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BUILDABILITY AS TOOL FOR OPTIMISATION OF BUILDING DEFECTS

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Defects in buildings harm the reputation of the construction industry and the amount of defects is believed to represent a loss in economy. The purpose is to study whether the buildability concept could serve as an efficient tool for reduction of defects. The project includes a literature study and the development of a technical-probabilistic perspective on the building process in which an optimal amount of defects exists. Three levels of risk are defined as a basis for proposing strategies for forming rules for optimisation of defects. It is concluded that a dynamic and flexible approach is needed, because different rules apply to different situations during the building period and because the economic potentials in better planning and in savings by a reduction of defects are different for different types of buildings.

KEYWORDS: buildability, buildings, defects, risk.

INTRODUCTION

The study of defects in buildings is important in Danish building research, partly based on interests from the construction industry and the authorities. One reason is that defects are often exposed in public media harming the reputation of the construction industry. Another reason is that the costs caused by defects are believed to represent a considerable loss in the economy, about 10 pct of the turnover in the construction sector (Nielsen et al, 2004).

A simple attitude to the reduction of defects is to map the number of building defects for different alternative technical solutions and then, in future designs, avoid those with a high score as non-buildable. However, this strategy may not lead to an improved economy, because an alternative technical solution may be considerably more expensive or have a poor building performance. Taking further into account that innovative solutions normally contain more defects than traditional ones, this simple attitude may block for innovation and long term improved performance in building construction. The purpose of the project is therefore to study whether the buildability concept, based on a technical-probabilistic perspective on the building process, offers a more adequate approach.

The term *defect* is used as a common term for a *physical defect* and for a *process defect*. It is considered *a physical defect* when *project documentation, a building material, a structure or a part of a structure lacks abilities which can be expected according to the construction contract, public requirements or good building practice*. It is considered *a process defect* when *the construction process takes place in a way that represents a significant loss in resources or time in comparison to an optimal process*. This means that a defect is seen as a technical problem independently of the cause for the defect and independently of when the defect is observed, which may be before, during or after the construction period. The economical consequence of a defect is either a direct cost to make up for the physical defect or for doing the work in a less efficient way, or an indirect cost, mainly as consequence of a delay in the construction process or as a reduced service life.

THEORETICAL FRAMEWORK

The theoretical framework consists of a perception of the building process being a probabilistic process, risk assessment, the engineering method, buildability, and quality management. These elements are presented, in some cases developed, and discussed.

A probabilistic perception of the building process

The building process is perceived as a process with many possible paths leading to a finished work, see Figure 1. The full lines represent successful processes which end up in an acceptable solution. The doted lines represent processes which either end up being corrected or continue until finished work as a solution with defects. It may or may not be known to the building contractors that a defect is present in the solution. The solid dots indicate decision points, which are points where the further process may follow different paths, including going back. Decisions are taken by people involved in the building process at all levels. People may or may not be aware of the presence of a decision point.

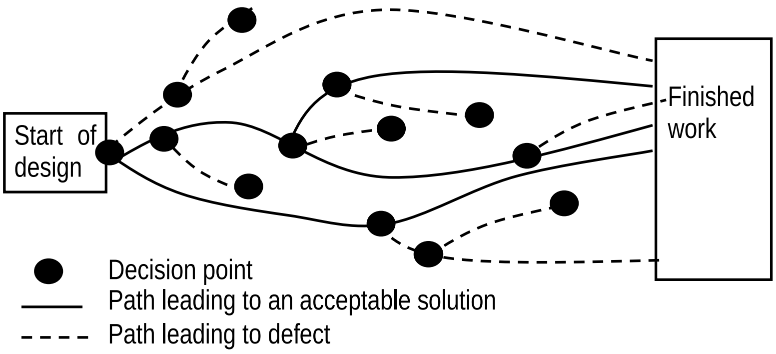

Figure 1: Perceived building process. Possible paths between start of design and finished work.

A building can be seen as a collection of a number of solutions (roof, walls, floors, bathroom, etc.). The number of decision points and of potential possible processes is huge. A deterministic view implies that, in considering all those potential processes, an optimal design may be developed, described and communicated to people involved in the building project so that no mistake is done. If not impossible in practice, such a deterministic approach will obviously be extremely expensive.

A probabilistic approach offers a more realistic view. It considers that design and planning must stop at a certain stage and that some decisions concerning details are to be taken in the construction phase. In this approach the expertise at the construction site is used. Seen up front it is then accidental exactly which process and which solution will be realised. This perception fits well with a probabilistic view on the construction process as illustrated in Figure 2.

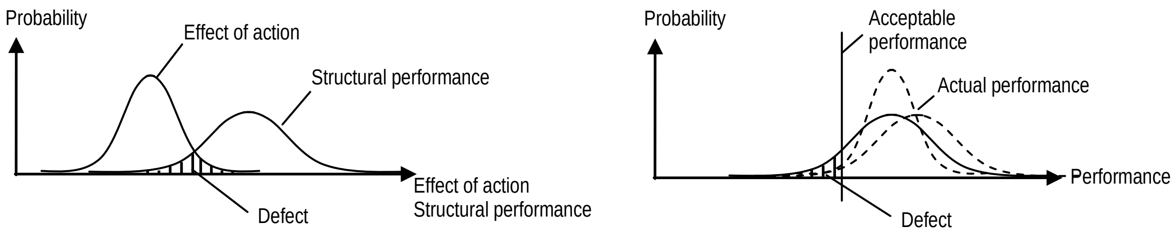

Figure 2. The probability of a defect is illustrated as the area below two curves showing probability distributions (left), one showing the effect of action (e.g. from an earthquake) and the other showing the performance of the realised structure (e.g. the strength of a wall). A defect materialises when a relatively weak structure is subject to a relatively large effect of action. The figure to the right shows the situation when an acceptable performance is just a matter of a simple measure. The probability of no defect may be improved by prescribing a better performance or by more emphasis on quality management leading to a smaller statistical variation in the outcome.

The probabilistic perspective has the following implications for evaluating risk of defects: 1) Defects are associated with decisions, and decisions are made at all levels and through the whole building process. Decisions taken at the construction site are often associated with a time pressure because the costs related to a halt may be large (Haugbølle and Forman, 2009), and decisions may be based on a high or low level of information concerning the decided solution as well as the possible consequences for the further construction process. Decisions may correct faulty design solutions and thus prevent defects. They may also lead to defects, typically if the decisions are taken due to lack of materials or lack of equipment and the consequences for the further process are not foreseen (Jørgensen, 2009), (Kreiner and Damkjær, 2009). 2) Efforts to prevent defects are oriented towards a process which is only partly known. Therefore, tools for a reduction of some types of defects have to contain rules that in general reduce the likelihood for defects rather than aiming at preventing a specific one. The rules must relate not only to technical solutions but also to the circumstances for construction (weather, organisation, worker skills, etc.). 3) Experience (learning) is gained only on processes which has been realised. Knowledge about alternatives which are seldom realised is therefore limited and sometimes unreliable. Furthermore an observed defect may be just one out of a large number of successful similar processes with no answer to why the defect is found in that particular case and not in other cases. Therefore learning from experience must involve statistics or calls for a very cautious and careful interpretation.

Risk assessment

Defects are here categorised by their consequences. Three risk levels are considered: Risk for lives and health, Risk for large economic losses, and Risk for small economic losses.

The acceptable *risk for life and health* is prescribed in building regulations which normally refers to standards. The formal acceptable probability of a defect is of the order of magnitude of 10^{-7}. An example is the safety of load bearing structures in which a defect may lead to a catastrophic collapse during construction or after. Defects of this category are seldom, they call for specialist knowledge to be prevented, and they are normally impossible to detect just by inspection. Preventing measures like project revision must therefore be part of a formal procedure to be carried out before start of construction.

The acceptable *risk for large economic losses* is not regulated by law, and although insurance companies are typically involved, the numbers of defects and the economic consequence of these are not well known. It is assumed that an acceptable probability of a defect is of the order of magnitude of 10^{-4} to 10^{-5} if the economic consequences are between 0.1 and 1 Million €. Defects of this type originate often from the design. BRE has estimated that 90 % of building design errors arises because of failure to apply existing knowledge (CSIRO 1986). Most of these defects will not be detected in time if they are not identified before start of construction. In some cases the insurance companies may require formal quality management, including a review of the design.

Risk for small economic losses covers many types of defects from small damages, which may be considered only an aesthetic problem, to defects which change the technical performance and must be corrected. The associated costs do not normally lead to an involvement of insurance companies. An acceptable probability of such defects may be decided by the contractor on a purely economic basis. The optimal amount of defects may in some cases correspond to a probability of existence of the order of magnitude 10^{-2}. Most of the defects are identified by the companies involved in the building process and corrected during the process (Nielsen et al., 2004). Because each defect has a small economic consequence it may look as if it is not important to try to avoid it. However, the total economic consequence of defects is almost exclusively caused by defects of this category because they are so numerous. They are found in every project and therefore they may be studied more systematically, using statistics, and in more details than defects in the two other categories.

This differentiation in risk levels calls for a flexible approach to risk assessment with rules that focus on different phases of the building process. Defects of the first two categories - the serious ones – call for formal tools and regulation, while the third category more or less may be considered an internal matter subject to economic optimisation based on rules of thumb.

Bayesian Networks is a rigorous decision tool used in relation to large engineering problems (Jensen, 1996). Practical use of the model involves a considerable investment for developing a probabilistic model of the decision process for an actual construction, including alternative solutions, and for collecting statistics concerning the probability of defects including cost consequences for the different alternatives. FMECA, Failure Modes, Effects and Criticality Analysis, is a similar method, which in relation to buildings has been used for service life prediction of building materials and components (Talon et al. (Eds.), 2006). It is not considered realistic to use these tools in connection with design and construction of a specific building, but the systematic approaches and the basic understanding are considered a good starting point for an engineering judgement of a complicated problem. In their report on risk, uncertainty and decision-making Willows and Connel (2003) focus on decisions related to climate change adaptation on a wide scope of complex problems. Decisions in relation to these problems have different nature, and one universal tool, adequate for all types of problems, has not been found. Instead reference is given to about 50 tools and techniques, from simple expert judgement to Bayesian methods. These tools are taken from risk assessment literature in general and are equally relevant for the construction sector.

The challenge therefore is to match a risk assessment problem with an adequate and economic method.

The engineering method

Koen (2003) defines the engineering method as *the use of heuristics* (common sense rules) *to cause the best change in a poorly understood situation within the available resources.* In this perspective the effort in planning shall be seen together with the likelihood for a successful process in a way that the total costs for planning, construction and correcting defects are minimized, see Figure 3. Rigorous risk analyses will be more relevant for large off-shore structures than for ordinary buildings, where rules of thumbs in many cases will have to do.

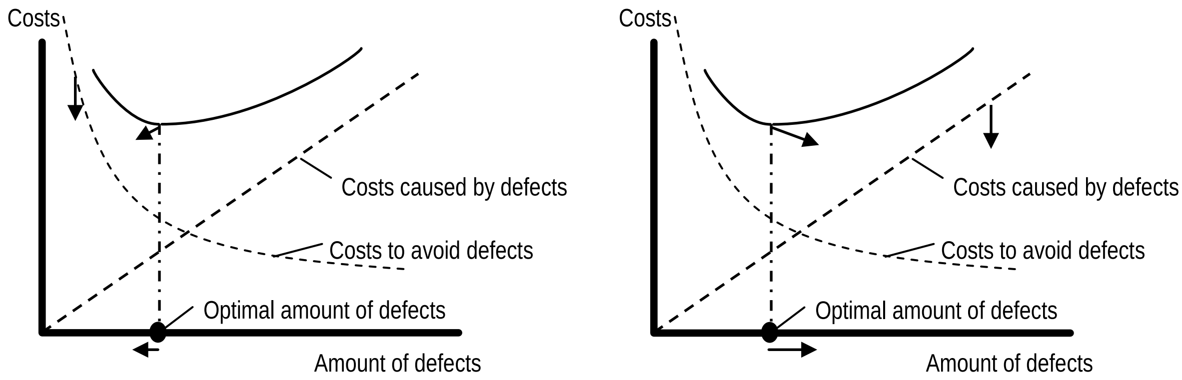

Figure 3. Optimal amount of defects. More efficient rules for a reduction of costs to avoid defects lead to an optimum at a lower amount of defects (arrows in the left figure). A reduction of costs caused by defects leads to an optimum at a higher amount of defects (right).

Buildability

Building projects have become very complex, and in most cases design and construction are more or less separated from each other and performed by different companies. This has lead to many examples of defective designs, i.e. designs that were not possible to perform or that needed redesign before it became buildable, resulting in delays and/or overrun budgets, e.g. (Glavinich, 1995), (Glavan and Tucker, 1991) and (Lutz et al., 1989).

In the late 1970s *buildability* emerged as an area of research, based on the assumption that buildability problems exist because of the comparative isolation of many designers from the practical construction process (Chen and McGeorge, 1994). A widely accepted definition of buildability is: *the extent to which the design of the building facilitates the ease of construction, subject to the overall requirements for the completed building* (CIRIA, 1983), focusing on how to improve the productivity in spite of the complexity of a building project. This definition was criticised for its narrowness in scope, in that it essentially confined buildability to the design process (Wong et al., 2007). Nevertheless, the achievement of good buildability depends upon both designers and builders being able to see the whole construction process through each other's eyes (Adams, 1989).

Chen and McGeorge (1994) conclude that a workable concept of buildability needs to recognise the many factors in a project environment which has an impact on the design process, the construction process, and the link between design and construction. They suggest that buildability might be redefined as: *The extent to which decisions, made during the whole building procurement process, ultimately facilitate the ease of construction and the quality of the completed project.* In accordance with this Glavinich (1995) states that the efficiency of a set of construction documents can best be measured by how easily a building contractor can meet project milestones set by the owner. This requires the architect/engineer to consider local conditions and construction practices as well as the availability of labor, materials, and equipment in the design.

Guidelines for buildability or constructability aiming at improving the productivity can be found in several references, e.g. (Adams, 1989), (Chen and McGeorge, 1994), (Nima et al., 1999), (Fox et al., 2002), (Lam et al., 2007). In Singapore, buildability has become part of the legislation or code of practice (BCA, 2005). A minimum Buildability Score is required for the building plan approval. The Buildability Score is a simplification of the buildability concept, acknowledging that the buildability of a design is a qualitative concept that is difficult, if not impossible, to measure objectively (Glavinich, 1995).

As a corresponding term, *constructability,* was introduced, widely cited as *the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives* (CII, 1986). Based on a comprehensive literature study, Wong et al. (2007) concluded that constructability is concerned with the whole process of project development to facilitate construction efficiency and achieve project goals. By contrast, buildability deals mainly with construction efficiency seen at the design stage.

It is generally acknowledged that buildability can give rise to better construction quality and productivity, but no concrete evidence has so far been presented to suggest that this is indeed the case. One of the main reasons for this lacuna is the lack of quantifiable measures for buildability, quality and productivity which make it possible to analyze their correlation meaningfully (Low, 2001).

Buildability – a definition related to defects

Buildability and constructability are both connected with 'ease of construction' which is highly relevant for an evaluation of risk of defects. However, buildability further is connected with 'design' and 'efficient and economical construction', while constructability is connected with 'integration of construction knowledge and experience' and 'optimisation'. Furthermore, by focusing on the quality of the completed project and on meeting project milestones set by the owners, the definition of buildability (CIRIA, 1983) to some extend limits the scope to evaluation of contractors for design-build projects and to defects in the *final* product, while the by far largest amount of defects, identified and corrected *during* the building process is not considered. Procurement types, such as design-build, public-private partnership (PPP), and private finance initiative (PFI), are expected to have an effect on the amount of defects, but an analysis of such an influence has not been part of this study.

In order to focus on defects the definition of buildability is therefore modified to: *The extent to which the management of the building process, the design, the skills of the workers involved and the circumstances at the construction site decreases the probability of a defect, either during construction or in the completed building*. This definition combines aspects of the CIRIA-definition of buildability (review at an early stage) with the wider perspective of the term constructability, e.g. (Glavinich, 1995), (Adams, 1989) and (Chen and McGeorge, 1994) as well as the definition of a constructability program as found in (ASCE, 1991).

Quality management

(ISO, 2008) introduces quality management in general terms: *At suitable stages, systematic reviews of design and development shall be performed in accordance with planned arrangements, a) to evaluate the ability of the results of design and development to meet requirements, and b) to identify any problems and propose necessary actions*. Low and Abeyegoonasekera (2001) conclude that the ISO 9000 quality management system can function as an effective and appropriate working platform for buildability. However, guidance is given only at a very general level, which is not directly applicable to practice.

IMPLICATIONS OF A TECHNICAL-PROBABILISTIC PERSPECTIVE

In line with the probabilistic approach, it is acknowledged that it is impossible to make a complete list of all elements with an impact on the amount of defects. Furthermore, one universal tool for a reduction of the amount of defects does not exist, and it is not economical feasible to arrive at zero defects in a building process. Therefore, different strategies and approaches should be adopted, dependent on the type of risk and which part in the building process they address.

An overall observation is that quality management according to (ISO, 2008) may serve as an adequate framework, but it must be detailed for use in practice. It shall not be implemented as a rigid system increasing the general formal planning and documentation at all levels, but as a flexible tool which reflects different types of risk elements.

Another observation is that buildability with a strong focus on evaluation of risk of defects seems adequate as a platform for formulating rules leading to an optimum of defects. In agreement with the engineering method, such rules may be as simple as just rules of thumbs, while in other cases guidelines or even law requirements are needed. The rules must concentrate on the most important matters, in order to efficiently direct the effort to elements with a high risk and suggest correcting actions with a high probability of leading to a reduced amount of defects. Many of the elements in existing guidelines for buildability or constructability are relevant in this context, e.g. 'consider access', 'use suitable materials', 'design for skills available', and 'simplify construction' (Adams, 1989).

Furthermore, the tool must represent a balance between the resources used on preventing defects and the consequences of defects, see Figure 3, and the rules must be flexible, dynamic (change with time) and multi-focused (a wide search for origins of risks):

Flexible, because 1) defects are associated with decisions, and decisions are made at all levels (different professions) and through the whole building process, 2) the risk profile and available resources are different from case to case (large buildings – small buildings, design/build – separate trade – PPP – PFI contracts, etc.) with a need for formal rules for categories of high risk and rules of thumb for risks with small economic losses, and 3) the rules shall address different actors. The authorities have a primary interest when it comes to risk for life and health, while risk for large economic losses involves insurance companies as a primary part. Risk for small economic losses is mainly a matter of interest for the parties directly involved in the building process: client, designer and contractor, including construction workers.

Dynamic, because specific risk elements change with time due to new experience (learning, partly based on statistics) and developments in new types of structures, industrialisation, IT, management systems, and education.

Multi-focused, because the risk related to a specific technical solution may depend on management, the design/complexity of the solution, worker skills, and conditions at the construction site. They shall be seen in the perspective of the whole building process as well as in the perspective of a specific technical solution.

The rules shall act as aid in decisions concerning correcting actions, including the use of an alternative – maybe more expensive – solution, se examples of rules in Table 1. It is a management responsibility to ensure that the person, who uses the rules, has sufficient insight and knowledge. However, the introduction of unspecific experience includes an extra risk element (Kreiner and Damkjær, 2009).

Table 1: Examples of elements associated with the management of risk of defects.

	Risk element	Corrective actions
Management	The skills of the people at all levels of decision making does not match the complexity of the chosen technical solutions, and the conditions at the construction site	Another solution, other people or instruction Ensure good access to technical guidelines and law requirements at all levels
Design or technical solution	New types of technical solutions	Critical review of the solution. If necessary get an expert evaluation e.g. a criticality analysis or a risk assessment
Worker skills	Decisions at the construction site under time pressure and based on limited information about consequences of changes	Use experienced staff
Construction site	Difficult weather conditions	Use weather protection systems

Can evaluation of buildability, in practice, significantly improve the likelihood of few building defects? Can the costs for evaluation and for defect preventing measures, including the possible choice of an alternative design, be kept small enough to ensure an increased productivity? Due to the nature of the problem no final answers can be given, but the analysis suggests that it is possible to move to a more optimal amount of defects according to Figure 3 by obeying to the approaches as presented. This may include development of specific tools and guidelines, especially for project reviews at the design stage in order to reduce the risk for large economic losses. However, the challenge is to develop a set of different rules of thumbs to be used at different stages during the building process in order to reduce the many risks for small economic losses.

CONCLUSION

A technical-probabilistic perspective on the construction process is developed. It implies that there is an optimal amount of defects.

A redefinition of the buildability concept with a stronger focus on defects is suggested as a necessity for buildability to become an efficient tool in the optimisation of defects.

Three levels of risk are defined as a basis for proposing strategies and rules for evaluation of risk of defects.

It is found that the approach for forming rules for optimisation of defects shall be flexible, dynamic and multi-focused for the following reasons: 1) decisions associated with defects are made at all levels and through the whole building process, 2) the economic potentials in better planning and in savings by a reduction of defects are different for different types of buildings, 3) the challenges in construction changes with time, and 4) risks may originate from the type of contract, management, the design/complexity of the solution, worker skills and conditions at the construction site.

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