QUANTIFICATION OF BUILDING/ENVIRONMENT SYSTEM PERFORMANCE

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Keywords: building performance, risk, reliability, probability, environment, climate

Summary
The paper points out the role of risk analysis methods in applications for sustainable development. The method for quantification of system performance in terms of probability of failure and reliability, referring to this kind of methods is presented. It is proposed to support urban, architectural and structural design of buildings in the context of comfort, healthy living conditions, and sustainability. The results of applications of the proposed methodology to evaluate the probability of excessive heat loss through the two types of building envelope are presented.

1. Introduction
Building design has to ensure structural stability and well-being of people both indoors and outdoors under limited negative impact on environment for example in the form of excessive energy use. It includes urban, building (form, façade and material) and installations design in relation to the environmental and climatic conditions of the place where the building is constructed. Climatic conditions, human activities inside a building and criteria for human comfort are random in nature. Even the properties of structures are comparatively uncertain. Probabilistic analysis appears as the appropriate approach to account for those uncertainties when evaluating building performance. Eventually, probability of poor-performance (failure) or reliability, which is a complement to the probability of failure, can be calculated.

The application of probabilistic methods of analysis in building design reaches back to the sixties and mostly concerns safety of structures (Ditlevsen 1996). In the fields of building design including human health, comfort and well being, some attempts to adopt probabilistic methods to support design have been introduced. The concept of evaluating the hazard of improper moisture conditions was introduced by (Nielsen A. 1987, Nevander et al 1991). This work has been continued by (Harderup 2000) (Monte Carlo Simulations), and (Pietrzyk et al 2004, Kurkinen et al 2004) (FORM, First Order Reliability Method). The risk of radon concentration in a building enclosure was analysed by (Ljungquist & Lagerqvist 2005). The probabilistic model PROMO has been developed and validated by (Pietrzyk 2000) to estimate the probability of insufficient air exchange or excessive heat loss. The limit state approach based on a random variable model and FORM techniques for applications in building physics is presented in (Pietrzyk & Hagentoft 2008). This enables quantitative comparisons of different design options, and hence the reliability-oriented (probability-based) analysis (Pietrzyk 2005).

Probabilistic model for evaluation (quantification) of building/environment system performance based on load-resistance (demand-capacity) random variable model (Kottegoda 1997) is referred to in this paper. It gives opportunity to take into account a random character of system load and also random character of system capacity expressed in the form of performance criteria stated for human health, human comfort, to meet economic standards or in order to prioritise the sustainable solutions. It offers estimation of the probability of performance failure using mathematical relationship between probability density functions (pdf) of the load parameters.

2. Risk analysis for sustainable development

2.1 General

Risk analysis has become a very important tool in assessment and governance of environmental and societal risks to sustainability. Figure 1 illustrates designing for sustainable urban development. The goal is stated to ensure well being for individuals (space of acceptable solutions is represented by the shaded area) under limitations introduced to prevent or mitigate the high risks (see bounds drawn with dashed lines – models 2). The bounds cut off and diminish the space of the satisfying solutions. The high risks (of great importance to mankind, societies or human beings, usually with catastrophic consequences) are identified by risk analysis methods and if not ignored, result in various decisions towards sustainability. Risk analysis methods are also used in order to ensure people well being (see models 1) for example in built environment or inside the buildings. In this case the appropriate design can be perceived in terms of reliability as the focus is put more on ensuring acceptable performance of the building rather than on defeating high risks.

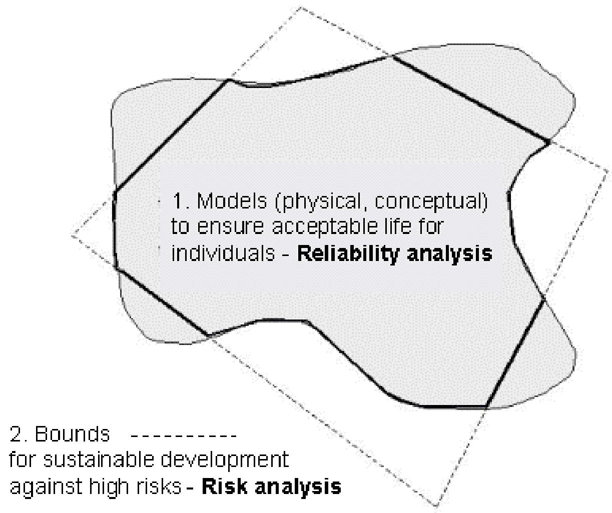

Figure 1 Designing for sustainable development

2.2 Towards quantitative risk assessment

Qualitative risk assessment describes a nature and source of the hazard, identifies alternative scenarios for the risk outcome and the severity of the consequences (McDaniels & Small M.J., 2003). There is a trend for completing the qualitative risk assessment with quantitative evaluation of probability of failure. Likelihood of occurrence of failure events multiplied by their consequences results in quantitative risk assessment. This allows more rigorous comparisons of alternatives. Probabilistic risk assessment offers estimation of the probabilities assigned to the outcome of the model representing variability and/or uncertainty in the model and its inputs.

3. Reliability of building/environment system performance

3.1 Definition of (considerations about) building/environment system

Building performance depends on the structure and the way that it is used, but also on the environmental conditions of the site and the microclimate in a vicinity of structure, which is influenced by the building itself. It supports the idea of using the concept of building/environment system performance. Generally microclimatic conditions outside the structure act as a boundary layer for processes inside the structure and in the building enclosure. But, there is also a reverse influence of the structure on the nearest environment, for example on the wind field in its neighborhood. It can encompass pedestrian discomfort or excessive heat loss through a building envelope, followed by consequences against sustainability in the form of increased energy consumption to warm up buildings or excessive use of motorized transport.

Figure 2 shows interdependence of the processes inside a building enclosure, in a building structure, and outside of a building. Focus is put on the measures important for humans' health, comfort, and energy performance of a building. Quantitative analysis may be used to examine such factors like ventilation, heat loss, moisture performance of building components etc. Many of them are listed within the gray boxes.

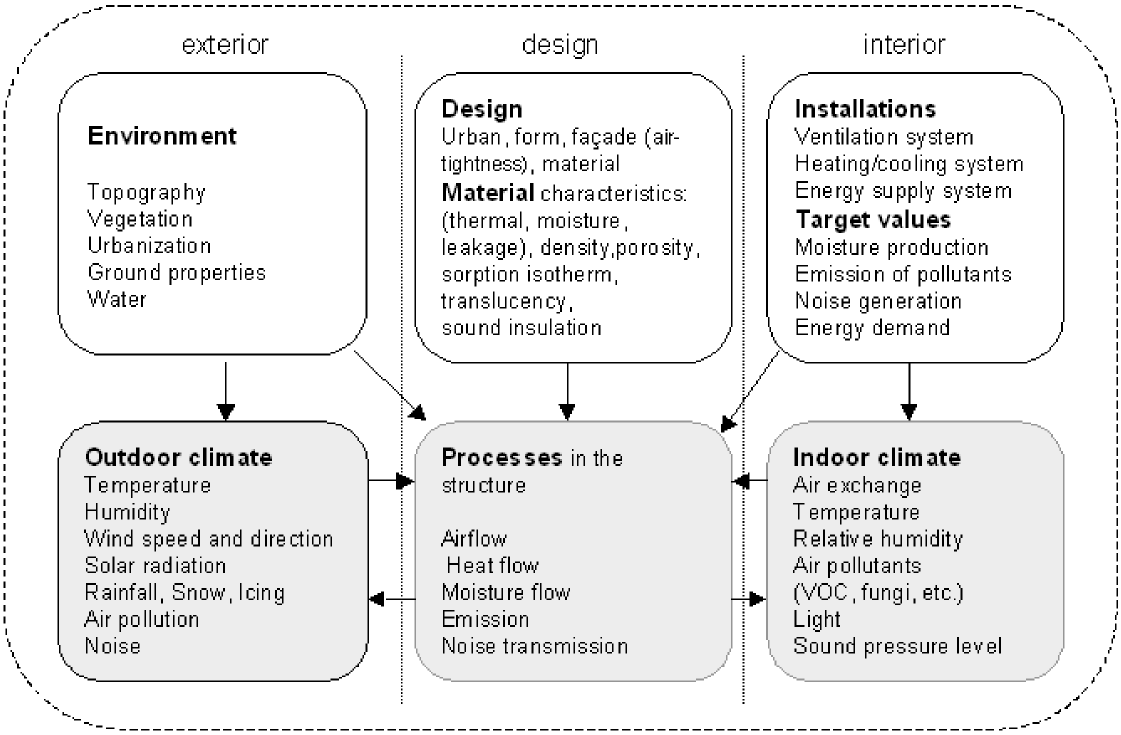

Figure 2 Interdependence of the processes inside a building enclosure, in a building structure, and outside of a building.

3.2 Evaluation of building/environment system performance – methodology

In carrying out a reliability analysis of building/environment system performance, a list of all hazards should be compiled. Those hazards are associated to failure events characterized by some sort of unacceptable serviceability (for example: insufficient air exchange, excessive energy loss, too high sound pressure level). Failure events are usually the consequences of the physical state of the building characterised by the parameters (performance aspects) S not meeting prescribed limits (performance criteria) R as presented in Figure 3. Unacceptable performance caused by air-, heat- and moisture flow through a structure, the illumination conditions, noise transmission, wind/structure interaction etc, can appear in the form of unhealthy conditions (mould growth, emission of irritating compounds from the material), discomfort (insufficient air exchange, esthetical changes of the surfaces, odour, draught, mites propagation, high level sound propagation, insufficient illumination, pedestrian discomfort), damage of the material (changes of physical or chemical properties of the material), and excessive energy loss (for example caused by high wind speed and turbulence around buildings).

In the probabilistic modelling the design variables and parameters are explicitly identified, as well as, load (demand) S and resistance (capacity) R probability distributions are determined (see Figure 3). Probability density function of load S is approximated, taking into account uncertainties of input parameters describing external and internal load and the structure (see fields within dashed rings in Figures: 2 and 3). Fundamentally, two common types of uncertainties may be present in any calculation: uncertainty resulting from the lack of information or uncertainty caused by the natural variability in a parameter. Uncertainties that arise from the lack of knowledge about parameters can be modelled with the help of expert judgement that can lead to assignment of probability distribution. Uncertainties that arise from variability can be modelled with the help of statistical approach if enough data is available (experiments, simulations).

Requirements for the system are specified in the form of performance criteria. The performance criterion R indicating the conditions favourable for a performance failure can be treated as a random variable with the probability distribution function evaluated from the probabilistic approximations based on deterministic function of input random variables, from experiment or by expert judgment. Generally, performance criteria result from the analysis of economic and social costs and benefits. Some of them are defined in the Code of Practice or in the international standards elaborated by International Organization for Standardization (ISO) or European Committee for Standardization (CEN). Minimum air exchange rate, minimum or maximum internal temperature, maximum speed of airflow inside the building, maximum relative humidity, the maximum overall average U-value of a building envelope or the minimum air tightness are examples of type minimum and type maximum limits for building performance parameters.

Reliability of the design is estimated by comparing if the system can carry effect of applied loads without jeopardizing well-being of people. It can be carried out with the help of performance function $Z = R - S$. The state $Z = R_2 - S = 0$ (for maximum type with threshold R_2) or $Z = S - R_1 = 0$ (for minimum type with threshold R_1) divides the response space into safe (positive Z) and unsafe (failure) (negative Z) regions characterized by reliability or probability of failure P_f.

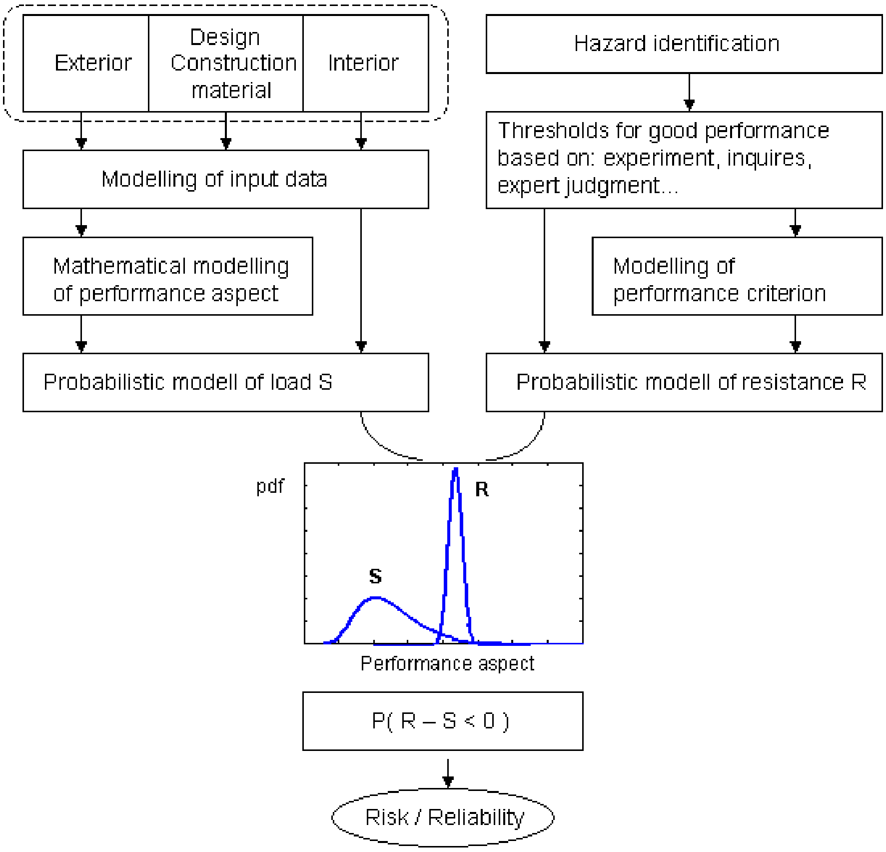

Figure 3 Methodology of quantification of building/environment system performance. Concept of load-resistance model applied (extended) to the problems of unhealthy conditions, discomfort, and excessive energy use

The process of reliability analysis does start with the hazard identification and description of the physical relationships between all influencing parameters. Analysis of the parameters leads to the conclusions about the importance of their variability or/and uncertainty to the investigated response of the system and the decision if they should be treated as deterministic parameters or random variables in the model. The time dependence of the random variables should be examined to choose an appropriate model for the system. The following steps should be performed:

- Description of the hazard of building/environment system performance
- Choice of the performance aspect
- Statement of the performance criterion ensuring that the system meets performance requirement R
- Specification of the mathematical models describing the performance
- Identification of the parameters important in the modelling of the performance
- Description of the uncertainties associated to the parameters
- Sensitivity analysis of the influence of the parameters on the model response
- Specification of the character of the time dependence
- Model formulation (performance functions) on the basis of the physical relationships, input data and time dependence analysis
- Decision on the reliability measures to be used
- Application of the reliability method in order to estimate the reliability measure for the stated hazard

4. Examples

Two examples of estimation of probability density functions (pdf) of heat loss (performance aspect S is presented by power loss (kW)) for two buildings of the same size with different properties of the envelopes and different ventilation strategies are presented. Performance requirement in the form of threshold power loss for heating can be introduced at the deterministic level of R (kW) (see Figure 6). The input parameters, which should be treated as random variables, are selected. They include temperature difference across the building envelope ΔT, thermal transmittance U and air change rate ACH. Probability density function of ACH is estimated in air infiltration model with wind and temperature input variables (Pietrzyk 2005). The modelling flow is shown in Figure 4. Performance function for heat loss Φ is proposed. Final results for the chosen examples are presented in terms of probability density function of power loss. It depends upon the interaction among the envelope construction, the local climate at the site and the chosen ventilation system.

The modelling details can be found in (Pietrzyk 2000). Two cases are considered (see Table 1). The first one for the building envelope working according to the dynamic wall principle with the thermal properties depending on the air infiltration rate when natural ventilation is assumed. The second case includes a tight envelope and balanced ventilation causing the constant (deterministic) air change rate equal to the mean value of the air change rate noted for the case 1: ACH = 0.7. For this case thermal transmittance depends only on the temperature of the material, hence indirectly on ΔT. The examples are calculated for the period when $T_{int}>T_{ext}$ (T_{int}=const) for the house situated in northern Sweden.

Table 1 Description of the calculated examples

Case	Envelope	Ventilation	Air exchange Mean / St.dev.	distribution	$\Delta T = T_{int} - T_{ext}$ Mean / St.dev.	distribution
1	dynamic wall	natural	0.7 / 0.3	lognormal	15.3 / 9.5	truncated
2	tight	balanced	0.7 / 0.0	(deterministic)		normal

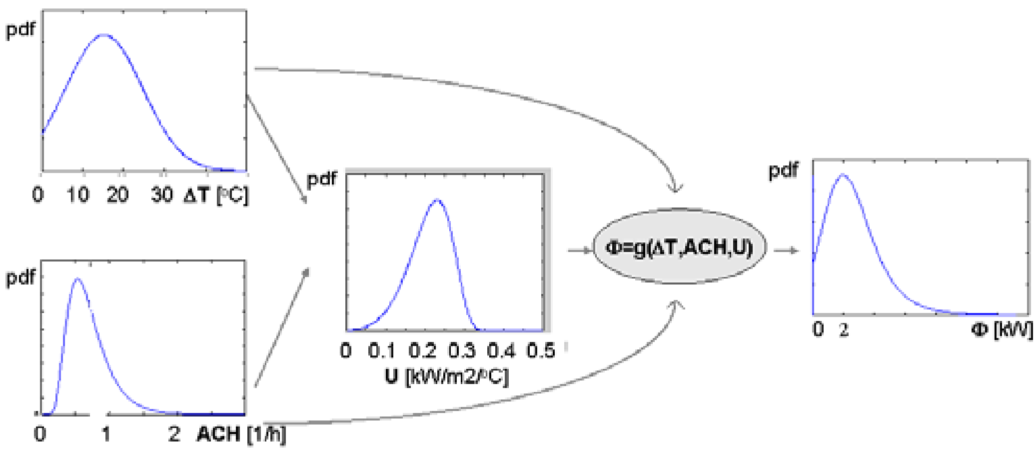

Figure 4 Modelling flow of random variables for estimation of probability distribution function of heat loss (case 1).

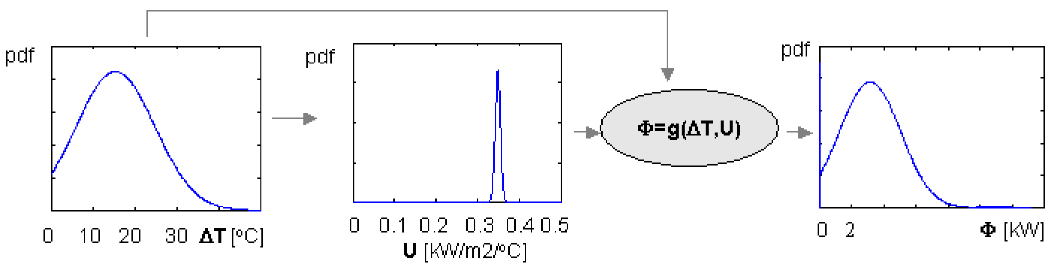

Figure 5 Modelling flow of random variables for estimation of probability distribution function of heat loss (case 2).

The power needed to compensate for heat and ventilation losses is presented in Figure 6 in the form of probability density functions for both cases. Threshold R can refer to the assumed maximum effective power of heating device. If other heating sources are absent, the probability of failure P_f defined as T_{int} decreasing below assumed constant value is equal to the area below the pdf to the right from the threshold. Probability of failure can be translated into the total time during which the prescribed performance criteria are not met.

Case	Reliability	P_f
1	0.91	0.09
2	0.86	0.14

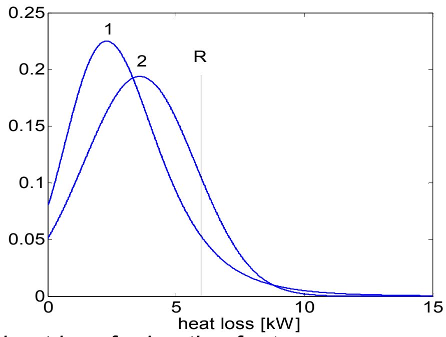

Figure 6 Results of probabilistic approximations of heat loss for heating for two cases: case 1 – naturally ventilated building with dynamic wall, case 2 – mechanically ventilated building (balanced ventilation) with tight envelope.

Comparison of these two options can be carried out in terms of probability of failure or in terms of reliability = 1- P_f. For R = 6.0 kW the results are given in Figure 6. For the assumed sufficient power of heating system, the conclusions about the uncertainty of the energy consumption for heating can be drawn.

5. Conclusions

Risk analysis methods can be used in order to ensure people well being in built environment or inside the buildings. In this context the appropriateness of a design can be better expressed in terms of reliability as the focus is put more on ensuring acceptable performance of the building rather than on defeating high risks.

Quantification of building/environment system performance in the form of probability of satisfying performance is proposed. It gives opportunity to probability-based approach in the design process relying on estimation of the reliability of a building performance for the alternative designs. It also allows obtaining the reliability-based assessment of existing buildings exposed to the changed conditions (climate change, local climate change due to urbanisation etc.) in order to promote the sustainable solutions.

A probability-based evaluation of building/environment system performance delivers an input to the risk-management models. The risk-management models prioritising different requirements should be developed.

6. Acknowledgment

Financial support of The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning FORMAS is gratefully acknowledged.

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