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RESEARCH ARTICLE

Fundamentals of Performance-Based Building Design

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Abstract The paper formulates some fundamental principles of performance-based design (PBD), suggesting a conceptual framework and systematic approach suitable for application in most areas of building design, and in the development of simulation tools and performance test methods required in the design and assessment processes. A schematic algorithm, which has been developed for the common engineering approach, was helpful in identifying the inter-relation with the required knowledge-based databases and tools that are needed for proper implementation of PBD. It is also shown that this schematic algorithm can serve not only as a conceptual model but also as the basic framework for developing or adapting simulation tools that are intended for PBD and assessment. The last part of the paper demonstrates the application of the fundamental approach in several areas of building performance (fire safety, acoustics, moisture safety, indoor air quality, and durability), outlining in each area the main user needs, ensuing performance requirements, and the most significant capabilities required of adequate simulation tools, with an emphasis on input/output.

Keywords performance-based design, buildings, conceptual framework, performance simulation, performance test method

1 Introduction

Performance-based building (PBB) is a building market environment in which all stakeholders involved in the various phases of the building process recognise the need to ensure long-term performance-in-use of buildings as an explicit target. One way of implementing PBB is using explicit and transparent performance-based procedures during all phases of the building process. This is accomplished by replacing prescriptive provisions on the demand side (i.e., in regulations, standards, design briefs, and tenders) with performance requirements, and allowing the supply side to provide alternative solutions that meet the requirements, thus enabling the choice of the most suitable solutions by means of cost/benefit analysis (i.e., life cycle cost/life cycle assessment), optimization (one or multiple objectives), or other tools.

The performance concept in building was first defined by the CIB W60 Commission (Gibson 1982) as "*first and foremost, the practice of thinking and working in terms of ends rather than means. .... It is concerned with what a building or building product is required to do, and not with prescribing how it is to be constructed*". This concise definition has been adopted and cited since its first appearance in almost every article and report dealing with the implementation of the performance concept in building. It reflects the manner in which most human activities are planned and carried out so naturally that any person not familiar with the building profession may assume that this is actually the prevailing situation in building as well. To those familiar with the profession and with the developments of the past century, however, it is clear that despite the fact that over fifty years have passed since the performance concept was first introduced in France with regard to its Agrèment system (CSTB publications; Blachere 1965), no building market anywhere in the world has adopted a full set of performance-based procedures.

Thinking in performance terms at the design stage is much older than it seems from the current literature addressing this subject (Spekkink 2005). In his book,

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submitted to Imperator Caesar in 1 B.C., Vitruvius wrote that "*the three departments of architecture, ..., the art of building, ... must be built with reference to durability, convenience, and beauty. 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*" (Vitruvius, 1B.C., Book Ⅰ, Chapter Ⅲ, section 2). Contemporary performance-based terminology has coined two widely used terms that formalize the above-mentioned targets, namely **user needs** (UN), and **performance requirements** (PR). In an explicit performance-based design (PBD) process, the words "*with reference to*" are replaced by the demand to identify UNs within the entire set of relevant **performance attributes** and PRs are then established for a hierarchical set of the building and its parts (Hattis and Becker 2001). Domain 3 of the thematic network PeBBu (Becker and Foliente 2005) has defined the PBD process as (Spekkink 2005) "*a process in which PRs are translated and integrated into a building design*" stating as well: "*PRs should express the real user needs behind the question for a built product*".

It is apparent that the seeds of PBD were planted over 2000 years ago. However, the approach that was adopted then and persisted until less than 50 years ago was that the achievement of building performance targets should be based solely on experience-based know-how, which is embedded in clear and strict prescriptions mandated by laws, regulations, codes, and standards. Assessment of design solutions and construction details was a simple technical procedure, which consisted of comparing the proposed design and executed details with their standardized prescriptions. Consequently, no simulation tools were needed for design assessment. This also enabled simple tendering based on detailed design documents, with minimal construction costs as the distinguishing decision variable.

During the second half of the 20th century, many local building markets experienced the need for increased flexibility in the formal documents and approval procedures to facilitate more fluent import/export of building goods and to enhance fast adoption and assimilation of innovations. A new approach to the procurement, design, contracting, delivery, management, and maintenance of buildings was emerging, PBB. PBD is an integral part of PBB.

However, despite the longevity of the performance concept and the multitude of research devoted to its implementation in building in the past forty years (Foster 1972; ASTM/CIB/RILEM 1982; CSTB 1988; Davis and Ventre 1990; Becker and Paciuk 1996; CIB 2001; Huovila 2005), a comprehensive and exhaustive set of fundamental tools for the systematic application of the concept in all areas of building design has yet to be fully developed.

This paper shows that simulation tools are an essential part of PBD. It first formulates some fundamental principles of PBD, suggesting a conceptual framework and systematic approach suitable for application in most areas of building design and in the development of simulation tools and performance test methods required in the design and assessment processes. The areas of structural engineering and building energy, which adopted a PBD approach, served as models in the derivation of these principles. The final part of the paper then demonstrates the application of this fundamental approach in several other areas of building performance (fire safety, acoustics, moisture safety, indoor air quality, and durability).

2 PBB — Conceptual framework and engineering approach

A conceptual framework for implementing a PBB market was identified while reviewing various viewpoints during the compilation of the 2nd International State of the Art Report for the PeBBu Thematic Network (Becker and Foliente 2005). The scheme of this framework is given in Fig. 1, and it is summarized by: The **building facility** is a multi-component system with a generally very long life

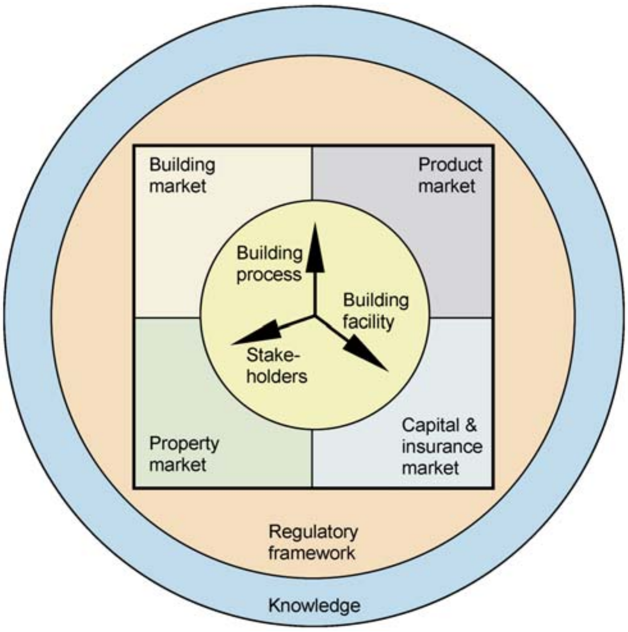

Fig. 1 Conceptual framework for implementing performance-based building (Becker and Foliente 2005)

cycle. The system's design agenda as a whole, and the more specific design objectives of its parts, originate from relevant UNs. These needs evolve into a comprehensive set of PRs that should be established by numerous **stakeholders**, who belong to the four markets, namely the **building market**, **product market**, **property market**, and **capital and insurance market** (Fenn et al. 2005). These requirements complement or surpass requirements stipulated by the **regulatory framework**. The **building process** comprises the supply side, with the various **stakeholders** identified in its different stages supplying the final outcomes and establishing the actually achieved levels of performance-in-use. It is the task of the **knowledge domain**, and subsequently of the **regulatory framework**, to supply the tools for a smooth match between the performance-demand and the building-supply sides.

Although the benefits may be significant, it is well accepted that employing a performance-based approach at any stage in the building process is more complex and demanding than using the simpler prescriptive route. Consequently, the application of this approach should not be regarded as an end in itself. Moreover, in most common situations (mainly when simple buildings are concerned and well-proven technologies are used), the prescriptive routine is faster, less costly, and more reliable for ensuring the building's long term performance-in-use. On the other hand, when complex projects or innovations are concerned, or when optimal solutions are sought, use of the performance-based route at almost every stage is indispensable, and in particular during design and evaluation. The focus in the rest of this paper is thus on PBD.

The main steps in a PBD process are

- identifying and formulating the relevant UNs,
- transforming the UNs identified into PRs and quantitative performance criteria, and then
- using reliable design and evaluation tools to assess whether suggested solutions meet the stated criteria at a satisfactory level.

The main stakeholders relevant to the PBD process during its various stages are the users, entrepreneur/owner, regulatory framework, design team, and manufacturers. These are discussed in the following section.

2.1 Stakeholders most relevant to PBD

Users — Users include (1) end users, who are the people and processes that inhabit the building, as well as guests, maintenance personnel, repair workers and rescue teams, who visit the building more sporadically; and (2) the general public.

The conditions required for the end users' well-being and for their activities within the building generate most of the UNs. These include needs for serviceability, accessibility, safety, security, health, comfort, and ease of maintenance. End users are also largely concerned with durability, as deterioration may affect all other aspects mentioned above.

Despite comprising the largest group of stakeholders who are directly affected by the constructed facility, end users are usually anonymous and are not explicitly present or represented in the pre-occupancy stages of an actual building process. Only when the entrepreneur is also the direct end user does he partially represent this stakeholder. Consequently, the main representative of the end user is the regulatory framework supplemented by the design team.

The general public may be affected by direct impacts of the building on air and water quality, traffic, noise, and obstruction of sun and view, as well as by its indirect impacts on the environment (resource depletion) and on climate change (energy consumption). Thus, the general public, as an end user, is represented in the building process by the regulatory framework.

Entrepreneur/owner — An entrepreneur who remains the facility owner and occupies the building upon its completion is its main end user. Being involved in the design process as well, this entrepreneur/owner may sometimes stipulate performance criteria that are more stringent than the minimal levels mandated by the regulatory framework (e.g., in the areas of durability or energy). On the other hand, an entrepreneur/owner who rents out the property to others will usually be more concerned with performance aspects that affect the renting rates, as well as with durability of the entire facility, and less so with those affecting the well-being of the end users. An entrepreneur who intends to sell the facility upon its completion will usually not be concerned with performance aspects that affect the well-being of the end users, nor with its energy consumption, long-term performance and durability, but rather with properties that enhance profit. Despite their different concerns with regard to user needs, entrepreneurs are usually interested in an optimal solution that enables meeting the relevant needs at a minimal cost.

Regulatory framework — The regulatory framework is concerned, first and foremost, with ensuring the basic needs of the end users and general public who are not otherwise represented in the building process. The regulator's main concern is the duty of care — i.e., addressing true needs that market forces may neglect to take care of properly or to an adequate extent. In addition, the regulator is concerned with the long-term protection of the environment against direct and indirect impacts affected by buildings during their entire life cycle.

Besides protecting the needy, the state is interested in maintaining a vital and economically stable building market, in promoting export, and in preventing raised building costs due to unjustified barriers on imports, excessive mandatory demands, or complex regulatory procedures. Consequently, the decision to enable a performance-based regulatory framework in the country and to provide conditions for performance-based procurement is usually obtained at the government level, with the objective of facilitating the introduction of innovations and somewhat eliminating barriers to free trade (European Commission 2000).

In order to accomplish all this without imposing a prohibitive economic burden on the building processes, most countries avoid a revolutionary change from a prescriptive-based regulatory framework to one that is solely performance-based, and enable the daily use of the commonly accepted prescriptive documents under the title of "Deemed-to-Satisfy Solutions" or "Approved Documents". The performance-based approach is then kept as an option for those parts of the process in which innovations are introduced, or for times when the entrepreneur, a member of the design team, or the contractor are interested in an alternative solution to that approved by the prescriptive approach, and are ready to exploit the longer design and assessment process this requires.

Design team — This group is composed of numerous professionals, including the architect and various engineers. The PBD framework implies that:

1) Each member of the design team should explicitly address all relevant PRs, including the regulatory framework PRs in his or her area, those imposed by the entrepreneur, and, within his or her professional expertise, any additional PRs that stem from relevant user needs that could not be explicitly expressed in the absence of such relevant users;
2) No aspect is solved at the expense of other aspects; and
3) Basic assumptions that may affect performance-in-use (e.g., service conditions, occupants' behaviour, modes of facility operation and maintenance, etc.) have been explicitly addressed and suitably represent the expected occupancy.

These points must be implemented routinely in every separate design discipline, yet a coordinated design process and teamwork is indispensable. When it is necessary to explicitly prove fulfilment of PRs the use of simulation tools is indispensable.

Manufacturers — Manufactures of building materials, components, and entire building systems regularly produce series of their products using well-established processes, and evaluate them using simple quality control tests. Products that conform to standards are accepted by the regulatory framework, assuming implicitly that the standardisation committees have considered the envisaged long-term performances and have prescribed provisions that ensure fulfilment of the overall requirements, including durability. The European Construction Products Directive (CPD) is based on this assumption, and uses the CE marking as a means for communicating the "fitness for use" information it implies (European Commission 1989). Products are usually classified according to a given set of properties (e.g., curtain-wall air permeability (CEN 2002)), and choice of the specific product for a given design solution depends on the combination of its nominal properties compared with those required in the design specification. The exchange of performance-related information between manufacturers and the other stakeholders is carried out using standard classification terms.

When a manufacturer introduces major changes into the materials or structure of a said product, or when a new component or entire building system is designed, the standard test methods may not be suitable for checking the new ideas at the design stage, and they may no longer provide a means for proving to others that the innovation meets their needs. Performance test methods (PTMs) are the commonly accepted simulation tool for prototype testing of innovations. Development of PTMs is based on the same fundamental principles outlined in this paper for PBD (Becker 2001).

2.2 Overall engineering-type scheme for PBD

The central circle in Fig. 1 shows the sub-framework for implementing a performance-based approach at the facility design level. Figure 2 outlines schematic features of a common engineering approach that can be applied to PBD in most performance areas and their inter-relation with required knowledge-based information and tools. According to this approach, the following sequence of steps takes place:

An exhaustive set of UNs in buildings is identified (usually expressed in non-engineering type terms) and transformed into PRs (expressed qualitatively in physical terms) accompanied by performance criteria (the quantitative values of a set of physical factors that serve as the **performance indicators**). On the other hand, general actions and conditions (referred to as **generalized loads**) that may potentially compromise the achievement of the UNs are identified and quantified. Generalized loads can stem from natural or man-made conditions outside the designed building, as well as from activities that take place within it. The design process consists of exposing the suggested solution to the generalized loads (using a simulation tool) and comparing the levels of performance indicators obtained with the criteria. Due to their stochastic nature and to the uncertainties embedded in both data sets (user needs and compromising actions/conditions), safety factors should

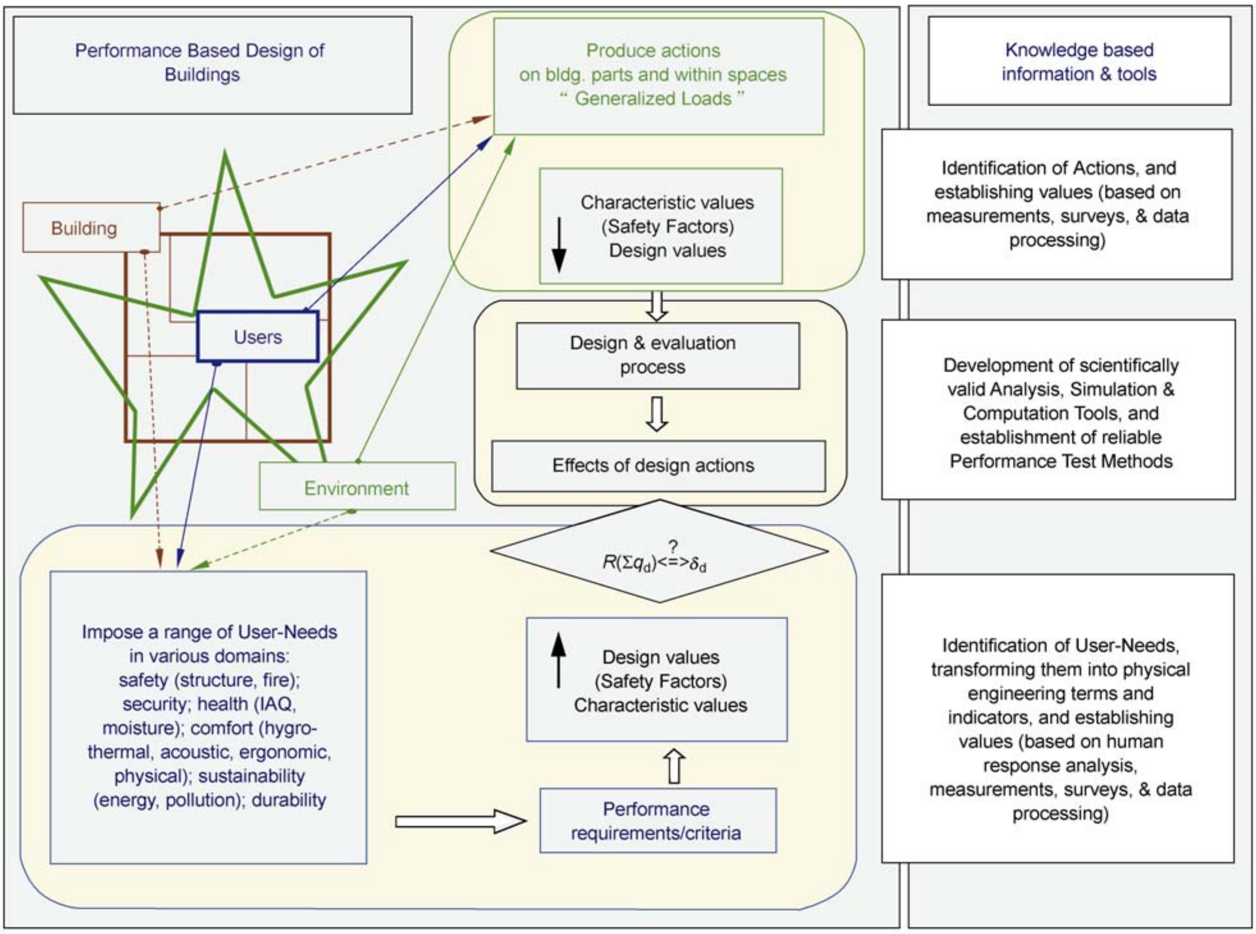

Fig. 2 Scheme of performance-based design and required knowledge-based information and tools (Becker and Foliente 2005)

be associated with the characteristic values of the criteria and the loads.

2.2.1 *User needs*

Formalization of qualitative user expectations began in the US in the 1970s, within the framework of the Operation Breakthrough project (NBS 1970), using listed performance attributes. This list was later extended by various groups (for instance, Blachere 1987; Jaegermann et al. 1978; ISO 1984; ASTM 2005), and in most documents it includes several or all of the following attributes, categorized into four main groups:

- Functionality — Spatial Characteristics and Accessibility, Serviceability, Operation and Maintenance, Structural Serviceability.
- Safety — Structural Safety, Fire Safety, Accident Safety, Body Safety, Security.
- Health and Well Being — Indoor Air Quality, Moisture and Mould Safety, Indoor Climate, Acoustics, Visual Comfort, Hygiene, Water Quality.
- Sustainability — Energy Efficiency, Durability, Environmental Impact.

Systematic derivation of UNs can be achieved by means of a top-down hierarchical procedure (Hattis and Becker 2001). Every building type (Occupancy) is regarded as a platform intended to host numerous User-Activity combinations with various diurnal, weekly, monthly, and annual schedules. These User-Activity modules are usually aggregated into functional spaces, which are accommodated within the total building layout. UNs are stated in general terms and refer to the User-Activity modules. Achievement of the conditions necessary in a given space in order to fulfil the needs depends usually on the building components that separate the given space from other spaces in the building or from the outside. Thus, the transformation of UNs into PRs starts at the whole-building level, and progresses down to building spaces, building parts and systems, components and connective details, and finally to materials and accessories. Still, some needs may be directly related to the building fabric (e.g., structural stability, moisture tightness) rather than to the users' activities within the spaces. Their elaboration will thus start at the relevant intermediate level.

Two kinds of terminologies may generally be distinguished in the expression of UNs: target oriented (TO) and fault preventive (FP).

TO terminology is used to express the request for specified achievements (e.g., an entrepreneur's request to provide solutions that enhance the building's grandeur, a request to enable assigned activities within the building, or a request to ensure a specified level of user satisfaction). Entrepreneurs may prefer this terminology.

FP terminology is used to express explicit requests for decreasing the risk of occurrence of faults that may interfere with the building's purpose or with the activities and processes it hosts. The regulatory framework prefers this terminology.

Examples of common TO and FP expressions for similar UNs are given in Table 1.

Despite their more positive appearance, needs expressed in TO terminology cannot usually be translated into justified quantitative performance criteria without addressing the faults that may occur (e.g., an economically justified quantification of the request "Users should be acoustically satisfied" can only be accomplished if the requirement not to disturb their sleep, concentration, and speech legibility is used to establish the threshold noise levels in the various spaces).

UNs are usually expressed in colloquial terms, which are easily understood by all stakeholders but lack the professional scrutiny needed for producing the actual design details. In essence, they should be regarded as a generally agreed list of statements that should be further elaborated into a working tool for the professional design team.

2.2.2 Performance requirements and criteria

User needs can be implemented implicitly by requesting specified solutions that are known with certainty to satisfy these needs, or explicitly using PRs that are amenable to quantification as criteria for design evaluation.

Various terminologies have been suggested in addition to the historical UNs, PRs, and performance criteria. The Nordic model, which was recently adopted by the ICC Performance Code (ICC 2006), uses the following: Objectives (synonymous to UNs), Functional Statements (similar to PRs), and Performance Requirements (similar to criteria). The ISO Sub-Committee TC59/SC3, standardised the UN attributes (ISO 1980), elaborated the procedure for establishing requirements (ISO 1984), and illustrated the process for several topics (ISO 1992) erroneously introducing prescriptive solutions as PRs.

An essential feature in the delineation of UNs into PRs is the identification of the physical factors that serve as performance indicators. These factors must be quantifiable, well understood, and preferably amenable to computational analysis in order to enable performance prediction during the generation of design solutions. In general, the transformation of a UN to a set of performance criteria is linked to the identification of threshold values for relevant physical factors that may cause either a given level of failure (e.g., minimal surface relative humidity beyond which visible mould growth is possible) or an acceptable dissatisfaction level (e.g., the predicted mean vote (PMV) values that may lead to over 10% thermally dissatisfied, or the minimal floor deflection that may be observed with a

Table 1 Examples of user needs, expressed in TO and FP terminologies

Attribute	Needs	
	TO terminology	FP terminology
Outlook	To provide a building whose outlook portrays a specific symbol (hi-tech, classical)	
Functionality	To enable a given list of activities and processes, as stems from the building's purpose, e.g., to provide a spacey feeling, to ensure accessibility	To prevent congestion, crowdedness, inaccessibility
Operation	To enable scheduled operation of service systems, as stems from the occupancy schedules	To prevent frequent operational failures of service systems
Indoor conditions	To provide comfortable thermal, lighting and acoustic conditions; to provide a healthy indoor environment	To prevent overheating, overcooling, excessive relative humidity, excessive noise, poor indoor environment, insufficient lighting or excessive glare
Structural safety	To provide structural safety	To prevent structural failure that is not proportional to the loads causing it
Fire safety	To ensure occupant safety in case of fire	To prevent fire and smoke from spreading beyond the zone of origin, and to prevent structural failure that is not proportional to the fire incident
Durability	To provide a durable building	To prevent decay, corrosion and excessive deterioration within a given life expectancy

naked eye by any person standing below it). Statistical data on relations between health, comfort, and perception of satisfaction and the effects of the physical factors must be analysed in order to derive the thresholds for dissatisfying performance and design values for satisfactory performance. At the same time, identification and statistical data are needed for actions that tend to prevent the achievement of the required conditions in order to derive the characteristic generalised loads.

The following ten-step algorithm, which is also reflected in the framework presented in Fig. 2, is suggested as the backbone for establishing a PBD process for any building occupancy and in every performance area:

Step 1 List potential User-Activity groups and their UNs.
Step 2 Identify all relevant actions/conditions that tend to adversely affect building performance and threaten achievement of the UNs (generalized loads) and the combinations that should be addressed simultaneously.
Step 3 Identify all relevant performance indicators for every UN.
Step 4 For each performance indicator, define the building-related meaning of the term dissatisfaction or performance failure.
Step 5 For every UN associated with every User-Activity, define the accepted percentage of dissatisfied or the accepted level of failure.
Step 6 Determine the characteristic values of the generalized loads.
Step 7 Determine the characteristic limit values of the performance indicators.
Step 8 Determine safety/modification factors for transforming characteristic values into design values.
Step 9 Establish acceptable evaluation tools that reliably predict the consequences of exposing the suggested design solution to the relevant combinations of generalized load (simulations, PTMs).
Step 10 Establish methods for deriving design values for all relevant material or component properties required in the evaluation process.

2.2.3 Design evaluation and decisions

UNs and PRs express the demand side of the building chain. The supply side provides design solutions, as well as the final constructed facility. To provide solutions, design tools are needed. To ensure that supply meets demand, accepted assessment methods are needed. Both design tools and assessment methods should be able to evaluate or simulate the behaviour and response of the building to the generalized loads, and predict the performance indicators stipulated in the performance criteria. However, the tools required during design and those required for final assessment of the integrated solution are not identical.

During design, each professional seeks answers for the set of given PRs under his responsibility. The process starts by considering several conceptual solutions that are first checked superficially against other requirements, and those that obviously conflict with other requirements are discarded. The architect combines all remaining solutions into the seemingly most favourable combination or into several alternative combinations of seemingly equivalent solutions. Each of the various members of the design team now elaborates the details in their area of specialization. Every single decision made by any of the various professionals may, to some extent, affect performance in other areas that are not directly his responsibility. Consequently, the finally chosen combination must be re-assessed by every design team member in order to verify that it fulfils the entire set of requirements.

Obviously, parts of the design process (mainly the initial stages) are highly intuitive and non-structured. During these stages, PBD relies mainly on basic knowledge and physical principles, and does not address the quantitative values of the requirements. Adequate tools for this stage are knowledge and previous experience, and for the young designer — informative guidelines and manuals explaining general trends and inter-relations between the design variables and the performance indicators (Ruck 1989). At the more advanced stages of design, when quantitative decisions are made, some assessment methods can also be used as direct design tools in a recursive process. Moreover, assessment tools based on whole-building simulations can be implemented by performing systematic parametric investigations or evaluating the results of numerous different alternatives, as well as linking them into an automated optimization process.

The entrepreneur needs assessment methods in order to check whether the design solution meets his requirements, or to prove the adequacy of the end product upon delivery. The authority having jurisdiction needs assessment tools in order to grant the building permit. Consequently, assessment methods and tools used by the different stakeholders need not necessarily be identical, but those used by the authority having jurisdiction must be elaborated in the regulatory documents, and those used by the entrepreneur must be clarified in the performance-based program and in the contracts.

Despite these differences, all simulation tools developed for design and assessment should at least accept the required combinations of generalized loads as input, use accepted mathematical models for the analysis, and yield the results of the relevant basic physical entities necessary for calculating the performance indicators as output. To follow the design process it would be best if input consists of characteristic generalized loads and partial safety factors and a definition of the loading combination. In addition the input module may include identification (from a given list) of the performance indicators needed as output. It is essential that this list has a user-friendly learning mechanism, so that the user can easily add indicators required by the design algorithm and their functional dependence on the calculated results. The output may include the set of performance indicators requested by the user.

2.2.4 *Material and components properties*

Each assessment or simulation tool used requires input of material and component properties. At the design stage, the materials are virtual entities with no specified manufacturer. Consequently, the properties incorporated in the design evaluation should represent the worst-case scenario likely to be encountered during construction, unless more exact information is available. A distinction is made between the characteristic value of a property and the design value.

The characteristic value (sometimes referred to also as the nominal value) accounts for the variability encountered in the specific property of a given material or product. To ensure conservative design, the characteristic property should be the value that only a small portion (say $\leq 10\%$) of the material used in the building may fail to achieve. This is also the value that the manufacturer should report. Design values, on the other hand, are the values to be used in the design and evaluation processes, and should be derived from the characteristic value using standardized partial safety factors, γ_p. However, in various areas of building performance, except structural engineering, these factors are neglected in the design process (i.e., taken implicitly as $\gamma_p = 1.0$). Moreover, in many areas, average values are used instead of characteristic values, leading to non-conservative design.

The simulation tool should request as input design values of the materials and/or components, as well as their change due to relevant conditions that develop during the simulation.

2.3 Impact limits

The entire set of user expectations is seldom achieved throughout a given building's entire life cycle. Even when design and construction have followed all the provisions stipulated in the codes and standards, decreased levels of performance may occur at various stages. This happens due to the stochastic nature of the various main factors affecting performance-in-use, such as the actual activities taking place in an actual building, the occurrence of unforeseeable exceptionally severe events, the actual variation of material and component properties, and the actual quality of workmanship. The explicit elaboration and exhaustive listing of presently known and future foreseeable needs, as well as of expected events and driving forces that tend to hinder their achievement, decreases the risk of overlooking random combinations that may be detrimental to the building's performance. It is therefore argued that identifying the multitude of needs and integrating them into engineering-type design tools may decrease the probability of occurrence of actual situations in which adequate performance is not achieved.

3 Demonstration of applications

The field of structural engineering can serve as a mature model for the application of a performance-based approach in design.

The Structural Eurocodes (CEN 2002 – 2007) are at this stage the most comprehensive example of implementing the performance concept in formal design documents. The approach adopted in them is predicated upon the notion that, from the users' viewpoint, a building should be safe and feel safe (damage should not be excessively disproportionate to the magnitude of the event causing it, and under regular service conditions no threat to safety should be sensed). It sets safety and serviceability targets in terms of performance indicators that are related to the physical factors that adversely affect the building performance from the users' viewpoint (e.g., deformations, vibrations, crack width, ultimate capacity). It provides characteristic limit values for said physical factors (e.g., displacement, crack width), or the method of deriving them when they depend on other factors (e.g., capacity). It lists the types of loads to be considered, and supplies information on their characteristic values, including partial safety factors associated with loading combinations. Finally, it lists the accepted analysis algorithms and calculation methods for evaluating the design, as well as algorithms for deriving material design properties from their characteristic values. From the viewpoint of the systems approach, structural design starts with verification that overall structural stability exists under various loading combinations, and only afterwards are subsystems and components designed. Explicit performance-based requirements for earthquake resistance have also been developed and are based on a procedure that coordinates the safety needs of occupants with those of rescue teams and the general public. Several levels of performance are defined: the more frequent quakes (e.g., 50% probability of being exceeded in 50 years) should not cause damage that impairs serviceability, a most severe quake (e.g., 5% probability of being exceeded in 50 years) may impair serviceability but should not cause an ultimate state, and for a rare event (e.g., 3% probability of being exceeded in 75 years) the only requirement is that it should not cause total collapse (Soulages 1995; Bozorgnia and Bertero 2004).

In addition to the structural design area, a performance-based approach has been implemented recently in the USA within the field of energy design of buildings. Besides the regular prescriptive option, the energy codes also include a performance-based option. The prescriptive option follows the traditional provisions for minimal thermal resistance of envelope elements, sizing of windows, etc. The performance-based option requires energy analysis of the building and a calculation of a total performance indicator such as energy demand, primary energy demand, or CO_2 emissions. Its value is then compared with a calculated energy budget that serves as the design criterion (DOE 2005a). Generalized loads in this case are the meteorological data for the typical meteorological year (TMY), as well as internal loads due to typical equipment, activities, and processes taking place in the given building spaces. The need to improve energy efficiency of the entire building makes it obvious, in this case, that requirements should be stated first at the highest relevant level and only then can criteria for lower levels be rationally developed.

Both, the structural engineering model and the building energy model, can thus be used as a basis for other performance attributes. Sections 3.1 to 3.5 below demonstrate such possible applications. Each section presents the main UNs in the given area, suggests the ensuing PRs and relevant generalized loads, and then discusses some major aspects of the PBD process and characteristics of relevant simulation tools.

3.1 Fire safety

The American Society of Fire Protection Engineering, SFPE, is advocating a performance-based approach to the overall fire safety design process (SFPE 2004; Rosenbaum 2005). The framework shown in Section 2.2 serves here for the derivation of fire safety PRs and a design algorithm in this area.

The main UNs and design goals are: (UN1) building occupants should be able to evacuate the building without excessive threat of suffocation, burns and death; (UN2) dangerous structural damage that may threaten the life of occupants, fire fighters or rescue teams should be prevented; and (UN3) fire should not spread to other buildings.

To meet these needs, the fire safety design process usually comprises five main areas of activity: (A1) design of detection and alarm systems; (A2) design of evacuation and rescue routes and means; (A3) design of fire suppression and fire fighting systems; (A4) selection of building materials according to their combustibility and fire-spread properties and design of fire partitioning (administered by means of fire resistance properties of walls and floors); and (A5) structural fire safety design.

Performance requirements and generalized loads for each UN are as follows.

UN1 — Two main PRs are relevant:

PR1 — Any fire that starts in any building space should be detected and should trigger an alarm so that safe evacuation of the building according to PR2 is possible. The maximum total response time from onset of fire to alarm, and the loudness and area coverage of the alarm signals should be adapted so as to ensure that all occupants (i.e., a reasonable percentage for “most occupants” is ~100%), regardless of their location and activity, notice the alarm. This requirement is the basis for design activity A1.

PR2 — Smoke and fire should not spread into the evacuation paths as long as occupants have yet to reach a safe exit (the evacuation path is the shortest, man-high route from any point on a given floor to a safe exit on that floor). This requirement ties the possible period of evacuation to the development and spread of the smoke layer, and to the spread of fire beyond the room of origin. Its optimal fulfilment can be ensured by coupling several design activities (A1, A2, A4, and A5).

The generalized loads for these requirements are the fire scenarios that may occur in the building and the possible number, activity, and location of occupants during each scenario. Decisions made in design activity A4 should be considered as part of the factors affecting the fire load.

UN2 — One basic PR is relevant:

PR1 — A given level of safety should exist against the onset of a structural ultimate state under the action of temperature-time curves that may develop within the building spaces during typical fire scenarios. Design activity A5 takes care of this PR.

The generalized loads in this case are the temperature-time curves that may develop within the building spaces under each fire scenario, coupled with the structural permanent service loads. For accidental fire scenarios, the temperature-time curves may be modified to account for the existence of automated fire-suppression systems. However, for arson fire scenarios, flashover under the characteristic fire load density should be assumed even when such systems are installed. Characteristic fire loads and geometric data of the designed spaces and their openings are used in the calculation of the temperature-time curves. Since the designer can not estimate the amount of combustibles in every space with sufficient certainty, values for characteristic fire loads should be stipulated in formal documents according to occupancy classifications and types of space. It should be noted that decisions made in design activity A4 may affect fire loads by (1) introducing additional combustible materials into the given space, and because (2) partitioning affects the size and geometric factors of the space whose structural elements are being designed, thus affecting the values of the calculated temperature-time curves (generalized loads). Analysis of overall stability and structural response should be performed using the temperature-dependent material properties. Temperature evolution in the structural members should be calculated using the temperature-time curves calculated for each space. The traditional prescriptive regulations, which stipulate fire resistance requirements based on a single-fire curve (e.g., the ISO curve), do not account for the specific conditions that may occur in the given building. Consequently, they are either exaggerated or under-rated, and only seldom can lead to a performance-based solution.

UN3 — Two PRs are relevant:

PR1 — No flame from a fire in one building should reach any combustible material in an adjacent building.

PR2 — Thermal radiation emanating from walls or openings in the burning building should not be strong enough to ignite combustible materials in an adjacent building.

The generalized loads in this case are fire scenarios within the building being designed (to ensure that fire does not spread to adjacent buildings), as well as fire scenarios in adjacent buildings (to ensure that fire does not spread into the building being designed). These requirements affect the fire characteristics of exterior surface materials (determined in design activity A4), but may also affect the size and location of envelope openings (an architectural activity that is usually performed without considering fire safety) and thermal features of the exterior wall cross-section (usually designed according to energy conservation, thermal comfort and moisture safety requirements). In a PBD environment, which requires coordination between the various attributes, optimization of these features is possible.

A unique simulation program that addresses all phenomena and responses that may occur in a building under any fire scenario (from inception of fire until its final decay and complete cooling down of the building) can be envisaged, but is not essential to PBD. In its absence, several simulation programs can be used in parallel to perform a complete performance-based assessment of the design. The outputs of such simulation programs for design activities A1 to A3 should be the time and spatial evolution of the smoke layer within the building spaces, the temperature-time curve within the spaces, and the rate of heat radiation from openings and exterior wall surfaces. In addition to the layout and geometrical features of the considered design solutions, simulations should accept as input fire loads and smoke production loads in every space, as well as additional fire and smoke loads associated with combustible surface materials. To assist design activity A2, a simulation program should yield the time required to reach a safe exit from the farthest point in every room. For this, occupancy density and walking speed should be part of the input. A simulation program for design activity A5 should accept the fire-induced time-temperature curves in the building spaces and structural loads as input, calculate the temperature evolution in the structural components, and then analyse the structural response accounting for the non-linear effects caused by the changing temperature-dependent material properties. Outputs should include the time development of deformations and stresses up to the point of instability. The program named SAFIR, which was developed at the University of Liege (Franssen 2003), has all these features.

3.2 Acoustics

Acoustic needs are directly linked to user activities performed in the functional spaces of the building being designed. Table 2 outlines activities that require specific acoustic conditions and their classification into several prototype groups.

The acoustic conditions beyond which the activity of most users may be impaired constitute the PR threshold values. These should be based on a statistical analysis of personal responses obtained from exposing large groups of people engaged in typical activities, to various acoustic conditions. Data is needed on the effects of ongoing background noise as well as for sudden short noises. Currently, however, many gaps still exist in the required databases, and criteria for the limit values of noise levels in various spaces are sometimes derived from incomplete data sets, relying on “personal knowledge” of acoustic experts. Assuming that the required database can be completed, a streamlined design process is possible: first, for every space, the activities that are to be carried out in it are identified as well as the relevant threshold acoustic conditions. Acoustic loads are then identified by establishing the characteristic noise levels that may be created in adjacent rooms or outside the building (e.g., 90% of the time noise levels will be lower than this level). Noise sources should be classified into the two types: continuous sources that generate the general/background noise levels,

Table 2 Acoustic user needs according to typical activities

Prototype activity	User needs	Typical spaces
Sleep (falling asleep and undisturbed sleep)	General noise level should not hinder falling asleep. Sudden short noise peaks should not cause awakening	Bedrooms in residences, hotels, elderly homes, dormitories, and childcare facilities; patient rooms in hospitals
Concentration (reading, writing, studying, taking exams, etc.)	General ongoing noise level, as well as frequent, sudden and short noise peaks (e.g., 6 times or more per hour), should not disrupt concentration	Bedrooms in housing and dormitories; classrooms; examination rooms; reading spaces in libraries; office rooms and spaces; prayer rooms
Listening to speech	General noise level, as well as reverberation within room, should not mask clarity of spoken words and sentences	Classrooms; meeting rooms; lecture halls; synagogues; churches
Listening to theatre, movies, music, etc.	Specific requirements according to type of activity	Concert and performance halls
Secretive or privacy-requiring activities	The noise level transmitted into other spaces should be masked by the ambient noise level, so that the activity is not detected or comprehended. The required level of masking depends on the required level of secrecy/privacy	Bedrooms; offices; management meeting rooms; special spaces in industrial / military buildings

and sudden, sporadic but repetitive sources that generate the short peaks. It would of course be best if typical values of acoustic loads for various spaces were given in standards. However, as long as such standards do not exist, the acoustic literature and long-term measurements remain the sole source of information. In the next step, scenarios and combinations of noise sources that are most likely to occur simultaneously should be identified. Partial safety / modification factors for the loading combinations are needed, and should be stipulated in standards.

Only when the acoustic criteria and loads at the building space level are clarified, it is possible to proceed to the next level, which includes design of partitions, floors, external walls, windows, doors, wall linings, and acoustic ceilings. It is also possible to establish requirements for minimal noise reduction values that are coordinated with the higher level spatial requirement, but these should address the non-linear interactive nature of combined acoustic loads. In a performance-based conceptual context, such lower level requirements are not actual PRs, but rather "deemed to satisfy solutions" provided in terms of acoustic properties rather than as technical solutions. Despite being conceptually erroneous, however, building codes and standards tend to portray noise reduction requirements as PRs (e.g., ISO 6242 part 3 (ISO 1992)). By doing so, they do not pave the way for optimal acoustic design, which should always be the main feature of a true PBD environment.

Although an enormously tedious task, acoustic performance evaluation of regular buildings can be performed using manual calculations. On the other hand, it is also very simple to add an acoustic module to any of the existing thermal and energy simulation programs, since the architectural building model they use is identical to that needed for the acoustic simulation. The added input should then include identification of the typical noise sources in every space and outside the building and their schedule, and the noise loading combinations and partial safety factors. The tool's database should include the characteristic values of typical noise sources, as well as design acoustic properties of building materials and components. Noise levels derived in the various spaces are the output. An advanced version of such simulation tool may include identification of typical activities in every space and their schedule as input, the threshold acoustic values for each activity in its database, and an alarm for not meeting a criterion as output.

3.3 Moisture safety

The general needs and design goals in this area are absence of visible moisture on the surface of building elements and absence of hidden moisture and its consequences (mustiness accompanied by a stale odour, mould growth on the surface of building elements, swelling and peeling of paints, deterioration of building materials, and disintegration of renderings accompanied by inflorescence). These needs are formalized by UN1 to UN5 presented in Table 3. Each UN is accompanied by the relevant PRs and generalized loads as should be addressed in a PBD process. Several examples of quantitative criteria are given in parentheses.

The design and assessment activities for requirements PR1, PR7 and PR8 require expertise and knowledge in the areas of water tightness, sealing technologies, building materials, and building details. Fulfilment of these requirements cannot be assessed using computational simulations. Although a virtual-reality simulation program may be envisaged as helpful in detecting water leakage routes, such tools have not yet been developed. As opposed to experience-based assessment of conventional construction, when a new building system or technological detail is considered, the most relevant simulation tool is a controlled experimental PTM. The test simulates the

Table 3 User needs, performance requirements, and generalized loads for moisture safety

User needs	Performance requirements	Generalized loads
UN1 — Absence of visible moisture	PR1. No penetrating moisture or water leakage through building elements	Rain, ground water, plumbing failure, house cleaning water, shower and faucet water
	PR2. No formation of visible condensation on room facing surfaces (e.g., surface temperature above surface dew point by at least 0.5℃ throughout the year)	External ambient temperature and humidity, indoor moisture supply, ventilation rate
UN2 — No mustiness	PR3. Indoor relative humidity does not exceed a specified level (e.g., 80%) in all spaces except in bathrooms when showers are taken	External ambient temperature and humidity, indoor moisture supply, ventilation rate
UN3 — No mould growth	PR4. Combination of simultaneous surface temperature and humidity does not support mould growth (e.g., surface relative humidity above 75% should not persist for more than two days)	External ambient temperature and humidity, indoor moisture supply, ventilation rate
UN4 — No paint swelling	PR5. No interstitial condensation at the interface of paint and substrate	External ambient temperature and humidity, indoor moisture supply, ventilation rate
	PR6. No moisture trapped behind paint	Construction moisture, rain water
	PR7. Uniform paint adhesion to substrate	Workmanship
UN5 — Surface and building material integrity	PR8. Ground moisture should not rise within walls and be transported to their surface	Ground water
	PR9. Moisture trapped during construction should dry out before application of surface finish	Construction moisture

application of the relevant loading scenarios (e.g., combinations of wind speed, rainfall intensity and direction, and air pressure differences) on a mock-up built using the actual method of construction.

For the other requirements, the use of programs that simulate the simultaneous dynamic heat, air, and mass transfer is essential in predicting the response of suggested solutions to the loading combinations. Due to the large typical time constants of vapour and moisture transport in most building elements, steady-state tools are not equivalent to the dynamic analysis. Simulation tools for the current purpose are similar to thermal analysis tools. The same typical meteorological year can be used as input, but the dependence of design material properties on moisture and temperature is an essential feature in this case. Output should include relative humidity in the various spaces, as well as relative humidity and/or moisture content at requested points within the construction and at the surfaces of building components.

3.4 Indoor air quality

This performance area is strongly associated with the well-being of the users, the main UN being: the health and well-being of building users should not be impaired by indoor conditions or composition of the indoor air.

Two main PRs follow:

PR1 — Thermal indoor ambient conditions achieved during most of a typical meteorological year (e.g., 95% of time) should be satisfactory to most users (e.g., 90%). Criteria should address threshold values of a thermal comfort indicator (e.g., PMV), or of a combination of air temperature, mean radiant temperature, relative humidity, and air velocity.

PR2 — Indoor air quality achieved in all building spaces during most of a typical year (e.g., only during 2% of the time may indoor air quality be worse) should not cause any health threat to most users (e.g., 99.9%), and the worst indoor air quality that may exist in any space at any time should not be definitely harmful to the health of any user. Criteria should include a list of the two types of characteristic threshold values (health-threatening background values and definitely-harmful peak values) for the concentrations of various contaminants known to affect human health, such as radon, aerosols, particulate matter, formaldehydes, NO_x's, CO, VOCs, and CO_2.

The generalized loads for PR1 are the exterior meteorological conditions, internal heat loads, electro-mechanical space conditioning system capacity, natural or mechanical ventilation rate, and the systems' operation schedules. Most programs used for thermal and energy analysis accept the same input necessary for analyzing thermal comfort, and provide the output needed for its assessment. Some of them even predict the thermal comfort PMV index (e.g., EnergyPlus (DOE 2005b)).

The generalized loads for PR2 are outdoor contaminant concentrations, indoor emissions from sources within the building and from building materials, and the air mixing scheme within the building. Simulations used in a performance-based design/assessment routine for assessing indoor air quality should accept time-dependent outdoor concentrations and indoor sources as input and should output the time and spatial evolution of indoor concentrations. Modeling should address sorption/de-sorption of gaseous contaminants into/from porous surfaces, as well as gravitational effects (mainly for gases that are denser than air). The main difficulty in implementing a PBD procedure in this case is the lack of statistically-based and accepted threshold values for all of the contaminants. In addition, the generalized loads are not yet documented in standards, except for CO_2 emissions from humans (ASHRAE 2007). Standard specifications of ventilation rates (ASHRAE 2007; CEN 2004) do not necessarily ensure an optimal solution (i.e., a solution that provides adequate indoor air quality while preventing excessive energy loss due to excessive ventilation) and should be regarded as prescriptive rather than performance-based.

3.5 Durability

Users may aspire that buildings be long lasting and maintenance free. However, economic restraints on initial cost turn such aspirations into unrealistic wishes, and all stakeholders accept that some maintenance must be part of the means for attaining durability. Consequently, it is more suitable to express the essential UN as: the attainment of all the PRs expressed under the other attributes should not be excessively impaired during the design life of the building, provided that the designed maintenance activities are performed by the users, who should be properly informed of these activities upon occupancy.

Time-dependent performance decrement is caused by deterioration of the building fabric (materials and elements). As a result, the PRs for this UN should be given at the various building hierarchy levels (i.e., first for the entire structure, then for sub-systems, envelope and separation elements, and only then for specific components, materials, and accessories). PRs at every level can be given in terms of design life periods and accepted deterioration levels of specific performance indicators during this period. Examples of some PRs are listed as follows:

- deterioration of structural elements due to corrosion, moisture damage, abrasion, and other relevant deteriorating agents should not threaten overall structural stability for a design life of 70 years;
- deterioration of thermal insulation materials concealed within the building envelope (no maintenance possible) should not cause more than a 10% energy consumption increment during the final year of the building's 50 years design life;
- water tightness of the envelope of a tall building will depend on maintenance and repair activities performed from within the building only, and should not be impaired to a level that requires maintenance or repair from the outside during a design life period of 50 years;
- water tightness of the roof is allowed to depend on simple yearly maintenance activities and 5-year replacement works.

The generalized loads are the actions and agents that tend to deteriorate the properties of building materials (e.g., typical annual variation of UV radiation, moisture, wind, chemical composition of the ambient air, hygro-thermal conditions), as well as actions that tend to affect the integrity of the construction elements (e.g., abrasion, sand-bearing wind, temperature and relative humidity variations, soil movement).

Models addressing hygro-thermal, chemical, and mechanical effects on building materials and entire building parts should simulate the deteriorating mechanisms and predict changes that occur in materials and building parts. Most of the changing properties are essential factors in the driving mechanism of the deterioration process (e.g., air, vapour, moisture and chloride diffusivities). Others are both an essential factor in the deterioration mechanism and are also involved in the calculation of the performance indicator (e.g., carbonation level, tensile strength, thermal conductivity). Only a few are solely a resultant performance indicator (e.g., surface staining). Consequently, simulation models for the prediction of durability should be non-linear and account for the changes that occur in the characteristic material properties over time (due to natural aging or to the deterioration process, causing a second-order non-linear effect). Simulation of the long-term deterioration of a given building design under the entire set of generalized loads cannot be fully accomplished at this stage due to gaps in mathematical modelling. Implementing PBD in the field of durability can, thus, be only partially accomplished at this stage, and is reserved to aspects for which the response to generalized loads can be modelled and simulated (e.g., corrosion of steel in concrete, deterioration of energy performance due to moisture accumulation).

Thus, design for durability is still treated in regular design routines in a prescriptive manner, with architects and engineers choosing materials and treatments (e.g., type of cladding, galvanization thickness) according to their personal experience and standardized prescriptions. Future inclusion of this attribute in PBD routines depends on further research that should provide (1) a better understanding of the deterioration mechanisms so as to incorporate them into mathematical models; (2) data for dose-response analysis; and (3) computational simulation tools that handle the diverse aspects of durability. These tools should be advanced extensions of the regular simulation tools used in the various attributes incorporating a module that predicts the deterioration of material properties with time. For example, an energy efficiency program should be able to predict the time dependent deterioration of thermal properties (e.g., thermal insulation, emissivity, solar absorption, visual transmittance) along the building's life span and evaluate the evolving energy demand versus time.

4 Conclusions

The conceptual framework of intention-based design embedded in PBB and the prevailing design concepts in structural engineering and energy analysis have triggered the systematic development of an engineering approach suitable for most areas of building performance. A schematic algorithm was developed for the common engineering approach to be applied to PBD. This algorithm was helpful in identifying the inter-relation with the required knowledge-based databases and tools needed for proper implementation of PBD. It was also shown that this schematic algorithm can serve not only as a conceptual model but also as the basic framework for developing or adapting simulation tools intended for PBD and assessment. Some of the most significant input/output capabilities of adequate simulation tools are listed below.

In addition to the building layout and spatial architectural features and geometry, input should consist, at least, of the following information:

- characteristic generalized loads, as well as the possible incorporation of partial safety factors and loading combinations (e.g., in an acoustics simulation, input should include schedules and characteristic levels of noise created in all typical spaces and outside the building envelope, and partial safety/modification factors for each noise source in a given combination).
- design values of the materials and/or components, as well as their change due to relevant conditions that develop during the simulation (e.g., effect of moisture content on thermal conductivity or on moisture diffusivity).
- identification (from a given list) of the performance indicators (e.g., PMV, mid-span deflection, level of smoke-air interface) needed as output, or of calculated factors that can be used later to predict the indicators (e.g., temperature, relative humidity, air velocity, and mean radiant temperature). It is essential that this list has a user-friendly learning mechanism, so that the user can easily add indicators required by the design algorithm.

Output of the simulation tool should include at least the following items:

- for every loading combination assigned by the user, the results of the relevant basic physical entities derived in the analysis (e.g., hourly values of indoor air temperature and relative humidity and at requested nodes within materials).
- the set of performance indicators requested by the user.

The same framework can be used to derive experimental or virtual reality PTMs, which are needed when computational simulation tools cannot yet be developed or are not suitable. These tests can be used to assess the performance of whole building parts or local building details. It is, however, essential that they simulate both the actual construction details and the design combinations of generalized loads.

There are still several gaps in knowledge that warrant bridging before comprehensive application of PBD can be accomplished. These include:

- a better understanding of human responses (including health and safety implications) in the transition zone from user satisfaction to user dissatisfaction and preparation of quantitative, statistically-valid databases for dose-response;
- preparation of quantitative, statistically-valid databases for generalised loads;
- benchmarking of performance indicators;
- in the area of durability, a deeper understanding of deterioration mechanisms and their mathematical modelling.

The following research and development are still needed to turn PBD into a practical routine:

- for most performance attributes (except the mature areas of structural engineering and building energy), refinement of basic tools for transforming UNs into PRs and preparation of standardized statistically-based characteristic values of the criteria and generalized loads;
- refinement and experimental validation of design and assessment tools to ensure their relevance and suitability for predicting performance-in-use;
- interfacing individual simulation tools in various performance areas with computerized design platforms that use n-D modelling (Aouad et al. 2005) to assist design collaboration and team work.

Finally, it should be mentioned that in order to implement a PBB environment, it is still necessary to develop tools, procedures and model documents for various performance-based procurement methods.

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