no option of a product recall on the full building scale. Moreover, buildings, because of their fixed position in space, are not comparable with other products in terms of procurement strategies; for

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[3] Do It Yourself.

[4] Sometimes named Deming cycle or circle, or Shewhart cycle.

instance, the decision on the purchase of a building also relates to facilities in the vicinity, not just the building itself. The supply chain of buildings also is different, with the clients who start building processes often selling the product on to other end users (Foliente, 2005a: 95–96).

Yet another complication arises from shifting approaches to performance measurement, driven by the rapid developments in the ICT sector. In the past, measurement of the performance of buildings was an expensive issue, requiring the installation of expensive specialist equipment. Computational assessment of building performance typically took place in a different arena, detached from the world of direct observation. However, the digital age has meant huge reductions in the cost of sensors; wireless technology reduces the need to put intrusive cabling into buildings, and increases in memory size make it easy to harvest data at high frequencies. As more data on building performance is harvested, it becomes obvious that performance predictions and measurement do not always agree, leading to phenomena like the 'energy performance gap' (Carbon Trust, 2011; Menezes *et al.*, 2012; CIBSE, 2013; Wilson, 2013; de Wilde, 2014; Fedoruk *et al.*, 2015; van Dronkelaar *et al.*, 2016). Some believe that the main reason for this energy performance gap is a lack of accounting for all energy use in a building such as ICT systems, plug loads, special functions and others (CIBSE, 2013). Others see issues with software, software users, building, commissioning, maintenance and recording (Wilson, 2013). Yet others hold that a key to improvement is a better understanding and representation of the energy-related occupant behaviour in buildings (Duarte *et al.*, 2015; Ahn *et al.*, 2016; IEA, 2016b). To bridge this gap, it seems obvious that some of the prediction and analysis tools used in the sector need to be revisited in depth (Sun, 2014). However, the different views of building performance also compound the debate and need to be addressed if prediction and direct observation are to become aligned. A common understanding of building performance is also a prerequisite to make sense of the large amount of data collected from buildings and to drive new analysis and management processes.

In spite of the interest of many in building performance and its importance in what clearly is a complex context, building performance remains so far a rather evasive concept. While the term building performance is used regularly in literature, there is a paucity of text that actually defines what it is; in most cases the meaning is left implicit. The generic concept of performance is far from limited to the building domain. Yet literature on the subject of building performance seems mostly restricted to discussions within the discipline, with only few authors looking towards other sectors. With further integration through concepts like machine-to-machine communication and the 'Internet of Things', it is important to bring the concept of building performance in line with the approaches in the other fields.

From an architectural stance, building design can be considered as the combination of three types of integration: physical, visual and performance integration. Here physical integration relates to the need for building components to connect and share space. Visual integration is combining the components in a way that creates the buildings' shared image. Performance integration then deals with sharing functions (Bachman, 2003: 4). In this structure, building performance can also be seen as a guiding design principle in architecture, similar to form making. In this context building performance covers a wide domain – from spatial, social and cultural to structural, thermal and other technical aspects (Kolarevic and Malkawi, 2005: 3).

The International Council for Research and Innovation in Building and Construction (CIB),[5] taking a technical view, defined the 'Performance Approach' to building as 'working in terms of ends rather than means'. Here 'ends' relates to desired technical attributes of a building such as safety or structural stability of load-bearing capacity; 'means' are actual systems and solutions. The CIB definition was originally positioned in the context of building legislation and how to define performance in building regulations (Bakens *et al.*, 2005). However, with the passing of time, many regulations are now performance based, and this definition has thus lost in importance and urgency; moreover a lot of the earlier fundamental thinking by CIB in the 1980s seems to be lost to the performance discourse. In the domain of standards, ISO 6241 (1984: 2) on 'the principles of performance standards in building' simply equals performance to 'the behaviour (of a product) related to use'.

Even so, only very few authors actually define building performance:

- Williams (2006: 435) notes that building performance is a complex issue. Listing a range of items that buildings need to accommodate (people, equipment, processes, places, spaces, image, convenience, comfort, support systems, costs, income, profitability), he then defines building performance as 'the contribution made by a building to the functional and financial requirements of the occupiers and/or owners and the associated physical and financial characteristics of the fabric, services and finishes over time'. Williams identifies three key facets of building performance: physical performance, functional performance and financial performance.
- Almeida *et al.* (2010) define building performance as the behaviour of buildings as a product related to their use; they note that performance can also be applied to the construction process (for instance, interaction between parties) and services (such as the performance of an asset in support of business).
- Corry *et al.* (2014) define building performance as 'delivering functional intent of each zone in the building while accounting for the energy and cost of delivering this functional intent'.
- An interesting view of looking at building performance is provided by Foliente *et al.* (1998: 16), who draw the attention to the opposite of performance: non-performance, which they define as the failure of meeting a specified performance level.

Key figures in the domain mostly leave the concept undefined. Clarke (2001: ix–x) emphasizes the complexity of buildings and the large search spaces required for analysis, as well as the different interacting physical domains, and then focusses on the benefits of building simulation and how this can be integrated into the design process. Preiser and Vischer (2005: 6) do not directly define building performance but list the priorities of building performance as health, safety, security, function, efficiency, work flow, psychological, social and culture/aesthetic. They also note the interplay between performance and the scale of any performance evaluation and the relation to occupants (individuals, groups or organizations). Hensen and Lamberts (2011: 1–14) build up the need for models and tools from a discussion of sustainability challenges, user

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[5] CIB is an abbreviation of the French version of the name, 'Conseil International du Bâtiment'.

requirements and the need for robust solutions; they mention high performance and eco-buildings, but do not define building performance. In terms of building performance simulation tools, they emphasize that these are multidisciplinary, problem oriented and wide in scope. Augenbroe, arguably a leading thinker on the role of simulation in performance-based building, approaches performance as central to a stakeholder dialogue and dissects that discussion into an interplay between building functions, performance requirements, performance indicators, quantification methods and system attributes (Augenbroe, 2011).

It is also interesting to note the position of some international organizations on building performance:

- The International Building Performance Simulation Association (IBPSA, 2015) has as its mission 'to advance and promote the science of building performance simulation in order to improve the design, construction, operation and maintenance of new and existing buildings worldwide'. IBPSA's vision statement mentions the need to address performance-related concerns, to identify problems within the built environment and to identify the performance characteristics on which simulation should focus, yet it does not provide a definition of building performance.
- The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2015) provides annual handbooks that are a key reference in this area. Yet their composite index across the handbook series, which does mention many topical areas such as building information modelling (BIM), performance contracting and performance monitoring, does not have an entry on building performance.
- The Chartered Institution of Building Services Engineers (CIBSE, 2015a) publishes the *CIBSE Guide A: Environmental Design* (CIBSE, 2015b). This opens with a section on quality in environmental design, which discusses key criteria such as thermal, visual and acoustic comfort, health, energy efficiency and greenhouse gas emissions. By focussing on quality assurance in buildings, this guide sidesteps the definition of building performance; however, the guide goes on to define legislation including the Energy Performance of Buildings regulations and discusses performance assessment methods (PAMs) as a key approach to select appropriate calculation methods to assess quality.

Standards typically address only aspects of the overall building performance, yet can provide interesting indirect insights. For instance, BS EN ISO 50001 (2011: 3) defines energy performance as 'measurable results related to energy efficiency, energy use and energy consumption'. It notes that these measurable results can be reviewed against policy, objectives, targets and other energy performance requirements.

Williams (2006: 435) and Cook (2007: 1–5) associate building performance with building quality. However, Almeida *et al.* (2010) note that 'quality' is a systems attribute that is hard to define; it is often taken to mean the absence of defects. It is related to a range of theories and approaches such as quality control, quality assurance, quality management, quality certification and others. Gann *et al.* (2003) agree, stating that 'design quality is hard to quantify as it consists of both objective and subjective components. Whilst some indicators of design can be measured objectively, others result in intangible assets'. Other authors, such as Loftness *et al.* (2005), use the term 'design excellence' rather than performance or quality.

Not having a proper definition of building performance also leads to misunderstanding, fuzzy constructs and overly complex software systems. This is especially the case where building performance is used in the context of a wide view of building sustainability, in the difficult context of building design or as part of larger ICT systems; see for instance Bluyssen (2010), Todorovic and Kim (2012), Becker (2008), Geyer (2012) or Dibley *et al.* (2011). Some authors such as Shen *et al.* (2010) promise systems such as 'fully integrated and automated technology' (FIATECH), which is based on a workflow that includes automated design in response to user requirements, followed by automated procurement, intelligent construction and ultimately delivering intelligent, self-maintaining and repairing facilities; clearly such systems are a good long-term goal to drive developments but require a deeper understanding of performance to become feasible. This has lead to a situation where the building industry is sceptical of the work in academia and prefers to move at its own pace and develop its own guidelines, standards and systems. This situation where building performance is, by and large, an undefined concept in both building practice and industry, and where the term is used without a clear frame of reference and common understanding, needs addressing. A clear definition and theoretical framework will strengthen the position of that part of the building sector that provides services, products and buildings in which performance is important; it will also provide a foundation to move scholarship in this area to a next level.

The purpose of this book is to explore and bring together the existent body of knowledge on building performance analysis. In doing so, it will develop a definition of building performance and an in-depth discussion of the role building performance plays throughout the building life cycle. It will explore the perspectives of various stakeholders, the functions of buildings, performance requirements, performance quantification (both predicted and measured), criteria for success and performance analysis. It will also look at the application of the concept of building performance in building design, building operation and management and high performance buildings. The following key questions drive the discussion:

1) What is building performance?
2) How can building performance be measured and analyzed?
3) How does the analysis of building performance guide the improvement of buildings?
4) What can the building domain learn from the way performance is handled in other disciplines?

In answering these questions, the book will develop a theoretical framework for building performance analysis.

1.1 Building Performance: Framing, Key Terms and Definition

Performance is of interest to many disciplines, such as engineering, computer science, sports and management. As noted by Neely (2005), some of the most cited authors in performance measurement come from rather different disciplines, such as accounting, information systems, operations research and operations management. Consequently there is a wide range of literature dealing with context-specific applications of the term such as structural performance, algorithm performance, athletic performance and financial performance. While a full coverage of the performance concept across all fields is impossible, the following gives an overview of some of the interests and approaches from outside the architecture, engineering and construction (AEC) sector, thus providing context and a wider frame of reference for the discussion of building performance:

- In *electronics*, performance typically relates to a system (for instance, a smartphone) or the components of a system (for instance, a transistor). In general the main performance targets are 'better' and 'cheaper'. Within devices, electronic engineers talk of analogue and digital performance of components (Guo and Silva, 2008).
- In *human resources management*, academic and job performance of individuals are key. This is typically measured across a range of factors such as verbal, numerical and spatial abilities, as well as knowledge, personality traits and interests (Kanfer *et al.*, 2010). However, team performance depends on the interaction between tasks, team composition and individual performance. Tasks typically have two key dimensions: speed and accuracy. Deep studies are undertaken to explore the role of incentives to make teams work faster and smarter, with tension between competitive and cooperative reward structures (Beersma *et al.*, 2003).
- In *organizations*, organizational performance is related to the workflow, structures and roles and skills and knowledge of the agents of the organization (Popova and Sharpanskykh, 2010).
- In *manufacturing*, the drive towards higher efficiency leads to more measurement, control and process improvement. Key aspects are the identification of key performance indicators and benchmarks (measurement) and monitoring, control and evaluation. An important enabler to achieve higher efficiency is ICT, which can lead to better process execution, resource planning, intelligent control and advanced scheduling. Standardization is another key enabler for better manufacturing performance (Bunse *et al.*, 2011).
- In the *medical sector*, performance of healthcare is typically measured by means of health and quality of life questionnaires, physical and psychological tests, costs and duration of treatment (van der Geer *et al.*, 2009). In healthcare it has also been noted that if performance is reviewed to steer the actions of employees, it is important that these employees have control of the performance variation and can manage the relation between actions and outcomes (*ibid.*).
- In the *performing arts*, the performance of for instance musicians is known to be related to various human tasks such as listening, reading and playing (Sergent *et al.*, 1992).
- In *social science*, measurements are undertaken to compare the economic, social and environmental performance of countries. Here the indicators used are for instance the Human Development Index (HDI), which takes into account the gross domestic product, life expectancy at birth and adult literacy rate. Other indicators have a more detailed view and might include such aspects as income inequality, carbon emissions or gender bias (Cracolici *et al.*, 2010).
- In *sports*, performance analysis is concerned with recording, processing and interpreting events that take place during training and competition. It covers

technical, tactical and behavioural aspects of both individuals and teams (Drust, 2010). Performance analysis in sport is considered to be a difficult undertaking, covering biomechanics, notational analysis (which covers movement patterns, strategy and tactics), motor control and human behaviour, so that one-dimensional analysis of raw data can easily lead to misunderstanding (Hughes and Bartlett, 2010).

- In the *tourism* sector, different offers are compared using Tourism Destination Competitiveness (TDC) studies. TDC looks at different aspects of competitiveness, but while it uses exhaustive lists of indicators, there is still some concern about completeness. One way to develop TDC is to review it by means of Importance–Performance Analysis (IPA), which basically positions efforts in four quadrants along an axis of importance and competitiveness, thus allowing to define where resources need to be sustained, increased, curtailed or remain unchanged (Azzopardi and Nash, 2013). Taplin (2012) gives a good example of application of IPA as applied to a wildlife park.
- In *transport and logistics*, management uses key performance indicators to measure and improve the overall process; the usual objectives are to decrease cost and to improve efficiency and effectiveness (Woxenius, 2012).

With all these different disciplines taking their own approach to performance, there clearly is a need to establish a clear definition of key terms. The following section reviews terminology that sets the scene for an initial definition of building performance at the end of this paragraph.

As mentioned in the introduction, the word performance has two meanings: in technical terms, it is 'the action or process of performing a task or function' and in aesthetic terms it is the 'act of presenting a play, concert, or other form of entertainment'. Within the technical interpretation, performance can be taken to relate to an object, such as a building, car or computer; alternatively it can relate to a process, such as manufacturing or data transmission. Within the literature, two generic disciplines cover these areas: systems engineering and process management. Systems Engineering is broadly defined as 'An interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete [design] problem' (INCOSE, 2016).

The area of (Business) Process Management is defined as 'A disciplined approach to identify, execute, measure, monitor, and control both automated and non-automated business process to achieve consistent, targeted results aligned with an organization's strategic goals' (ABPMP, 2015).

It must be noted that the relation is not one to one: systems engineering is concerned not only with systems but also with the process of creating and managing these systems, whereas process management also relates to the product/outcome of the process.

A system can be defined as a set of interacting elements that, together, accomplish a defined objective. The elements may include products, processes, people, information, facilities and others (INCOSE, 2015: 5). Systems exhibit behaviour, properties and functions, which are characterized by emergence and complexity. Most systems interact with other systems and their environment (SEBoK, 2014: 65). In a slightly different wording, systems consist of *components*, *attributes* and *relationships*. Here components are the operating parts of the system, attributes are properties of the components, and relationships are the links between components and attributes (Blanchard and Fabrycky, 2011: 17). Systems normally sit in a hierarchy; the components that make up a system can be named a subsystem. The designation of system, subsystem and component is relative; a reason for defining systems is to understand and handle complexity. Similarly, there are different classifications of systems, such as natural and human made, physical and conceptual, static and dynamic or closed and open (*ibid.*). Thinking in systems helps scientists, engineers and designers to think about the world by defining categories, guiding observation and measurement and supporting the development of models and generic laws (Weinberg, 1975: ix–xii).

There are many reasons for analyzing the performance of systems. On a high level, these include an interest in for instance (Montgomery, 2013: 14–15):

1) Factor screening or characterization – to find out which factors have most impact on the performance.
2) Optimization – to find the parameter values and system configurations that result in the sought performance.
3) Confirmation – to verify that a system performs as is expected.
4) Discovery – to establish the performance of new systems, combinations and so on.
5) Robustness – to study how system performance changes in adverse conditions.

In the context of systems engineering, performance is defined as a 'quantitative measure characterizing a physical or functional attribute relating to the execution of a process, function, activity or task. Performance attributes include quantity (how many or how much), quality (how well), timeliness (how responsive, how frequent), and readiness (when, under which circumstances)' (INCOSE, 2015: 264).

In different words, performance is an attribute of a system that describes 'how good' a system is at performing its functional requirements, in a way that can be measured (Gilb, 2005: 382). Gilb gives a slightly different classification of performance types, discerning quality (*how well* a system performs its functions), resource saving (*how much resource* is saved in relation to an alternative system) and workload capacity (*how much work* a system can do). Performance relates not only to the physical design of a system but also to the particular use of a system. As exemplified by Hazelrigg (2012: 301), 'the performance parameters such as acceleration and top speed of a car depend on its physical design. However, another performance parameter might be the lifetime of the engine. This will depend on the maintenance of the engine, such as the frequency of oil changes, the conditions under which the vehicle is driven, and manner in which it is driven. These items are a function of the use of the product, not of its physical design.'

As a consequence, performance requirements should include a description of the conditions under which a function or task is to be performed (SEBoK, 2014: 292).

A function of a system is a 'characteristic task, action or activity that must be performed to achieve a desired outcome' (INCOSE, 2015: 190). There are two kinds of functions: (i) functions that relate to the requirements the system has to meet and therefore relate to an 'outer environment' and (ii) functions that are intertwined with the actual design of the system; these relate to an ‘inner environment’ and are partly a consequence of design choices. As stated by Simon, ‘The peculiar properties of the artifact lie on the thin interface between the natural laws within it and the natural laws without .... The artificial world is centered precisely on this interface between inner and outer environments; it is concerned with attaining goals by adapting the former to the latter’ (Simon, 1996: 113).

In order to analyze performance, ‘how well’ a system meets the functional requirements, one needs to compare the measured performance with clear criteria. Different words are used in this context, such as goal, target and objective. The Systems Engineering Body of Knowledge defines a goal as ‘a specific outcome which a system can achieve in a specified time’ and an objective as ‘a longer term outcome which can be achieved through a series of goals’; this can be extended with the concept of an ideal, which is ‘an objective which cannot be achieved with any certainty, but for which progress towards the objective has value’ (SEBoK, 2014: 115). A target can be defined as a performance requirement defined by the stakeholder, which is to be delivered under specified conditions (Gilb, 2005: 430). In most cases there are multiple criteria, and often these criteria conflict, resulting in a need for trade-off decisions (SEBoK, 2014: 414). Augenbroe (2011: 16) considers the notion of a criterion to be central to the whole process of performance analysis: a criterion is closely interrelated with the experiment that is required, the tool(s) that must be used and the way in which data is collected and aggregated into a performance statement while also defining what is required.

The concept of measurement is crucial to performance analysis of systems. Measurement is the process that collects, analyzes and reports data about products developed or processes implemented; this allows the demonstration of the quality of these products and the effective management of these processes (INCOSE, 2015: 130). Measurement is often governed by industry standards and policies and sometimes by laws and regulations. Data analysis and reporting typically includes verification, normalization and aggregation activities, as well as the comparison of actual data against targets (SEBoK, 2014: 406).

Analysis can be encountered at different stages of a project; different categories of analysis are estimation analysis, feasibility analysis and performance analysis. Estimation analysis is carried out during the initial planning stage and is based on projections to establish objectives and targets. Feasibility analysis aims to establish the likelihood of achieving objectives and targets; it provides confidence in assumptions and ensures that objectives are reasonable. It might also include a check with past performance of similar projects and technologies. Finally, performance analysis is carried out during development and operation in order to check whether objectives and targets are being met (INCOSE, 2005: 42–43).

On a fundamental level, the analysis of building performance can be approached through four routes:

1) Physical testing, either in laboratory conditions or under ‘live’ conditions.
2) Calculation, mostly in the form of computer simulation.
3) Expert judgment, depending on the insights of professionals.
4) Stakeholder assessment, capitalizing on the insights of occupants who know a specific building best.

It is interesting to note that ISO 7162 (1992), still actual on content and format of standards for performance evaluation of buildings, only mentions categories 1–3, but excludes category 4.

Quantification of performance is useful, but when doing so it is important to remember the context and not to get blinded by numbers. As phrased by Cameron (1963),[6] 'not everything that counts can be counted, and not everything that can be counted counts'. In some areas of management and policy, making quantifications sometimes becomes obsessive, leading some to comment that measurement and regulation are leading to an 'audit society' (Neely, 2005).

Traditionally, construction management has focussed on the key factors of cost, time and quality, sometimes named the 'iron triangle' where trade-off between these three factors is required (Atkinson, 1999) and where poor performance leads to time delays, cost overruns and quality defects (Meng, 2012). Recent work indicates that the emphasis in construction management is now shifting to a wider range of issues such as safety, efficient use of resources and stakeholder satisfaction (Toor and Ogunlana, 2010) and specific studies are taking these individual issues further – see for instance Cheng *et al.* (2012) on the interaction of project performance and safety management or Yuan (2012) on waste management in the social context of construction.

In the arts, the word performance mainly appears in the context of the performing arts such as dance, theatre and music. Here a key aspect is the involvement of artists who use their bodies and voices. It is less associated with other types of arts such as literature and visual arts. Performing art typically involves a creative process that develops an underlying source or text into a specific production. Here a director, playwright, scenographer and others use their own creativity and interpretation to define what will be presented to the audience (Féral, 2008). In the resulting production, there is a second creative process, where actors interpret their roles and interact with the audience, the stage and objects or props (Lin, 2006). In the communication with the audience, visual, auditory and verbal stimuli are of importance (Cerkez, 2014). In the arts, performance lives next to rhetoric. Both of these are concerned with communication, but performance sets itself apart by having some form of 'embodiment' and attempting to 'enchant' the participants and audience (Rose, 2014). In musical performance, overall quality, technical skills and individuality are all key aspects of a performer's expression (Wöllner, 2013). The notion defining performance in the arts is not uncontested, as exemplified by Bottoms (2008) who makes a case for staying with 'theatre' as visual and time-based art forms with specific social–cultural contexts. Counsell and Wolf (2001: i–x) present a number of ways to analyze artistic performance by looking at aspects such as decoding the sign, politics of performance, gender and sexual identity, performing ethnicity, the performing body, the space of performance, audience and spectatorship and the borders of performance.

The aesthetic notion of performance in the field of architecture is still under development. Some work showing progress in performative architecture or architecture performance can be found in Leatherbarrow (2005), who explores how buildings perform through their operations and how this concept of performance interrelates actions,

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[6] Sometimes related to Albert Einstein, either as quote or sign in his office, but not verified; see, for instance, Blyth and Worthington (2010: 84).

events and effects, or in a wider sense in Kolarevic and Malkawi (2005). Kolarevic (2005b: 205–208) himself writes that architecture typically takes place on a spectrum between 'blending in' and 'standing out'. Recent architecture sometimes takes the standing out position, with the building performing in its context, which acts as a stage. Sometimes there even are active interactions with occupants, dynamically changing light patterns and other movements and reaction to create movement and action. Hannah and Kahn (2008) discuss the tension and interplay between performance and architecture in a special issue of the *Journal of Architectural Education*. Schweder (2012) explores avenues such as 'architect performed buildings', 'buildings that perform themselves', 'bodily performance in architectural time', 'rescored spaces' and 'its form will follow your performance'. Hann (2012) discusses performative architecture as move from 'form follows function' towards a mixture of both 'form is a consequence of actions and events' and 'events and actions are shaped by form'. Hensel (2013) describes in his book on performance-oriented architecture how the concept of performance may even transform the complete notion of architecture and the built environment. Dwyre and Perry (2015) discuss architecture and performance in terms of a contrast between static and permanent qualities versus temporal and impermanent ones, with architecture and landscape design starting to take up more dynamics and movement since the start of the 21st century.

Based on these key terms, building performance can be defined as follows:

> Building performance relates to either a building as an object, or to building as construction process. There are three main views of the concept: an engineering, process and aesthetic perspective. The engineering view is concerned with how well a building performs its tasks and functions. The process view is concerned with how well the construction process delivers buildings. The aesthetic view is concerned with the success of buildings as a form for presentation or appreciation.

This position on building performance is summarized in Table 1.1. This initial take on building performance will be developed into a theoretical framework that defines in more detail what building performance is, and how it can be operationalized, in the remainder of this book.

While the definition of performance as being something that the building actively does is logical, it is important to keep in mind that most buildings are immovable artefacts. In most cases the concept of action involves interaction with occupants such as humans entering and experiencing the building (Leatherbarrow, 2005: 10). Taking this

Table 1.1 Building Performance Views.

Building Performance			
View	**Engineering**	**Process**	**Aesthetics**
Definition:	Action or process of performing a task or function	Action or process of performing a task or function	Form for presentation or appreciation

further, two views of building actions are important. One concerns the active actions and operation of buildings, such as that of exterior surfaces, screens, doors, furnishing and building services; most of these actions concern the adjustment to foreseen and unforeseen conditions. A second view concerns the more passive action that the building needs to take to stay as it is, in terms of reacting to ambient conditions such as climate and gravity. While this second view of 'action' concerns something that is more resistance towards forces and events, buildings actually are subject to serious loads in terms of the weather, (mis)use by occupants and alterations (Leatherbarrow, 2005: 13).

1.2 Performance in the Building Domain

In spite of the lack of definition of building performance, the concept has implicitly been around for a long time. As long as humans are concerned with shelter, performance will have been of importance. Emerging humanity will have selected caves to dwell in based on performance criteria such as protection from the elements, access and stability. Similarly, primitive dwellings must have been constructed with a focus on keeping the inhabitants safe from the weather and wild animals. But after some development, early humans have also constructed some formidable buildings such as the Stonehenge monument depicted in Figure 1.1 (3000 BC–2000 BC) or the Great Pyramid of Giza (2580 BC–2560 BC). Neither of these has reached the modern age with historical records of their full purpose and leave archaeologists to discuss the construction process and meaning of details; however both have fascinating astronomical alignments that may point to these buildings performing roles as solar clock or stellar representation.

Figure 1.1 Stonehenge Monument, Wiltshire, UK.

Both are on the UNESCO World Heritage list, demonstrating sociocultural importance; both remain impressive in terms of the effort and organization that must have gone into their construction, especially with the means available at that time, and whatever detailed functions these buildings may have had, they have been made with a quality that has allowed them to endure more than four millennia and can thus be said to be early 'high performance buildings'.

A full history of architecture and construction is beyond the scope of this work; however a range of major cultures left the world a fascinating built legacy – see the buildings, cities and infrastructure created by the likes of for instance Mesopotamia, Egypt, India, China, Greece, the Roman Empire, the Christian middle ages in Europe and the Pre-Columbian societies of the Americas. In many cases the buildings followed typical architectural styles, such as Ancient Persian, Ancient Egyptian, Karnataka Architecture, Song Dynasty Architecture, Doric/Ionic/Corinthian Order, Romanesque/Gothic/Baroque or Mesoamerican and Maya. Many of these styles prescribe form, construction methods and materials. The construction of these buildings involved complex design, planning and coordination of large workforces. How building performance was incorporated in their design will often remain a question.

1.2.1 Development of the Notion of Building Performance

Amongst the oldest documents in archives are legal codes; these often relate to buildings. It should thus come as no surprise that the earliest and often quoted example of building performance in building regulations (Bakens *et al.*, 2005) stems from the oldest code of law in the world, dating back to about 1754 BC: the Hammurabi Code by the King of Babylon. This states in § 229: 'If a builder has built a house for a man and has not made strong his work, and the house he built has fallen, and he has caused the death of the owner of the house, that builder shall be put to death' (Johns, 1903).

Another crucial source from antiquity on design and construction of buildings, and the oldest work written by someone from the same period, are the ten books on architecture by Vitruvius,[7] named *De architectura*. This work includes the first deep discussions of how buildings should meet user requirements (Foliente, 2000; Becker, 2008). Vitruvius states that buildings must possess three key qualities: *firmitas*, *utilitas* and *venustas*. The standard English translation of these Latin terms gives them as *durability*, *convenience* and *beauty* and adds the explanation by Vitruvius that 'durability will be assured when foundations are carried down to the solid ground and materials wisely and liberally selected; convenience, when the arrangement of the apartments is faultless and presents no hindrance to use, and when each class of building is assigned to its suitable and appropriate exposure; and beauty, when the appearance of the work is pleasing and in good taste, and when its members are in due proportion according to correct principles of symmetry' (Morgan, 1960: 17).

Other translations name firmitas, utilitas and venustas as *strength*, *utility* and *beauty* or as *firmness*, *commodity* and *delight*; they can also be interpreted by a focus on Build

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[7] Marcus Vitruvius Pollio, a Roman architect, civil engineer and military engineer, and author.

Quality, Function and Impact (Gann *et al.*, 2003). While Vitruvius is not directly speaking of building performance, this is clearly implied in the three key qualities. It is interesting to note that the ten books of *De architectura* span a wide field, covering amongst others urban design (Book I), building materials (Book II), architectural design principles for temples (Books III and IV), civil buildings (Book V) and domestic buildings (Book VI) and decoration in terms of pavements and plasterwork (Book VII). Beyond this, Vitruvius also covers underlying building science and services in terms of water supply (Book VIII), astronomy and solar access (Book IX) and machines and building services (Book X). Included in the work are discourses about architectural education, structural engineering, physics and music, and acoustics (Morgan, 1960: vii–xii). Another interesting point about Vitruvius is that in many cases *De architectura* gives prescriptions on how to build in specific detail and solutions; for instance on the layout of a city in respect to winds (*ibid.*, 26), relative dimensions of a theatre (*op. cit.*, 148) or foundations of houses (*op. cit.*, 191). Such prescriptions are one way to ensure building performance, staying with solutions that are known to work.

When looking at the role of performance in building, it is important to note that for a long time and in many cultures, building design and construction was a craft, with the know-how of the trade being passed on from master builders to apprentices. Moving forward from Vitruvius and through roughly two millennia, this remained the generic case. But the industrial revolution, which started in the United Kingdom and roughly took place from the mid-18th to mid-19th century, meant a change in manufacturing and production processes. Key developments that impacted on construction and buildings were, amongst others, availability of new building materials such as iron and steel, the invention of Portland cement, gas lighting and new production processes for glass. But the industrial revolution also changed the construction sector from a craft-based undertaking into an industry with different production processes and approaches. An interesting account of many of these changes, and how they impacted on the built environment, is contained in *At Home – a short history of private life* (Bryson, 2011). The industrial revolution also was one of the drivers towards changes in architecture and the development of modernism, functionalism and determinism (Braham, 2005: 57). In terms of performance, it is interesting to note the famous statement by the American architect Louis Sullivan, made in 1896, that 'form follows function' and the impact this had on architectural design.

The industrial revolution gave rise to the emergence of host of new disciplines in the building domain, most notably structural engineering and a new field dealing with heating, cooling, ventilation and lighting.[8] Specialist in these areas quickly organized themselves, founding organizations that have been dealing with building performance for over a century. With the start of the industrial revolution in the United Kingdom, it is not surprising that many new associations were founded here, such as ICE, the Institution of Civil Engineers (1818), ImechE, the Institution of Mechanical Engineers (1847), and IstructE, the Institution of Structural Engineers (1908). CIBSE, the Chartered Institution of Building Services Engineers in the United Kingdom, has roots in the Institution of Heating and Ventilating Engineers (1897) and the Illuminating Engineering Society (1909). CIBSE still publishes guides, application manuals and technical memoranda.

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[8] In the United Kingdom, this field is typically named building services engineering.

In the United States, ASCE, the American Society of Civil Engineers, was founded in 1852; this covers many domains as evidenced by the 33 academic journals still published by ASCE to this day, which cover such diverse fields as architectural engineering, structural engineering and urban planning. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) traces its history back to 1894. ASHRAE still publishes, amongst others, influential handbooks and standards. In the southern hemisphere, the Institution of Engineers Australia (IEAust) dates back to 1919, with a similar coverage as ASCE. The German VDI (Verein Deutscher Ingenieure) was founded in 1856 and covers a range of disciplines, including construction and building technology. The profession of architecture continued and its professionals also organized themselves, leading to the foundation of the likes of the RIBA, the Royal Institute of British Architects (1834), AIA, the American Institute of Architects (1857), BDA, Bund Deutscher Architekten (1903) and others. In other countries, organizations were founded only much later; for example, the Union of Chambers of Turkish Engineers and Architects was only created in 1954.

In the early 20th century, after World War I, the concept of building performance became more prominent. In the United States, the Division of Building and Housing developed a publication titled *Recommended minimum requirements for small dwelling construction*, which was published in 1922 and is often considered to be the first modern model building code (Zingeser, 2001). Another key publication was the *Recommended practice for arrangement of building codes*, published by the National Institute of Standards and Technology (NIST) (Gross, 1996; Foliente, 2000). Obviously, World War II directed attention elsewhere, and afterwards the prime concern was rebuilding. In the 1960s the concept returned to the fore, not just within the engineering disciplines but also as a guiding principle in architectural design. Braham (2005: 57) mentions a special issue of the magazine *Progressive Architecture* that appeared in 1967 on the topic of 'performance design'. This positioned performance design as a scientific approach to analyze functional requirements, stemming from the developments of general systems theory, cybernetics and operations research and combining psychological needs, aesthetic needs and physical performance. This enabled radical new designs, such as the Centre Pompidou in Paris – built between 1971 and 1977 – which makes building services, and thereby to some extent building performance, into the key design feature.

As with many disciplines, the rise of the personal computer starting in the 1960s also had a profound impact on work in building performance. Right from the start in the 1960s and 1970s, researchers at the University of Strathclyde's ABACUS unit already promoted the use of digital performance assessment tools as a guiding principle for building design (Kolarevic, 2005a: 196). The first group completely dedicated to the study of building performance as a subject in itself was probably the Building Performance Research Unit (BPRU), again at the University of Strathclyde (United Kingdom). BPRU studied appraisal of building performance in the context of design and was an independent unit from 1967 to 1972. Findings were presented in a book that appeared in 1972, describing the interrelation between design decision making and performance, the interaction between various performance aspects (physical, psychological, economic), the use of computing tools and application in practice. The work has a strong basis in systems theory and covers a range of issues such as lighting, sound, thermal comfort, limited use of resources and costs. Interestingly there also is significant attention for spatial elements and organization, as well as bounding spatial elements, compactness and circulation patterns, topics that feature less in later work on the subject (Markus *et al.*, 1972).

In the 1960s, another new building discipline came to prominence: building science, typically named building physics in mainland Europe. This is an applied science that mainly studies thermal, lighting and acoustic performance of buildings. First handbooks that appeared at the end of the decade are *Handbuch der Bauphysik* (Bobran, 1967), *Thermal Performance of Buildings* (van Straaten, 1967) and *Architectural Acoustics* (Lawrence, 1970). Obviously, the importance of building science – and accordingly building performance – increased with the energy crisis of the 1970s, turning the field into a domain studied across the globe.

Yet another discipline concerned with building performance emerged in the 1960s: environmental psychology. Generally this field came into being as response to dissatisfaction with the built environment of the time (Gärling, 2014). Originally environmental psychology focussed on the impact of the human environment on people's well-being; more recently this is looking to change people and human behaviour in order to preserve the environment (*ibid.*). Environmental psychology views building performance from a range of viewpoints, such as individual choice, consumption, sacrifice, values and attitudes, education, motivation, incentives and lifestyle (Stern, 2000). These play a role in efforts to deal with global challenges such as climate change, human population growth and the use of finite resources (Sörqvist, 2016). Stern (2000) however warns against a tendency to put too much emphasis on psychological interventions and points out that it is important to position the role of human actions in a wider frame; in some cases there are more effective interventions in other domains.

Early computers led to further changes in the construction sector by the evolution of digital building models. From the development of the first computer-aided design (CAD) by Sutherland in 1963, there was progress in geometric modelling, discipline-specific analysis models and central models shared by a range of applications. Of course many of these specific analysis models dealt with various aspects of building performance. In the early days the shared cross-application models were named building product models; the seminal book on the subject is the work by Eastman (1999), which includes a full chapter on their history. Pioneering work on product modelling was carried out in the context of the European COMBINE Project (Computer Models for the Building Industry in Europe), with stage I (1990–1992) focussing on the development of an Integrated Data Model (IDM) and stage II (1992–1995) exploring the development of this IDM into an Intelligent Integrated Building Design System (IIBDS). Early on, COMBINE demonstrated the importance of the process dimension of information exchange between various stakeholders in the building performance dialogue (Augenbroe, 1994, 1995; Clarke, 2001: 311–316). COMBINE had a lesser-known follow-up in the United States through the Design Analysis Integration (DAI) Initiative, which ran from 2001 to 2002 and again had a strong emphasis on process (Augenbroe *et al.*, 2004). Another noteworthy effort combining computer models with building performance was the SEMPER project carried out at Carnegie Mellon University from 1996 to early 2000s (Mahdavi *et al.*, 1997a). Around 2002 the key term for work on digital building models became Building Information Modelling (BIM); with the increasing move towards digitalization, this became a key change for the building industry in the first decades of the 21st century. For a recent overview, see

Eastman *et al.* (2011). It is noted that BIM is becoming a regular data carrier for new buildings; however there are challenges in capturing the existing building stock and legacy buildings (Volk *et al.*, 2014).

Internationally, CIB (International Council for Research and Innovation in Building and Construction) started efforts on the subject of building performance by launching Working commission W60 on the *Performance Concept in Building* in 1970. Later a range of CIB Task Groups focussed on related aspects: Task Group TG36 dealt with *Quality Assurance*, TG11 with *Performance Based Building Codes* and TG37 with *Performance Based Regulatory Systems*. Many of these were active over a long period. Through W60, CIB supported a range of conferences together with RILEM (Reunion Internationale des Laboratoires et Experts des Materiaux) and ASTM (American Society for Testing and Materials) in Philadelphia in 1972, Otaniemi in 1977, Lisbon in 1982 and Tel Aviv in 1996 (Foliente, 2000).

In the early 1980s, the CIB Working Commission W60 published their seminal Report 64 on 'Working with the Performance Approach to Building' (CIB Report 64, 1982). It opens with the famous and often-quoted line: 'The performance approach is, first and foremost, the practice of thinking and working in terms of ends rather than means'. The report is a position statement that was developed by the Working Commission over a decade and builds on earlier CIB Reports and W60 Working papers. It describes the meaning of the performance approach, especially when contrasted with prescriptive requirements and specifications. It discusses who might benefit from the performance approach and what these benefits might be, the knowledge base required, how to establish performance requirements, how to predict and measure performance and how to evaluate the suitability for use, and it concludes with a discussion of application at various levels (whole building, component, design, manufacture, regulations and standards). Underlying the work is a drive to develop consistency in the building domain, combined with the promotion of innovation in the sector. As quoted from the report: 'In essence … the performance approach is no more than the application of rigorous analysis and scientific method to the study of functioning of buildings and their parts…. However it does break new ground by attempting to define unified and consistent methods, terms and documentation, and by subjecting all parts of the building to systematic scrutiny' (CIB Report 64, 1982: 4).

It is interesting to note that within the W60 report, significant attention is paid towards applying the performance approach on component and product level (CIB Report 64, 1982), whereas most recent texts on building performance tend towards holistic performance assessment of complete buildings or even address the district and city levels. In terms of the development of the building performance field, CIB Report 64 contains a bibliography that gives a good historical perspective. It is noted in the report that 'this bibliography is limited to major national and international publications on the performance concept and its application. Individual articles and conference papers are not listed' (CIB Report 64, 1982: 26); however the bibliography already covers 92 publications from 17 different countries as well as international organizations like CIB itself. Many of these references are extensive standards that consist of several parts or volumes, showing the considerable interest and progress on the subject. Out of these 92 publications, only 11 date from before 1970, with the oldest one being conference proceedings from the National Research Council of the United States on

'Performance of Buildings' dating back to 1961 (CIB Report 64, 1982: 26–30). CIB Report 64 contains important thinking by the experts of the time. Unfortunately it appears to have had a limited circulation only and is seldom cited in recent work.

The CIB Proactive Program on Performance-Based Building Codes and Standards (PBBCS) ran from 1998 to 2001. This was a networking platform for furthering the earlier work done by CIB on the subject, establishing the state of the art and setting the agenda for new initiatives (Foliente *et al.*, 1998: 5–6). In 2001 this was followed up by a European Thematic Network named PeBBu (*Performance-Based Building*), which ran from 2001 to 2005 (Almeida *et al.*, 2010) and was coordinated by CIB. PeBBu was funded by the European Union (EU) Fifth Framework Programme. This network brought together over 70 organizations with an interest in the subject, facilitating information exchange and dissemination of knowledge. As a network, the main activities of PeBBu were to promote performance-based building; however the project also included activities that mapped research in the area, and it developed a compendium of knowledge on the subject (Jasuja, 2005: 19–20). In parallel to this EU PeBBu, there was also an Australian counterpart – AU-PeBBu, which started in 2003 (Jasuja, 2005: 28–29). Both PeBBu networks aimed at moving the performance approach as defined by CIB towards wider application through engagement with a variety of stakeholders such as policymakers, regulators, building officials, investors, developers, owners and owner–occupiers, architects and designers, engineering professionals, specialist consultants, product manufacturers, project managers, contractors and builders, facility managers, service providers, users and tenants, ITC professionals, researchers and educators (Bakens *et al.*, 2005; Augenbroe, 2011: 16). PeBBu developed scientific reports in nine domains: (i) life performance of construction materials and components, (ii) indoor environment, (iii) design of buildings, (iv) built environment, (v) organization and management, (vi) legal and procurement practice, (vii) building regulations, (viii) building innovation and (ix) information and documentation. Domain iv on the built environment positions building performance within the urban context (Jasuja, 2005: 10–12, 31). Some work resulting from PeBBu was published in the journal *Building Research and Information* (Jasuja, 2005: 104). It must be stressed that PeBBu was mainly a networking and dissemination project; most underlying thinking stems from CIB Report 64.

The proliferation of computers meant that the building science discipline was able to advance quickly and move from traditional calculations to computer simulation; the history of building performance simulation is outlined by Augenbroe (2003: 6–10) and Clarke (2001: 3–5). The year 1985 saw the emergence of an entity that was initially known as the Association for Building Energy Simulation Software (ABESS). This developed into IBPSA, the International Building Performance Simulation Association, which was formally founded in 1987. IBPSA organizes a biannual conference named 'Building Simulation'; it has regional affiliates of various levels of activity across the globe, such as IBPSA-USA, IBPSA-England, IBPSA-China, IBPSA-Netherlands + Flanders and many others. In the United Kingdom, there also was an entity named the Building Energy Performance Analysis Club (BEPAC), which acted as a predecessor to a regional affiliate; BEPAC existed from 1985 to the mid-1990s.

In the 1980s the building industry in many countries was faced with pressure from government, clients and increased international competition to improve building quality and construction speed and reduce costs. At the same time a range of deep studies into the performance of actual buildings (case studies) emerged. Often these found issues with energy efficiency and indoor air quality. The relation between buildings and ill health became a subject of study and gave rise to the use of the term of 'sick building syndrome' (Cohen *et al.*, 2001). These developments led to the emergence of the new discipline of Facilities Management[9] (Cohen *et al.*, 2001). Starting from a simple basis in building maintenance, service and cleaning, Facilities Management grew to the profession that 'ensures the functionality of the built environment by integrating people, place, process and technology' and is concerned with performance in each of these domains (Atkin and Brooks, 2009: 4). Beyond the performance of buildings and building systems, Facilities Management is also concerned with the performance of the processes that take place inside and around the building, such as change management, in-house provision and outsourcing and workplace productivity.

With Facility Management addressing the performance of buildings in use, there also re-emerged an interest in the handover of buildings at the end of the construction stage. This is typically named building commissioning, allegedly a term rooted in shipbuilding, where a ship undergoes a process of testing before it goes into operation as commissioned vessel. The idea of building commissioning has been around for a long time. Already in 1963, the Royal Institute of British Architects (RIBA) Plan of Work of included a stage for feedback, where the architect was to return to the building to assess the success of the design and construction (Bordass and Leaman, 2005). This was later dropped but brought back in a revision of the Plan of Work in 2013, which reintroduced a review of buildings in use, post-handover and closeout. At the end of the 1960s, CIBSE published the first edition of their Commissioning code A, which was regularly updated and still is available to the current day (CIBSE, 2006). A recent development is the application of commissioning throughout the building usage, which is named continuous commission and abbreviated as CC (Liu *et al.*, 2003). In the United Kingdom, the 'Soft Landings' process also includes the design and construction stages, thus also involving the actors that produce the building in the operational performance (Way and Bordass, 2005). Since 2016 the UK Government requires centrally funded construction projects to be delivered through a Government Soft Landings (GSL) process, which ties in with a requirement to use Building Information Modelling (BIM) of these projects. While Soft Landings is promoted as an open-source framework, unfortunately some aspects are commercialized by the Building Services Research and Information Association and the Usable Buildings Trust; for instance, the guide on how to produce soft landings and some checklists are only available via the BSRIA bookstore.

The 1980s also saw the concept of sustainability gain traction, with as notable moment the publication of the United Nations World Commission on Environment and Development (WCED) report *Our Common Future* (Brundtland *et al.*, 1987). Where the effects of the energy crisis of the 1970s had worn off, this renewed the interest in the environmental performance of buildings. It sparked interest in a range of concepts, such as sustainable buildings, eco-buildings, bioclimatic and autarkic buildings and, more generally, green buildings (Roaf *et al.*, 2003). Around the end of the millennium, the broader interpretation of sustainability, which augments environmental concerns with economic and social issues, led to an expansion of the aspects typically taken into account in assessing building performance beyond the traditional energy efficiency,

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[9] Equivalent to Facility Management.

health and environmental aspects (Lützkendorf and Lorenz, 2006). There is no final definition of sustainability, as the concept is still under development (Mann, 2011b; Smythe, 2014). As exemplified by Hrivnak (2007), there are many issues to consider when applying sustainability to buildings, with a conflict between 'pure' and 'relative' sustainability and issues of where to position the system boundaries. As in other industries, the lack of definition leads to 'greenwash' – the use of token systems and interventions to promote buildings as sustainable, without actual intent to make true on the image invoked. The use of solar panels on buildings that are otherwise of mediocre construction specification is a prime example. As such, most attempts to define and appraise sustainability in construction – such as the appraisal method for infrastructure projects by Ugwu *et al.* (2006) and Ugwu and Haupt (2007) or the planning model for sustainable urban planning by AlQahtany *et al.* (2013) – have a rather transient nature.

The building sector in the United States started using the term High Performance Buildings (NYC DDC, 1999); initially this mainly concerned non-domestic buildings, but ultimately the concept was also applied to homes (Trubiano, 2013). Especially in the United Kingdom, the concept of Zero Carbon Buildings rose to prominence, amongst other things leading to the establishment of the Zero Carbon Hub in 2008. For a time there were plans by the UK Government to require all new homes to be Zero Carbon by 2016; however this plan was abandoned in 2015. More recently the focus has returned to energy efficiency, and the system boundary and grid connection is being taken into account, leading to the use of the term Net-Zero Energy Building (nZEB); for a deeper discussion, see Pless and Torcellini (2010). An overview that lists some of the many definitions and exemplifies the confusion in this domain is provided by Erhorn and Erhorn-Kluttig (2011).

The United States introduced a Government Performance and Result Act in 1993, which also impacted commissioning and management of constructed assets. Hammond *et al.* (2005) describe how this was implemented by the US Coast Guard. They highlight the importance of measurement in relation to accountability of governmental organizations, especially those with a military role; here performance is related to organizational strategy, scope and mission assessment, operations and logistics, and tactics. Further work looking at the performance of the construction industry, beyond building performance, was sparked in the United Kingdom by a range of publications such as the 1994 Latham Report and the 1998 Egan Report *Rethinking Construction*. These reports are not without criticism; for instance, Fernie *et al.* (2006) discuss some of the issues with the underlying work, warning for the need to distinguish cause and effect, the need to ensure that measurement captures the wider context and issues with sample selection for representing 'best practice'. However, both reports led to a strong focus on time and cost of production, as well as some interest in waste and defects but possibly also to less interest in the design quality of the resulting buildings (Gann *et al.*, 2003).

Another approach towards building performance was developed under the title of Post Occupancy Evaluation (POE). In the present time, POE is often defined as a human-centred framework for building performance evaluation (BPE), with a strong emphasis on end-user requirements (Burman, 2016: 59). There may be some confusion about the name as some work in the POE area is completely technical and based on hard technical measurements; other efforts are actually user perception studies, whereas a third category combines both methods. There are different claims regarding the background of POE. Preiser and Vischer (2005: 4) suggest that POE is founded in cybernetics, whereas others emphasize a background in environmental psychology (Cooper, 2001). User feedback already played a role in the work by the Building Performance Research Unit at Strathclyde in the late 1960s but became much more prominent through the Probe (Post-occupancy Review of Buildings and their Engineering) project in the United Kingdom. Starting in 1995s, Probe studied a series of 20 buildings, combining walk-through surveys, energy surveys, discussions with occupants and management and pressure tests. Among other things, Probe found that buildings were overly complicated and often failed to address fundamentals first and reported 'poor airtightness, control problems, unintended consequences, a dearth of energy management, a tendency for systems to default to "on", and a pathological trend for information technology and its associated cooling demands' (Bordass *et al.*, 2001b). Probe typically studied buildings 2–3 years after completion (Cohen *et al.*, 2001).

In the humanities and social disciplines, the 1990s brought a development named the 'performative turn'. Grounded in intellectual theory from the 1940s to 1950s, the performative turn emphasizes the interaction between human behaviour, actions and practice and their context; this means that performance depends on both action and the context in which the action takes place. The performative turn started in areas such as literature and theatre but then expanded to the arts, including architecture (Hensel, 2013: 17–21), leading to the developing concept of performative architecture as described by Kolarevic and Malkawi (2005).

1.2.2 History of Building Codes, Regulations and Rating Schemes

The words *building regulations* and *building code* are used to indicate the requirements for a building imposed by government. Laws and regulations are put in place by the government to make sure buildings meet a range of basic building performance requirements. These laws and regulations aim to ensure the health and well-being of those that cannot influence the design and construction process themselves and benefit society at large. As such, performance as imposed by the government represents a minimal building performance; typically higher performance can be achieved by setting higher ambitions. Laws and regulations are closely related to building standards, which set rules and processes for the activities and processes that relate to construction. Rating schemes are similar but often voluntary. The history of building regulations, standards and rating schemes gives a unique view on how the concept of building performance developed, dating back all the way to the Hammurabi Code of 1754 BC. Therefore, they are discussed in this separate section.

In the early days, building performance regulation often developed in relation to fire incidents, such as the burning of Rome in 64AD, which led to rules that required the use of stone and masonry. There are also fragments of Greek and Roman laws that indicate requirements for buildings to be inspected during construction (Holt *et al.*, 2007). Historically codes, regulations and standards overlapped; in modern times building codes typically refer to standards where technical issues are concerned (Foliente, 2000). The Mayor of London in the United Kingdom put in place, as early as 1189, regulations known as the 'Assize of Buildings', which addressed issues around boundaries including passage of light, sanitation and rainwater discharge and encouraged the use of stone to reduce fire risk (British History Online, 2015). Spain produced the 'Laws of the Indies',[10] developed in the 16th century, which set out the rules for the development of towns and missions for the overseas territories of the Spanish Crown. The Great Fire of London in 1666 drove the development of the Rebuilding of London Act 1667, which regulated distances between houses and their heights, width of walls, and empowered surveyors to enforce the act. Original French building legislation developed from Roman laws into a range of feudal laws. There was a major step change with the introduction of the 'Code Civil' in 1804 with book III of the code dedicated to property; it must be noted that due the geopolitical status of the time, this code applied to many countries under French influence such as Belgium, the Netherlands, Poland, Italy, Spain and Portugal. In the early 1960s, CSTB launched the French *Agrément* system, which decided on approval of systems and techniques in France (Becker, 2008); this was later replaced by a system named *Avis Technique*. Building laws in Germany initially developed at the state level, such as the Prussian Code of 1794; during the Weimar Republic, there was a discussion about a National code, but this did not materialize; the same happened during the Third Reich. Only after formation of the Federal Republic of Germany in 1949 did work start on the 'Bundesbaugesetz' that was put in place in 1960. In the United States, the Building Officials and Code Administration (BOCA) introduced a National Building Code (NBC) in 1915, but in spite of its name, this mainly covered the East Coast and Midwest; other codes by the International Conference of Building Codes (ICBO) covered the West Coast, while the Southeast had building codes by the Southern Building Code Congress International. These were later replaced by the International Building Code (IBC) by the International Code Council, first published in 1997 but taking hold from 2000 onwards. Chinese law has a long tradition but was completely reworked following the revolution of 1911. Initially building matters were covered by the State Council, Ministry of Construction and both local and regional governments. The current national building regulations in the United Kingdom were introduced with the Building Act of 1984; the detailed requirements are covered by a range of 'Parts', such as Part B: Fire Safety, Part E: Resistance to the passage of sound, and Part L: Conservation of fuel and power. For an overview of coverage of the related 'Approved Documents', see Table 1.2. In 1997 China put in place a national Construction law that covers building quality and safety issues; with various revisions this is still in place. Modern building codes typically address issues like fire risk, building access and evacuation, structural stability, energy provision and sewerage and drainage.

For a long time the guarantees towards good building performance were based on experience and know-how, as can be handed down from master craftsmen to apprentices. Such know-how is best captured by prescriptive regulations, laws, codes and standards (Becker, 2008). Towards the end of the 20th century, the regulations and standards in many countries became performance based rather than prescriptive (Augenbroe and Park, 2005). The fundamental differences between prescriptive and performance-based buildings codes and standards are discussed in the seminal paper by Foliente (2000). Prescriptive building codes describe solutions that are acceptable. In other words, they define the parts that may be used in a building. These parts have

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[10] Leyes de Indias in Spanish.

Table 1.2 Overview of the Approved Documents in the UK Building Regulations 2010.

Part A	Structure	A1 Loading
		A2 Ground movement
		A3 Disproportional collapse
Part B	Fire safety	B1 Means of warning and escape
		B2 Internal fire spread (linings)
		B3 Internal fire spread (structure)
		B4 External fire spread
		B5 Access and facilities for the fire service
Part C	Site preparation and resistance to contaminants and moisture	C1 Site preparation and resistance to contaminants
		C2 Resistance to moisture
Part D	Toxic substances	D1 Cavity insulation
Part E	Resistance to the passage of sound	E1 Protection against sound from other parts of the buildings and adjoining buildings
		E2 Protection against sound from within a dwelling
		E3 Reverberation in the common internal parts of buildings containing flats or rooms for residential purposes
		E4 Acoustic conditions in schools
Part F	Ventilation	F1 Means of ventilation
Part G	Sanitation, hot water safety and water efficiency	G1 Cold water supply
		G2 Water efficiency
		G3 Hot water supply and systems
		G4 Sanitary conveniences and washing facilities
		G5 Bathrooms
		G6 Kitchens and food preparation areas
Part H	Drainage and waste disposal	H1 Foul water drainage
		H2 Wastewater treatment systems and cesspools
		H3 Rainwater drainage
		H4 Building over sewers
		H5 Separate systems of drainage
		H6 Solid waste storage
Part J	Combustion appliances and fuel storage systems	J1 Air supply
		J2 Discharge of products and combustion
		J3 Warning of release of carbon monoxide
		J4 Protection of building
		J5 Provision of information
		J6 Protection of liquid fuel storage systems
		J7 Protection against pollution

(*Continued*)

Table 1.2 (Continued)

Part K	Protection from falling, collision and impact	K1 Stairs, ladders and ramps
		K2 Protection from falling
		K3 Vehicle barriers and loading bays
		K4 Protection against impact with glazing
		K5 Additional provisions for glazing in buildings other than dwellings
		K6 Protection against impact from and trapping by doors
Part L	Conservation of fuel and power: new dwellings	L1A Conservation of fuel and power: new dwellings
		L1B Conservation of fuel and power: existing dwellings
		L2A Conservation of fuel and power: new buildings other than dwellings
		L2B Conservation of fuel and power: existing buildings other than dwellings
Part M	Access to and use of buildings	M1 Access and use
		M2 Access to extensions to buildings other than dwellings
		M3 Sanitary conveniences in extensions to buildings other than dwellings
		M4 Sanitary conveniences in dwellings
Part N	Glazing: safety in relation to impact, opening and cleaning	N1 Protection against impact
		N2 Manifestation of glazing
		N3 Safe opening and closing of windows, skylights and ventilators
		N4 Safe access for cleaning windows
Part P	Electrical safety: dwellings	P1 Design and installation of electrical installations

performance attributes that are known to satisfy the requirements of the legislator. In contrast, performance-based codes only prescribe the overall performance that is required of the building; it is left to the design team to specify the parts and to demonstrate that these parts provide the required performance. As pointed out by Gross (1996) and Foliente (2000), performance-based codes are actually not new. In fact, the Hammurabi Code itself is performance based (no body shall be killed by a building) and leaves it open how the building is to achieve that aim. Foliente (2000) lists three main problems with prescriptive building codes: they can act as a barrier to innovation, they might hinder cost optimization and they might hinder international trade. However, prescriptive codes might also have some advantages in terms of being easier to apply, check and enforce. One of the first countries to introduce performance-based building regulations was the Netherlands, which put these in place in 1991. The Dutch Government Buildings Agency subsequently introduced performance-based procurement and tendering (Ang *et al.*, 2005). Another early adapter of a performance-based building code was New Zealand, which introduced this in 1992. Here implementation issues led to a review of the code between 2005 and 2008 and more weight for the 'Acceptable Solutions' that supplement the code. The experience in New Zealand demonstrated that training of all stakeholders is crucial in successful introduction of performance-based regulations (Duncan, 2005). The leading disciplines in performance-based regulations were structural engineering and fire engineering, and the fields of project initiation and construction were leading in implementing performance-based codes and standards (Foliente, 2000).

Back to building performance legislation in general, in the European Union, the following Pan-European work is of importance: the Construction Products Directive (originally introduced in 1988), the work on EN Eurocodes (emerging since 1990) and the Energy Performance of Buildings Directive (originally introduced in 2003). The 1988 Construction Products Directive encouraged national legislation to formulate functional and performance requirements, while leaving the technical solutions to the market, with the aim of encouraging innovation (Ang *et al.*, 2005). The EN Eurocodes complement the Construction Products Directive, especially focussing on structural stability and fire safety (Gulvanessian, 2009). The Energy Performance of Buildings Directive, published in 2003 and implemented in 2006, requires that the member states of the EU have in place a system of building energy certificates, a system for boiler inspections and a system for inspection of air-conditioning systems (Olesen, 2005; Raslan and Davies, 2012). The EPDB was 'recast' in 2010 to set more strict targets and with the aim towards net-zero energy buildings (Janssen, 2010). However, most building regulation is still left to the national level with significant differences in organization and technical regulation remaining (Pedro *et al.*, 2010). It must be noted that the actual impact of legislation may be more moderate than hoped by politicians and those developing them; for instance, Oreszczyn and Lowe (2010) present a graph that shows a very slow reduction of household gas consumption between 1920 and the late 1990s, with an unlikely steep decent required to achieve zero consumption in the years beyond 2010 – which, in fact, has far from materialized by 2016.

Concerning standards, the International Organization for Standardization (ISO) was founded in 1947. ISO started work on building performance in 1980 when it published standard ISO 6240:1980 on contents and presentation of performance standards in building. This was followed 4 years later by ISO 6241:1984 on performance standards in buildings, which sets out how such standards are to be prepared and what factors are to be considered. From there ISO has developed a wide range of standards that pertain to building performance, such as thermal requirements (ISO 6242-1: 1992), air purity requirements (ISO 6242-2: 1992), acoustical requirements (ISO 6242-3: 1992), area and space (ISO 9836: 2011) and others. Note that many ISO standards find their way into national European regulations and are combined with Euronorms, for instance in Germany as DIN EN ISO, the Netherlands as NEN EN ISO and the United Kingdom as BS EN ISO. Generic quality systems developed by ISO such as standard ISO 9000 and ISO 9001 have been found to be applicable to the construction industry. However, research such as Landlin and Nilsson (2001) suggests that the building industry neglects the innovation and learning perspectives.

In the 1990s, the mandatory codes and regulations were supplemented with a range of voluntary rating schemes. Most of these have an environmental background. Examples are BREEAM (Building Research Establishment Assessment Methodology), introduced in the United Kingdom by the Building Research Establishment in 1990; Passivhaus, developed by Lund University and the Institut für Wohnen und Umwelt in 1990; LEED (Leadership in Energy and Environmental Design) by the US Green Building Council and introduced in 1994; MINERGIE, a Swiss rating system launched in 1994 and upheld since 1998 by the Minergie Association; NABERS (National Australian Built Environment Rating System) by the Australian Office of Environment and Heritage in 1998; CASBEE (Comprehensive Assessment System for Built Environment Efficiency) by the Japan Sustainable Building Consortium in 2004; and QSAS/GSAS (Qatar/Global Sustainability Assessment System) by the Gulf Organisation for Research and Development in 2009. A recent addition is the WELL standard, which specifically links building performance to human health and well-being. Many of these rating schemes are available worldwide and are in competition. An overview of selected rating systems is provided in Table 1.3. The way in which building performance is handled in rating systems is very diverse; sometimes credits may be awarded on the basis of extensive quantification of performance, as in the case of energy use; at the same time credits may be obtained by simply being located close to a railway station or for employing certified personnel during the design stage, which are not building performance aspects in a strict sense.

Some key points in this brief history of performance in the building domain are depicted in Figure 1.2.

1.2.3 Selected Recent Developments in Building Performance

Establishing the state of the art in building performance analysis is the subject of this book and the subsequent chapters. However, to set some context for the following discussion and to guide the reader, this paragraph mentions a (personal) selection of some of the current trends and developments. This is not intended as a full state of the art, but is a subjective selection of works and developments that are worth highlighting. As mentioned, building performance can be analyzed using physical testing, calculation/simulation, expert judgment and user assessment.

Recent advances in digital technology have resulted in an exponential growth of the amount of data that is measured in buildings. Automated Meter Reading (AMR) makes it possible to collect data on for instance indoor temperatures, electricity use and water consumption at high frequency; however due to the continuous use of buildings, such data tends to quickly turn into large data that needs proper analysis to be of use. Guidance on how to measure the performance of actual buildings in use is provided by the International Performance Measurement and Verification Protocol (IPMVP), a protocol for the monitoring of energy and water use by buildings. It defines standard terms and best practice and aims to support measurement and verification (M&V) while acknowledging that these M&V activities typically need to be tailored to each specific process (Efficiency Valuation Organization, 2014a: iv). The IPMVP makes generic recommendations in terms of making sure that accuracy of measurements should be balanced against costs. Furthermore, it encourages work to be as complete as possible (considering all effects of an intervention), the use of conservative values when making estimates, and efforts to ensure consistency across different projects, staff, measurement periods and both demand reduction and energy generation projects. Work done as per IPMVP should be relevant and transparent (Efficiency Valuation Organization, 2014a: 2).

Table 1.3 Overview of voluntary rating schemes.

Scheme	Developed/maintained by	Website
BEAM (Building Environmental Assessment Method)	BEAM Society	www.beamsociety.org.hk
BREEAM (Building Research Establishment Assessment Methodology)	BRE (Building Research Establishment)	www.breeam.org
CASBEE (Comprehensive Assessment System for Built Environment Efficiency)	JSBC (Japan Sustainable Building Consortium) + JaGBC (Japan Green Build Council)	www.ibec.or.jp/CASBEE/english/
DGNB System	DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen)	www.dgnb.de/en/
HQE (Haute Qualité Environnementale)	ASSOHQE (Association pour la Haute Qualité Environnementale).	www.assohqe.org
LEED (Leadership in Energy and Environmental Design)	USGBC (US Green Building Council)	www.usgbc.org/leed
MINERGIE	Minergie Association	www.minergie.ch
NABERS (National Australian Built Environment Rating System)	Office of Environment and Heritage	www.nabers.gov.au
Passivhaus	Passive House Institute	http://passiv.de/en/
	EU CEPHEUS project	www.passivhaus.org.uk
		www.phius.org
QSAS/GSAS (Qatar/Global Sustainability Assessment System)	GORD (Gulf Organization for Research and Development)	www.gord.qa
WELL	IWBI (International WELL Building Institute)	www.wellcertified.com

On the level of building components, there is a large amount of performance test procedures and a corresponding body of knowledge on detailed aspects. For instance, façade sound isolation can be measured according to ISO 1628-3, with authors like Berardi (2013) describing issues around instrument positioning. Similarly, the fire hazard of materials used in building can be tested in fire test rooms according to ISO 9705, with Li *et al.* (2012a) discussing specific work on curtain materials. Wang *et al.* (2013) describe fire testing at a larger level, addressing work on continuous reinforced concrete slabs. With regard to thermal performance, a guarded hot box

2012	
2011	'*BPS for design and operation*' (Hensen and Lamberts)
2010	EPBD recast
2009	
2008	
2007	
2006	'*Assessing building performance*' (Preiser and Vischer)
2005	'*Performative architecture*' (Kolarevic and Malkawi)
2004	
2003	
2002	EU Energy Performance of Buildings Directive (EPBD)
2001	PeBBu (2001–2005)
2000	
1999	
1998	CIB Proactive Program
1997	
1996	
1995	Probe Studies (1995–2001)
1994	Launch of LEED
1993	US Government Performance and Results Act
1992	EU Combine II (1992–1995); NZ Performance-based building code
1991	NL Performance-based building code
1990	EU Combine I (1991–1992); launch of BREEAM
1988	EU Construction Products Directive
1987	Foundation of IBPSA; '*Our common Future*' (Brundland)
1982	'*Working with the performance approach in building*' (CIB W60)
1972	'*Building performance*' (BPRU)
1971	Centre Pompidou (1971–1977)
1970	Launch of CIB W60
1967	BPRU Strathclyde; '*Handbuch der Bauphysik*' (Broban)
1897	Inception of what later became CIBSE
1894	Inception of what later became ASHRAE
1852	Foundation of ASCE
1834	Foundation of RIBA
1800	Start of industrial revolution
1666	Great Fire of London
0064	Burning of Rome
15BC	'*De architectura*' (Vitruvius)
1754BC	Hammurabi Code
2580-2560BC	Great Pyramid construction
3000-2000BC	Stonehenge construction

Figure 1.2 Timeline of selected building performance events.

experiment, standardized through ISO 12567-1, can be used; Appelfeld and Svendsen (2011) discuss the analysis of a ventilated window using this approach. Exploration of the impact of real outdoor conditions on façades in a semi-controlled experiment is studied using the EU PASSYS test cells (Wouters *et al.*, 1993), with Alcamo and De Lucia (2014) describing the modification of these cells to meet further requirements.

For theory on the use of calculation and simulation to assess building performance, the work by Augenbroe is seen by many to be leading the field. Building on the work of the EU COMBINE project, Augenbroe has provided a range of publications on building performance resulting from the work with his students at TU Delft and Georgia Tech. The insights into the use of building models, fundamental work in uncertainty and risk analysis (de Wit and Augenbroe, 2002; Heo *et al.*, 2012), a broader view on the use of knowledge in the construction industry (Kamara *et al.*, 2002) and the experience of teaching an MSc programme in High Performance Buildings have been integrated into a chapter in the book by Hensen and Lamberts (2011); see Augenbroe (2011: 15–36). This provides a deep review of the position to date on the role of building performance simulation in performance-based building and especially performance-based building design. A key in this work is the need to have a dialogue between stakeholders about the objective specification of performance measures. Augenbroe views building simulation as a 'virtual experiment' and approaches design as a choice from a range of alternatives, where systems theory helps to support multi-criteria decision making. Most of this theory applies not only to building simulation but also to the other assessment approaches.

Expert assessment has a long tradition in the construction industry. It is the key approach in assessing and handling risk in construction (Yildiz *et al.*, 2014). It also plays an important role in construction litigation, where courts pay special attention to the opinion of professionals in establishing why a building failed (Lindsey, 2005). Expert opinion is also used in advanced analysis efforts of rapidly developing and changing fields, such as the prediction of the home networking market (Lee *et al.*, 2008), as well as for complex areas such as the vulnerability assessment of buildings towards earthquakes (Dolce *et al.*, 2006). Professionals used for expert assessment are typically specialist working in academia and research institutes, ensuring that they are on the forefront of developments.

For building occupant or stakeholder assessment, the book by Preiser and Vischer (2005) presents a good overview of building user surveys; the appendices contain generic checklists as well as examples of detailed occupant questionnaires (Preiser and Vischer, 2005: 212–228 and 232–234). In terms of actual studies, the Probe project (Bordass *et al.*, 2001b) is the most prominent application. Probe studies consist of a number of stages. Stage 1 involves establishing an agreement for undertaking a Probe study. Stage 2 collects data in advance of a first visit by means of a pre-visit questionnaire (PVQ). Stage 3 is a first site visit, which includes an interview with the host, walk-around the building, informal discussions with stakeholders and staff, review of specifications, system control settings, initial spot measurements and readings. Stage 4 consists of initial analysis and the development of a draft report. Stage 5 is second site visit, with the aim to address some issues in more depth and to discuss preliminary findings with the stakeholders. Stage 6 comprises a Building Use Studies (BUS) occupant survey. Stage 7, which actually runs throughout the Probe study, is energy analysis based on meter readings as well as billing data; this is based on the Energy Assessment Reporting Method (EARM) and Office Assessment Method (OAM). Stage 8 is a pressure test to check air leakage of the building. Stage 9 results in the final Probe report. Some buildings went on to a Stage 10, where results were published in the CIBSE Building Services Journal (Cohen *et al.*, 2001). After working in this area for many years, the people behind Probe find that there still is surprisingly little detailed information about the measured performance of modern buildings available. Leaman *et al.* (2010) suggest that this may be due to poor results, which are not published for obvious reasons; unfortunately this leads to a lack of learning and improvement. The BUS methodology and survey is available through a network of partners named, unsurprisingly, BUS methodology. While this helps to maintain quality of the surveys, this also means that the process is not open source and open to general external scrutiny. Soft Landings, the methodology for ensuring a good handover from construction to use stage, supports current efforts in this area.

While the previous paragraphs outline key exponents of building performance assessment, the overall context of building performance is highly dynamic. There are various trends in building science and beyond that are impacting on the field. One recent development is a shift of interest beyond the system boundary of individual buildings towards studies at district and urban level. An obvious extension is from buildings to district heating systems; as an example of ongoing work in this area, Steer *et al.* (2011) report on the control settings for such networks. At district level, Tian *et al.* (2015) have studied correlations between building stock variables in the analysis of the thermal performance of university campus buildings. Orehounig *et al.* (2015) show how considerations at neighbourhood level lead to novel concepts such as an 'energy hub'. Stossel *et al.* (2015) present a study on the development of a composite environmental quality index for cities, while Yigitcanlar and Lönnqvist (2013) have explored the measurement of knowledge-based urban development performance. Kontokosta and Tull (2017) demonstrate the use of machine learning to model the thermal performance of the building stock of New York, which consists of 1.1 million buildings. Azadi *et al.* (2011) have applied the concept of performance to green urban spaces. Reinhart and Davila (2016) give an overview of the field of urban energy modelling, albeit leaving out some of the thorny issues of data input and the associated uncertainties as presented by Choudhary (2012). Obviously, the analysis of the built environment at district or urban level does not solve the problems that are still left in designing, modelling and understanding individual buildings, as there is no guarantee that errors at this single building scale will be cancelled out by the higher number of units at the urban scale.

Clarke (2015) presents a vision for the development of building performance simulation that includes a critique of the lack of a shared vision for a beneficial end goal for the discipline. He mentions the need to spend further efforts towards positioning performance analysis in the design process, abstracting building performance design problems, and to develop performance criteria, metrics and performance assessment procedures. Some of the issues are elaborated further in the paper by Clarke and Hensen (2015); this suggests that 'high integrity representation of physical processes', 'coupling of different domain models' and 'design process integration' should be the ultimate goals. Interestingly, the authors do not include a critique of the lack of definition of the concept of building performance itself. Also of interest are the 'ten questions' papers launched by the journal *Building and Environment* (Blocken, 2015), which discuss particular subjects in a way that 'provide younger researchers directions for future research'. These articles show some of the frontiers in building performance analysis that are currently being explored, such as work in pollen concentrations, allergy symptoms and their relation to indoor air quality (Bastl *et al.*, 2016), thermal environment and sleep (Lan and Lian, 2016) and hybrid computational–physical analysis of wind flow in the built environment (Meroney, 2016).

At various levels, ranging from systems to full cities, there is an interest in 'smart'. Kwon *et al.* (2014) present a system that fuses data from a range of sensors to detect elevator users even before they call the elevator, thus improving scheduling. Lin *et al.* (2014) provide an example at the building level, discussing how smart systems can improve the response to an earthquake. A general overview of the prospects of smart power grids, combining microgrids, a high-voltage national grid, storage, distributed generation and interaction with the energy users, can be found in Amin (2013). Lombardi *et al.* (2012) take a holistic look at smart city performance, incorporating governance, economy, human capital, living and environment. O'Grady and O'Hare (2012) present a discussion of how ambient intelligence may impact citizens of a smart city and some of the issues and technology involved. McLean *et al.* (2015) provide an example of a case study that explores the social and political implications of introduction of a smart energy grid.

The interaction between buildings and humans is another area where a lot of efforts is being invested. This fits in a much wider trend where there are high stakes in predicting human behaviour, such as sales, unemployment and healthcare. In these, the Internet is becoming an important tool, helping to establish what people are presently doing but also what they are likely to do in the future (Goel *et al.*, 2010; Chandon *et al.*, 2011). Humans play a role as clients, as explored by Hoyle *et al.* (2011) who present a study into the understanding of customer preferences in the automotive engineering domain. In other domains, humans are controlling systems. In automation, there is a long tradition of research into human computer interaction (HCI), which is built around the idea that humans control the computer; more recently this is developing into new models of collaboration between humans and machines (Hoc, 2000). When it comes to buildings, humans have a complex, tri-way relationship with performance. First of all, the simple presence of humans creates loads that buildings have to respond to, for instance in terms of structural loads resulting from body weight or excitation from walking, or in terms of heat and moisture emissions. Secondly, human beings actively operate buildings, changing control settings, opening and closing windows and blinds as well as a range of other systems. Thirdly, buildings are in place to meet human needs, so human perception is a key factor in judging the final performance of buildings. Seminal work in the area is the chapter by Mahdavi (2011) who reviews this interaction in the context of building simulation. The relation between lack of building performance and occupant complaints is discussed by Goins and Moezzi (2013). Webb *et al.* (2013) show how studies of human behavioural change can be linked to the energy us of households and thus to building performance. In general, for performance analysis to become an integrated part of the building cycle, it must be useful to the people that actually work with and inside these buildings rather than imposed from above (Bordass and Leaman, 2005). Further work on the interaction between occupants and the thermal performance of buildings is ongoing in the International Energy Agency Annex 66 on the definition and simulation of occupant behaviour in buildings (IEA, 2016b). At the same time, Stern (2000) warns against a bias that expects too much of psychological interventions in human–environment interactions. Kim (2016) provides evidence of some of the limitations of overly detailed occupant behaviour models in building performance simulation.

Advances in data analysis, as well as parallel and cloud computing, also make for a change in context. O'Neill *et al.* (2013) present advances in building energy management using advanced monitoring and data analytics for US Department of Defense naval station buildings; Hong *et al.* (2014) provide a similar analysis of data collection and analysis for the retrofit of the head office of a financial institution in California. Mathew *et al.* (2015) show how the gathering of energy use data from a group of over 750 000 buildings leads to 'big data' issues in terms of data storage, cleansing and analysis. Cloud computing and related developments such as Software as a Service (SaaS) are changing the concepts used in software and IT hardware design and purchasing (Armbrust *et al.*, 2010). Cloud computing is also starting to have an impact on academia; typical analysis tools like Matlab are already being tailored to work in a cloud computing environment (Fox, 2011). Ventura *et al.* (2015) describe how parallel and cloud computing support complex nonlinear dynamic analysis in structural building engineering, whereas Zuo *et al.* (2014) show how parallel computing can be used within building daylighting simulations. Barrios *et al.* (2014) present a tool for the evaluation of the thermal performance of building surfaces that is designed to run in the cloud. The PhD thesis of Obrecht (2012) focuses on the use of parallel computing to support airflow analysis of buildings. Beach *et al.* (2015) explore the relation between building information models, data management and cloud computing.

Developments on the Internet of Things (Kortuem *et al.*, 2010; Dijkman *et al.*, 2015) also relate to buildings and bring their own inherent challenges such as privacy risks (Weber, 2015). Qin *et al.* (2015) describe data flow and energy use pattern analysis for a smart building. Palme *et al.* (2014) present a practical application to classroom access control in schools, while Uribe *et al.* (2015) demonstrate an implementation that manages the acquisition, storage and energy transfer in an energy-efficient building. Caragliu and Del Bo (2012) conducted an econometric study into the relation of smart city attributes and economic growth.

1.3 Outline of the Book

This book brings together the current knowledge on building performance and its analysis. It discusses the concept of building performance in depth, explores how building performance can be measured and analyzed and how such an analysis of performance can be used to improve buildings, and explores how other disciplines can help to improve the field. The book aims to illustrate the rich and complex context in which building performance analysis takes place, which means that setting up a meaningful analysis effort typically requires a deep dialogue between the various stakeholders. It deliberately makes regular references to other areas in order to break the isolationist approach that sometimes dominates building science.[11] From this, an emergent theory of building performance analysis will be developed.

The remainder of the book emphasizes the engineering view of building performance being a concept that captures how well a building performs a task or function. It attempts to cover building as both a process and an object; it aims to integrate the aesthetic view

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[11] Testing whether external concepts are applicable in the context of building performance is a job that can only be done by experts in this area.

of presentation or appreciation in this approach by seeing this as one of the key functions of a building. Dedicated comments about the other interpretations of building performance are included where relevant.

The book is structured in three main parts. Part I provides a theoretical foundation on building performance, Part II explores assessment and Part III deals with impact. Part I starts from a wider view on building performance, zooming in to user needs and requirements. Part II builds up the fundamentals of an approach for building performance analysis and develops this approach into a conceptual framework for working with building performance. It explores what is needed to carry out analysis efforts, combining criteria for performance, performance measurement and quantification and operational building performance analysis. Part III discusses how building performance analysis impacts building design and construction, building operation and management and high performance buildings. The final chapter (epilogue) summarizes the emergent theory of building performance analysis. In other words, Part I introduces building performance, Part II explores building performance analysis and Part III deals with the application of building performance and its analysis. Figure 1.3 describes this structure in a graphical format.

While the book develops an emergent theory of building performance analysis, it emphasizes the significant work that is required to implement this theory in daily practice by discussing case studies in the main chapters of Parts I, II and III. The case studies highlight the complexity of real buildings and provide an indication of the future work that will be required to operationalize the theory.

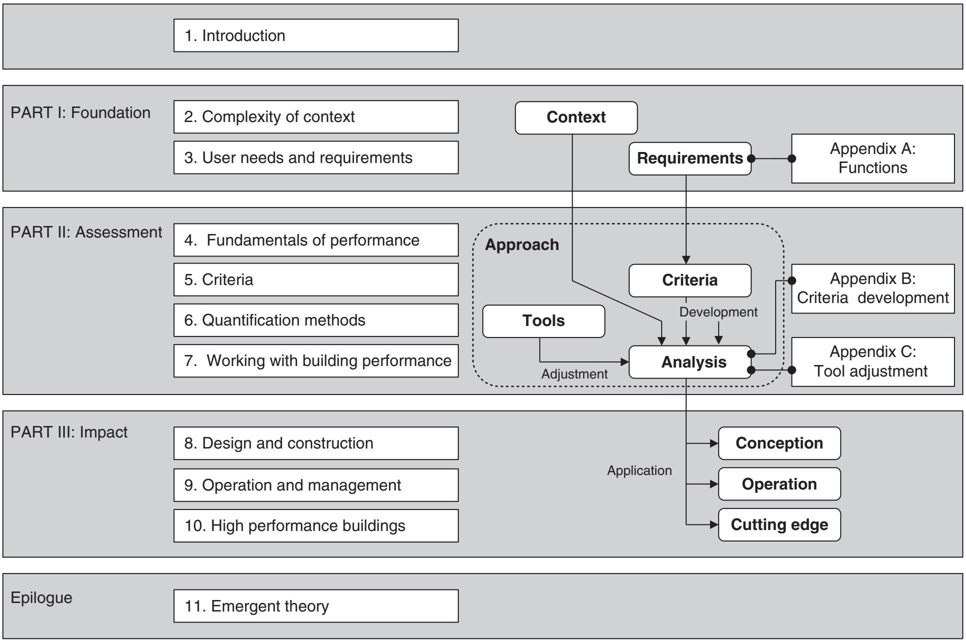

Figure 1.3 Structure of the book.

Within this structure, detailed contributions are as follows:

Chapter 2 starts by positioning building performance in its complex context, thus providing the basis for deeper discussion in the subsequent chapters. It discusses the building life cycle, the main stakeholders in building, building systems and the interaction between the fields of architecture and engineering. It then moves on to review some of the deeper challenges to the industry in terms of building performance, followed by general approaches to ensure building performance as well as some of the specific tools available.

Chapter 3 covers needs, functions and requirements. It explores the different world views of the various stakeholders, the corresponding building functions and their respective functional requirements. This is complemented with a discussion of how buildings typically meet these functional requirements through a range of systems and subsystems.

Chapter 4 deals in depth with the central concept of building performance and discusses the different attributes of performance and yardsticks to measure it. The chapter covers the experiments, observations and performance measures that are important for quantification.

Chapter 5 introduces performance targets and criteria, which are needed for the analysis of the performance that has been measured and which allow establishing 'how good' any score is. To do so the chapter reflects on goals, targets, ambitions, constraints, thresholds, limits, benchmarks and baselines. It also introduces performance banding.

Chapter 6 covers performance quantification. The chapter covers the four main approaches that can be used to quantify performance: calculation and simulation, monitoring and measurement, expert judgment and stakeholder evaluation.

Chapter 7 covers working with building performance and presents a conceptual framework for building performance analysis. It explores how performance criteria need to be developed for each specific case and matched to an appropriate quantification method. It also discusses the adjustments of methods to the specific situation, as well as iteration in the analysis process.

Chapter 8 returns to building design; it reviews how building performance concepts as established in Chapters 2–6 can be applied in a design context. This chapter covers some challenging issues like decision making under uncertainty and visualization; it focuses on virtual analysis, as there is no real building that can be analyzed at this stage apart from potential precedents or mock-ups. The chapter also briefly covers the construction phase and how buildings materialize from the original design.

Chapter 9 covers building operation, control and management. Here the focus shifts to performance analysis of real objects in use, looking at the data that can be harvested from buildings and how this can be employed to manage performance. The chapter also covers fault detection and diagnosis and how this feeds into the development of performance contracts.

Chapter 10 reviews the concept of high performance buildings. It discusses the forefront of the application of building performance analysis in construction and how this fosters innovation and emerging concepts such as smart and intelligent buildings.

Finally, Chapter 11 brings together all strands of the book in an emergent theory of building performance analysis.

1.4 Reflections on Building Performance Analysis

Building performance is an important concept, but so far the term has been left mostly undefined. This is an undesirable situation: it means the industry is working with a vague value proposition, while academics lack a strong foundation to move forward on the subject. It is important to fill this void and provide a working definition of building performance and establish an emergent theory of building performance analysis.

The current position on building performance is not surprising, given the complexity of the field. A deep understanding of building performance requires a broad knowledge base, which covers the domains of architecture, construction and science; typically it requires further insights in specific areas such as architectural design, engineering, building technology, construction, physics, material science, systems theory, computing and mathematics. To complicate matters, there also is a division between industrial practice and building science, with practice emphasizing the need to know how things work in the real world, while science often feels the industry is locked into proceeding with business as usual – a classical situation of conflicting views between 'boots in the mud' and 'ivory tower'. There are very few people who have the full overview of all aspects and can provide a unified view on building performance.

So far, development of theory on building performance has mainly taken place from within the discipline. However, there are other fields that all have their own interest in performance and that have made some progress in furthering the subject. It thus seems worthwhile to explore the adjacent fields, especially those of systems engineering and process management, to find out what concepts may fit within the building context. But the filtering of what external concepts can be integrated into a theory of building performance analysis should be left to experts in this specific discipline, who appreciate the uniqueness of building design and engineering, construction and building operation. In general, the building performance analysis field should be inquisitive and be neither xenophilic (Clarke and Hensen, 2015) nor xenophobic.

While there is no unified theory on building performance analysis, there have been a lot of contributions to aspects of the field. Journals like *Building and Environment*, *Energy and Buildings*, *Automation in Construction* and the *Journal of Building Performance Simulations* have published literally thousands of articles on related efforts. An attempt to filter this work and see what joined-up picture emerges is overdue. This book hopes to provide a solid starting point in this direction. A review of the history of the concept of building performance analysis as an area of scholarship demonstrates that this specific field can be tracked back for about 50 years, to the late 1960s, but the roots of building performance go much deeper and reach all the way to shelters built by early humans. It is important to build on this legacy, including the pioneering work by BPRU and CIB Report 64 and the contributions of many others, so as not having to reinvent the wheel again and again.

Ultimately, building performance analysis is an applied science. So, as pointed out by Hensen and Lamberts (2011: 3), one not only needs to ask how the field helps to support the production of desired results and products, but also has to strive for deep understanding and appreciate the inner workings. In this context it is worth remembering that while building performance analysis focuses on buildings, which are material objects, buildings in the end are created to serve humans and their activities.

1.5 Summary

This chapter introduces the concept of building performance analysis and its importance in the architecture, engineering and construction sector. It discusses the technical interpretation of performance, as in performing a function, and the aesthetic view of presenting and entertaining; it combines this with building as both an artefact and process. Buildings are shown to be complex systems, both in terms of the many systems involved and the long life cycle, which results in many disciplines having an interest in and interaction with the area of building performance. The architecture, engineering and construction industry itself adds further complications by its make-up and collaboration practices and the highly individual products it creates. Yet building performance is not immune into the rapid developments in ICT, and new developments in digital metering and measurement are presently driving a change in how building performance is analyzed.

While the term building performance is used frequently, there is no clear definition of the term. This is not uncommon in other fields. However, the absence of a common understanding impedes progress in both the building industry and the related academic fields. The lack of a unifying theory on building performance limits the credibility of the disciplines, a problem that is further exacerbated by casual use of concepts from other domains. The problem of the ‘performance gap’ also indicates a tendency to overpromise, with the ultimate product of the construction industry, buildings, regularly failing to meet the expectations of its stakeholders.

Building performance lives in a context of other disciplines, such as electronics, human resources, sports, manufacturing and others that all have their own interpretation of performance. Two fields that provide a deeper view are systems engineering and process management. Key concepts that help to better handle performance are systems, functions, criteria, goals, objectives and measurements. On a fundamental level, the main approaches for building performance analysis are physical testing, calculation/simulation, expert judgment and stakeholder assessment.

Based on the introductory discussion, this chapter then defines building performance as a tripartite concept that can relate to an engineering, process or aesthetic perspective. The engineering view is concerned with how well a building performs its tasks and functions. The process view is concerned with how well the construction process delivers buildings. The aesthetic view is concerned with the success of buildings as an object of presentation or entertainment.

This initial definition of building performance is followed by a brief history of the building performance, starting from shelter for emerging humanity, the impressive Neolithic monuments, and Vitruvius all the way to the present. Milestones in this history are the following:

- The industrial revolution and foundation of associations that represent specialisms.
- The post-war interest in performance as architectural driver as well as subject in itself.
- Development of building performance in relation to computers and ICT from 1960s onwards.
- The relation with the emergence of the field of building science/physics, again from 1960s onwards.

- The link with Computer Aided Design and Building Information Modelling, and notably the EU COMBINE project of the early 1990s.
- The work of CIB on building performance through Working Commission W60 on the Performance Concept in Building (1970 onwards) and the PeBBu project (2001–2005).
- The foundation of IBPSA, the International Building Performance Simulation Association in 1987.
- The emergence of Facility Management as a separate field.
- The interest in sustainability from the 1980s.
- The rethinking of construction industry processes from the late 1990s.
- The continuous work on user surveys and Post Occupancy Evaluation, and especially the Probe Project in the United Kingdom.
- The performative turn in the humanities since the 1990s.
- The emergence of diverse concepts such as High Performance Buildings, Zero Carbon Buildings and Net-Zero Energy Buildings that have appeared around the turn of the millennium.

Another area where developments are worth discussing is the field of building regulations, standards and rating schemes. From the Hammurabi Code of 1754 to modern performance-based regulations, this gives a good insight in some of the developments in performance thinking. European developments such as the Construction Products Directive, Eurocodes and the Energy Performance of Buildings Directive are presently shaping and driving developments. Also of note are the ISO standards, which include building performance since the 1980s. Voluntary rating schemes, such as BREEAM, LEED, NABERS and others, complete this overview.

Finally, a brief selection of more recent work in building performance is presented to help set the scene for the following chapters. Discussed are advances in monitoring and measurement, with a focus on AMR and the IPMVP, and test methods for building components as often defined in ISO standards. A theoretical framework on role of simulation in performance-based building is provided by Augenbroe (2011) and is mostly applicable to other analysis methods as well. In both the juridical context and prediction, expert assessment still plays an important role. For evaluation of building performance by stakeholders, POE is a key approach, with the Probe studies and the descendant BUS methodology representing important exponents of the field. Changes in building performance analysis are currently driven by expansion of the system boundaries towards inclusion of the district and urban level. Further development takes place in the field of smart systems, both at building component and whole building level, via smart grids, and smart cities. Another area driver of change is increased interest in the role of occupants and the introduction of elements of human computer/machine interaction into the building sector. And like in many fields, the progress on data analysis, cloud and parallel computing and the emergence of the Internet of Things are impacting building performance analysis.

The remainder of the book sets out to define building performance and establish how this can be measured and analyzed and how it can guide the improvement of buildings. The findings will be combined into an emergent theory of building performance analysis.

Recommended Further Reading:

- *Working with the Performance Approach in Building* (CIB Report 64, 1982) for generic introduction to performance-based building.
- *The role of simulation in performance based building* (Augenbroe, 2011) for a leading theory on the use of performance analysis in making decisions in building design and beyond.
- *Developments in performance-based building codes and standards* (Foliente, 2000) for a good overview of the emergence of performance-based codes at the end of the 20th century.
- *Assessing Building Performance* (Preiser and Vischer, 2005) for the wider view on post-occupancy evaluation and stakeholder surveys.

Activities:

1 Make a list of your top-three favourite buildings and your three most despised buildings. Then analyze what it is that makes you like or dislike these buildings, and express this in terms of building performance.

2 Find examples of specific buildings that perform well in terms of
A Acoustical quality
B Efficient use of water
C High workload capacity in handling numbers of people going through the building
D Responsiveness towards the difference between working week and weekend
E Readiness to cope with an earthquake.

Explore the design of these buildings and whether any special systems are in place to make the building perform well in this specific area. Review the design and engineering process of the building; where did the interest in this specific performance aspect originate from, and what was done by whom to ensure that the building would perform in this aspect?

3 Discuss the relations between a well-managed building construction process and the resulting building. Does proper quality assurance processes during construction guarantee that the final building performs well? Why or why not?

4 Identify a building that performs in the aesthetic interpretation of the word by making a creative statement and communicating with its context and the observer. Explore what mechanisms are used for communication and what attributes the building has to enhance this communication.

5 Review your national building regulations regarding the protection against noise hindrance of commercial aircraft for residential properties, and find out whether these are prescriptive or performance-based regulations.

6 Ask some colleagues or friends to give a definition of building performance. Contrast your findings with the discussion of the concept given in this chapter.

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