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INVITED PAPER

Scientific basis and rules of thumb in civil engineering: conflict or harmony?

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Abstract. Science and engineering intermingle in the area of construction. Engineering works, often of great dimensions and design life cycle of many decades, have to be designed on a scientific basis since the safety of hundreds of users depends on their design. The task of scientific institutions is to define the construction performance within categories that correspond to the contemporary level of knowledge and technology. A construction appraiser who speaks out in a way that ensures unquestionable competence about the performance of elements and buildings (existing and under construction), should be convinced of the scientific basis of his opinions. A comparison of construction sections vs. basic requirements presents an archetype of the science of construction. A matrix of the science of construction reveals its multi-faceted nature; if related to time – the issue of durability has to be considered, and if related to the scale – the complexity. Defining the construction performance in terms of technical features is a constant search for a relationship between the material model and the usability model of a building. The construction industry uses a lot of "rules of thumb", more than any other sector of technology. In the era of computer-aided design, CAD, and building information modelling (BIM), those rules of thumb remain invaluable verification tools.

Key words: building performance, appraiser, matrix of the science of construction, rules of thumb, durability, complexity, diversified development.

1. Introduction

It is better to be roughly right than precisely wrong.
J.M. Keyness, 1924

The design of a construction or the evaluation of the performance of buildings and construction elements in a way that ensures unquestionable competence should be scientifically based. This is even more important as such evaluations often concern large-scale engineering works, which determine the safety of many users and a design life cycle of many decades. This is even more important today, when well sustainable development requirements and necessities are imposed by building laws. Aiming at ensuring the durability and reliability of buildings means that almost all of them have to be controlled in the course of design, construction and use. The issues of infrastructure security and sustainable development should be considered more broadly as well. Given that at present many buildings are entering a period of a high degradation rate due to their age, that disasters such as floods and fires occur more often, and also that some buildings and structures such as nuclear installations, dams and dikes, present a significant permanent risk for the environment, thus requiring monitoring from the very beginning of their operation, the appraisal issues cover an ever broader field of expertise. This requires a constant intake of new knowledge.

The issues included in the title of this study were partially presented in the monthly *Materiały Budowlane* [1] in an article titled "Shaping the scientific basis for the development of the construction industry" published in connection with the 70th anniversary of the Building Research Institute.

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2. Defining building performance

The primary task of universities and research institutes in the scientific discipline of construction is to continuously define building performance in a manner consistent with the current level of knowledge and technology. This means permanently seeking true solutions [2] – the relationship between the two corresponding models [3]: the material model (material model is used here to represent materials, analyses and geometries) and the usability model, which combines properties and requirements (Fig. 1).

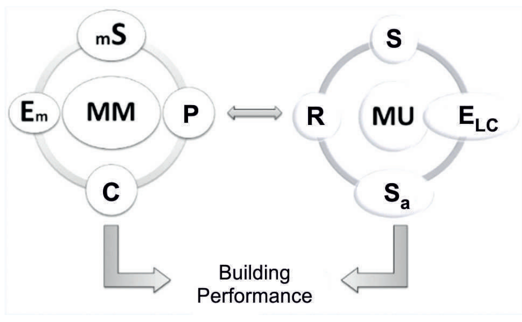

Fig. 1. Relation between material model (MM) and usability model (UM): P – properties, mS – microstructure, E_m – energy (material manufacturing), C – components; R – requirements, S – structure, E_{LC} – energy (life cycle), S_a – serviceability [4]

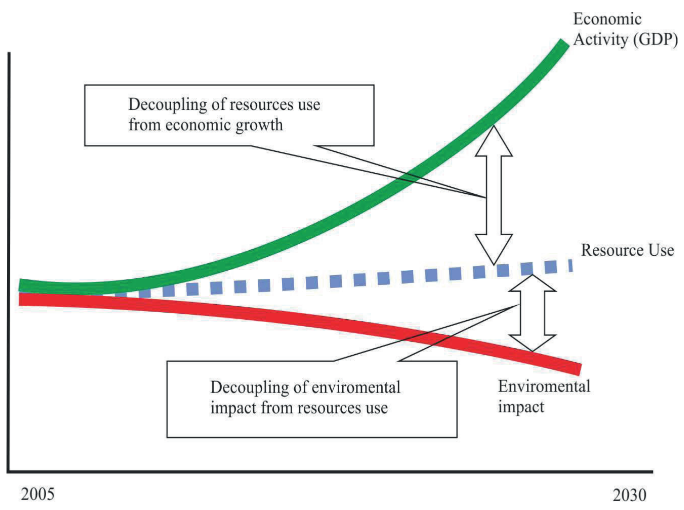

Fig. 2. Ideological presentation of sustainable development: ensuring the growth of GDP (share of construction > 10%); only a slight increase in the consumption of resources; reducing the impact on the environment. Modelled according to Illomaki [6]

The solution should be contained in the E3-space (energy × ecology × economy), i.e. within the limits of minimum energy consumption during the entire "cradle to grave" cycle, of minimum impact on the environment and within the economic rationale, ensuring the functionality and the comfort of use as well as meeting the basic requirements (see Fig. 4). In other words, the solution should comply with the requirements of sustainable development (Fig. 2) [4]. Two key assumptions are important here:

- the supremacy of the demand for performance (Fig. 3),
- the minimization of criterial features.

The material solution should be formulated in terms of product characteristics (functionality and aesthetics), rather than its specific components and/or materials. We shall be guided here by the 90-year-old idea taken from the US Building Code, 1925 [5]: "Wherever possible, the requirements should be formulated in terms of performance, based on the research results referenced to the performance conditions, and not in terms of the material referenced to the components and the method of preparation. Otherwise, any new material or new material systems (new sets of already known materials) that could meet the technical requirements and are satisfactory in economic terms, will encounter barriers that would slow down the technological progress".

This principle is being adopted in the European construction industry very slowly. It was not until 10 years ago in the Concrete Standard PN-EN 206 that it became acceptable to define concrete in accordance with its properties: concrete designed by performance as an alternative to concrete prescribed by its composition.

Minimisation of criterial features means that we need to draw conclusions from the fact that it is the user who will pay for the unused technical characteristics, both related to the quality (unnecessary features) and the value (excessive range). Rational performance criteria are the choice of both the features (size) and the numbers / criterial ranges (value). At the same time, not all of the required characteristics will need to be verified. Aggregated features may appear, and the decision regarding a further research programme is taken only once it has been determined whether these features have been met or not.

Assessment methods are subordinated to the performance criterion. We should pay special attention here to the aspect of credibility – that is the uncertainty which may accompany the

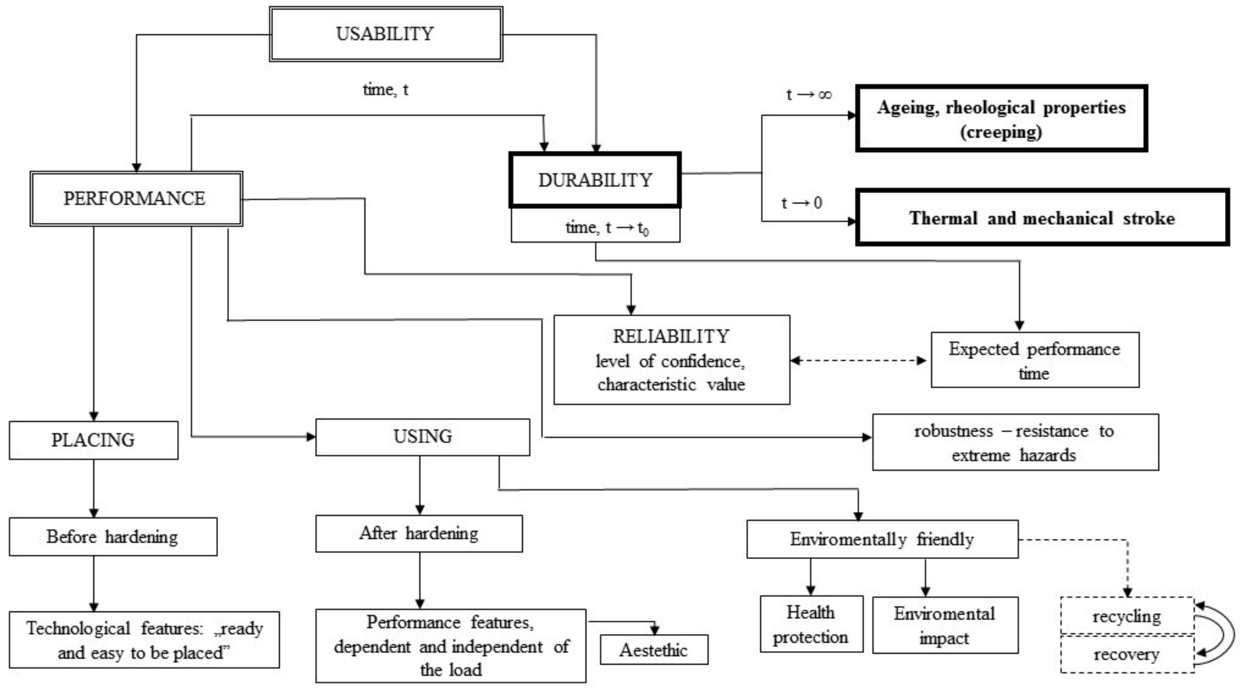

Fig. 3. An example algorithm for formulation of the assessment criteria of the construction product usability (t_0 – expected performance period) [9]

Sections / Basic Requirements	Geotechnics/ Foundation Works	Structural and Material Mechanics	Construction Materials Engineering	Construcion Physics	Civil and Engineering Structures	Sanitary Engineering	Fire Safety Engineering	Enviromental Impact Engineering	Construction Undertakings Engineering	Communications Engineering
Mechanical Resistance and Stability	★	★	★		★		★			
Hygiene and Health, Enviroment	★		★	★	★	★	★	★	★	
Safety of use		★	★	★	★	★	★	★	★	★
Fire Safety		★	★	★	★		★			
Protection against noise	★	★	★	★	★	★		★		
Energy Saving		★	★	★	★	★		★	★	★
Sustainable use of resources	★	★	★	★	★	★		★	★	★
Durability	★	★	★	★	★	★	★	★	★	★

Fig. 4. Archetype of the science of construction

result [7], and, therefore, the number of repetitions or sampling [8] and, consequently, the cost of the assessment. In general, heterogeneous products are used in construction. It is important to strive to obtain accurate values, i.e. average values converging to real and precise values, which means repeatable and reproducible results. The task of an appraiser is to read these criteria and conduct an assessment in a manner suited to a given building.

3. Matrix of the science of construction

Construction is of a multi-faceted nature. How the ten sections of construction, listed horizontally in Fig. 4, deal with seven basic requirements listed vertically in Fig. 4, may be assumed to be the archetype of the science of construction (Fig. 4). Due to the functions and safety guarantees which buildings have to fulfil, the Basic Works Requirements [10] have always been formally and legally imposed to the construction industry since the times of Hammurabi [9].

Specifically in construction the design and execution engineers face a fascinating challenge with relation to time – durability, and in relation to space and size from nano- to kilometres. There is no other engineering field where the life cycle of the engineering work can be measured in multiples of the creator's life. The durability requirement is usually over 50 years, and often buildings are expected to have even longer life cycles (monumental buildings). This means that it is not enough for a building to meet the requirements at the time of testing. We need to ensure that it will also meet those requirements in the future: for how long are the performances assured? The building service life must be predicted: a prognosis of service life is needed [11, 12]. This is an extremely complicated issue. At the engineering level, for instance, more than 30 factors can be mentioned which affect the durability of concrete structures (Fig. 5).

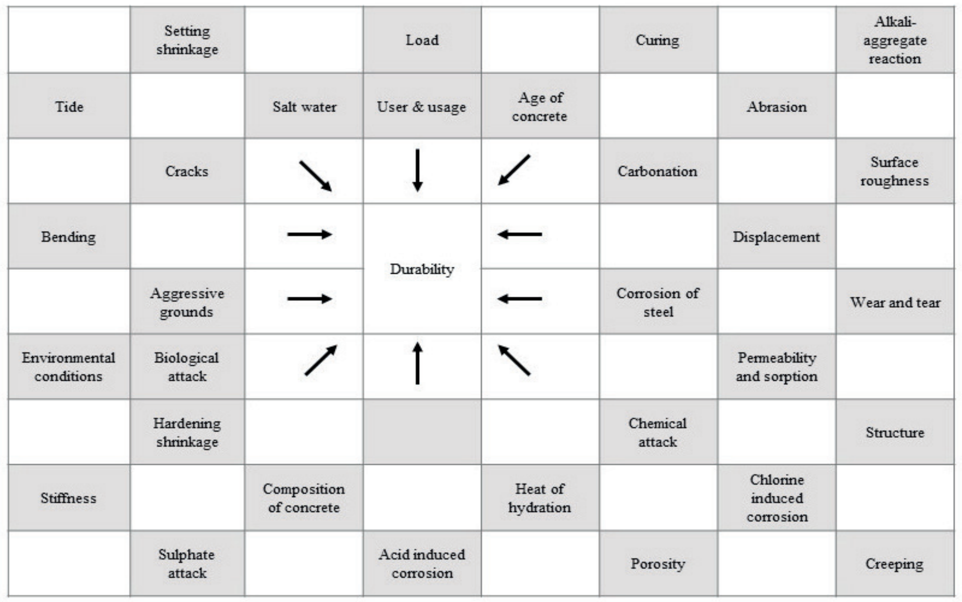

Fig. 5. Factors which affect the durability of concrete structures – engineering level (according to Engineered Material Solutions, EMS)

A huge development of diagnostic methods is occurring. In 2015, a special issue of the *Bulletin of the Polish Academy of Sciences: Technical Sciences* dedicated to diagnosis and durability of buildings was published [13]. Studies published in that issue: K. Flaga [14]; Z. Owsiak et al. [15, 16]; Z. Rusin et al. [17]; L. Czarnecki, P. Woyciechowski [18]; B. Goszczyńska et al. [19]; K. Wilde et al. [20]; A. Garbacz [21]; Z. Hoła [22]; M. Iwański [23]; A. Szydło [24]; A. Piekarczuk et al. [25]; M. Kolbrecki [26]; D. Kowalski et al. [27] are considerable evidence of achievements and research ambitions in this area.

In civil engineering we are facing a wide scope of research topics, on objects with sizes spanning 15 orders of magnitude. At the nano level (10^{-9} –10^{-7} m) we form the properties of a material, at the micro level (10^{-7} –10^{-5}) – we form the microstructure and recognise flaws that define performance and durability, and at the engineering level (macro: $>10^{-1}$ m) we produce building components and erect and use the building. Size versus complexity determines how complicated the research issues are which we face in civil engineering area (Fig. 6). In the engineering of construction materials, there is also a tendency to control the properties at an ever lower – more subtle level of the microstructure:

- µm – in ordinary concrete technology,
- nm – in high-performance concrete technology, including polymer-cement concrete,
- at the atomic level in ceramics.

When considering the construction – environment relationship [29], it is worth mentioning that:

- 70% of utilised matter (in particular energy) is absorbed not during erection, but while the building is used. Hence the demand for an overall assessment of a "cradle to demolition" type, and the demand for reuse, recycling, use of recycled and waste materials, as well as environmentally friendly operation. Once again this emphasises how important it is to define performance in accordance with technical characteristics, not with the composition;
- construction consumes more than 40% of the produced energy;

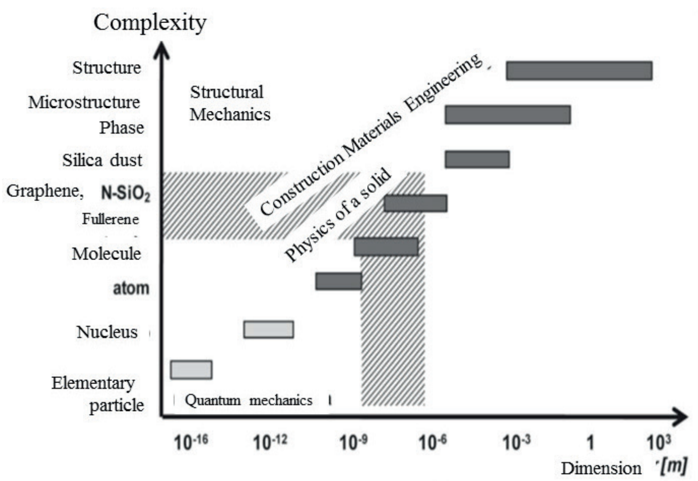

Fig. 6. Schematic representation of the complexity of the research issues at the level of "size-complexity"(according to [28])

- approx. 50% of weight of the materials being processed;
- over 30% of total water consumption (7% irretrievably);
- emits 35% of greenhouse gases;
- produces 30% of waste.

Assigning construction to the rules [6] of sustainable development is therefore a necessity of civilisation. Whereas in the EU only from 1st of July 2013 the sustainability requirements became obligatory, very soon after, in 2015, this argument was reinforced with transcendental considerations. The Holy See (Sancta Sedes in Vatican City) issued the "Laudato Si': On Care For Our Common Home" encyclical (18 June 2015). The encyclical points out the need for a new dialogue about the future of our planet and the recommendation to avoid ecological misconduct.

4. Rules of thumb

Science and engineering intermingle within the scientific discipline of construction and sometimes it is difficult to determine the demarcation line. Radomski [30] points out that "discovering the new is a scientific action, and seeking improvement or an increase in the scale and scope of applications of the known is a technical action". Furthermore, as shown by the quoted matrix (Fig. 4), there is a great diversity of problems in the construction area. All these considerations mean that the construction industry uses a relatively large number of "rules of thumb" [31–35], perhaps even more than any other sector of technology [36]. These rules, known as the "rules of thumb", have been formed due to many years of observation and experience, thanks to which correlations were found between different properties of a given substance or between different substances, as well as between various factors within a given process.

In the past, a classic illustration was the paradigm to design effective roof waterproofing protection: a three layer felt flat roof using cold adhesive. The classic rules of thumb include an indication that the minimum dimension of the concrete element should be three times as big as the maximum aggregate grain to avoid concrete pouring problems as well as to obtain a quasi-homogeneous material. The classic scientific rules may include the Bolomey equation, whereby it is possible to determine the compressive strength of concrete based on the water / cement (w/c) ratio. Concrete technologists, knowing the concrete compressive strength, may "intuitively" estimate most of the other technical characteristics of this concrete (in a group of types of ordinary concrete). A technologist also knows that if a hand immersed in the sand comes out dirty, the clay content is beyond the acceptable level. They also know that adding 4 litres of water per m³ to an ordinary concrete mix would increase the slump (consistency) by approx. 25 mm, and would reduce the compressive strength by approx. 2 MPa, and would increase the shrinkage by approx. 10%. Similarly, increasing the air content by 1% would cause a decrease in the compressive strength by approx. 1.5 MPa. It should be noted, though, that concrete additives are unable to change a poor concrete mix into good concrete, they are only able to make better concrete out of a good concrete mix.

The Arrhenius rule, which has obtained scientific status, states that a 10 degree increase in temperature doubles the rate of a chemical reaction, i.e. the reinforcement corrosion rate is twice as high. Recently, the Arrhenius equation has been recommended [37, 38] in modelling of concrete maturity, which enables the calculation of concrete strength development in the given combination of temperature and time [39].

The Boyer-Beaman rule is not as widely known, although it says that the ratio of glass transition temperature to the melting point in a polymer is a constant value, $T_g/T_m = \text{const}$. Within the heat treatment of concrete we may consider a series of rules (Saul, Ganin) which reduce the setting time. In relation to massive structures it is known that each 10 kg/m³ increase in the content of cement in the mix would cause an increase in the temperature of the "fourth day" by 13 degrees, which is important for cold weather concreting.

Design of spillways in hydraulic structures largely relies on experimentally derived formulas. As an example, Flamant's simplifying formula [40] gives the discharge of water through a rectangular spillway as a function of the water head H, Fig. 7.

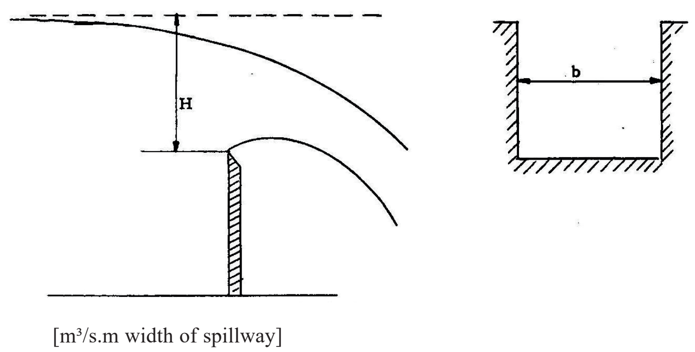

Fig. 7. Discharge through a rectangular spillway, according to A. Flamant

Fig. 8. Collapse of separation wall between full basin at down left, and emptied basin at right

This formula might have been used to calculate the water levels in the basins of a large (about 200,000 population equivalent) water purification station in Antwerp as a function of expected discharges during rain periods. In September 2012, after some rainy days, a separation wall between two adjacent basins collapsed during the night, Fig. 8.

Estimations of the discharge varied between 6000 (design discharge in 2002) and about 15000 m³/hour (during exploitation afterwards), corresponding to an increase of water head of 0.6 m. During the decade before collapse, this caused no direct problem. However, at the time of collapse the adjacent basin was empty, because maintenance works at the aeration installation were planned, and because of that full water loading was acting on the separation wall, which together with some material defects led to the collapse of the upper half of the ten-meter-high wall. Due to the water pressure, that upper part was smashed against the opposite wall of the empty basin, Fig. 8, which also collapsed. Of course, the footbridge supported by the walls also collapsed. Fortunately, the collapse took place during the night, when no technicians were at work at the bottom of the adjacent basin. If someone had checked the situation with Flamant's simple formula, which is given in all university civil engineering textbooks on basic hydraulics of open channels, at least the imminent danger would have been recognized, and necessary precautions could have been taken.

We should remember, though, that the rules of thumb represent only an approximation of reality, often an inadequate one, and therefore, they may be subject to considerable uncertainty. They are often formulated as statistical correlations. This imposes the need to stay particularly cautious in order to avoid the illusory associations, i.e. to demonstrate statistical significance despite the absence of the cause and effect relationship. However, even the apparently "illusory associations" are in some case useful in an engineering meaning. Lots of equations exist in concrete technology, describing various physical features in relation to a compressive strength (f_c). In physical meaning such relations do not exist. There is usually an indirect relation via porosity content. But in practical meaning they are very useful anyway.

5. Threats and precautions: precision and accuracy, validation and verification

The lexical meaning of rule of thumb is:

- a method or procedure based on experience and common sense

or even

- a general principle regarded as roughly correct but not intended to be scientifically accurate.

Due to the responsibility involved with the engineering works the meaning of rules of thumb in civil engineering is restricted to the first statement. In such situation the rules of thumb in civil engineering are beyond the name, much more close to a heuristic technique. It means an approach to problem solving that employs a practical method which is probably approximately correct, and which is sufficient for the immediate goals.

Civil engineering activity needs and requires that rules of thumb should be in certain range (frequently $\pm 3\times$standard deviation – and this represents a rule of thumb as well) of precision and accuracy (Fig. 9). There is a need or even necessity to estimate uncertainty.

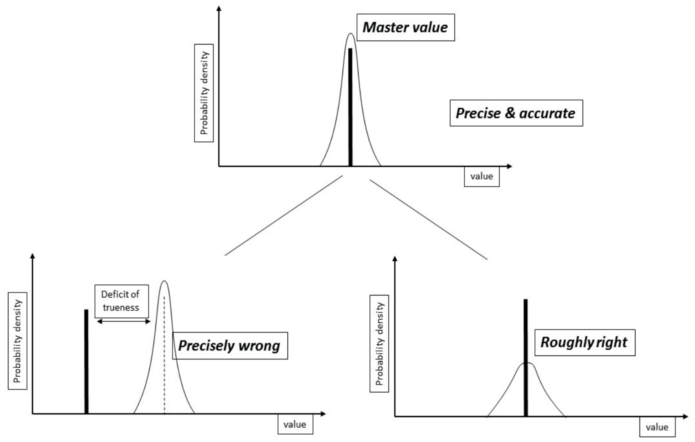

Fig. 9. Accuracy and precision of the statement

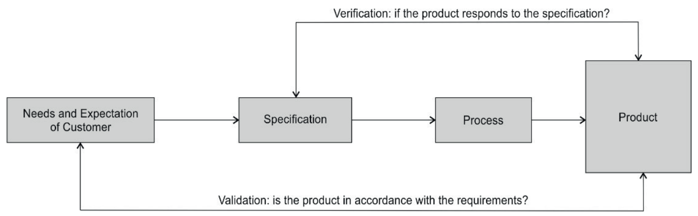

Fig. 10. Verification and validation

Verification and validation are two terms which originally came from information technology, but in present time are spread out on other domains as well. A verification takes place before validation. Verification evaluates documents, plans, codes, requirements and specifications. Experimental validation is the final check to reveal possible errors and to estimate the accuracy of the simulation. Validation can be practically split into three tasks:

- to detect and separate the model's significant discrepancies,
- to remove and reduce removable and unavoidable errors,
- to evaluate uncertainties in the result.

Shortly, verification replies to the question: was the right product applied or built in the right way? and validation answers on: does the built product meet the required performances?

The uncertainty resulting from tests is a combination of parameter (material properties and element geometry) and model uncertainty and may be considered in terms of both, the probability(parameter uncertainty) and the approximate reasoning (model uncertainty). In this paper the authors focus mainly but not solely on the analytical modelling.

Probabilistic analysis methods can be used to predict the time to failure of existing constructions, taking into account load, material and geometrical uncertainties. Viscoelastic modelling with damage parameter enables to simulate the creep behaviour under sustained load, and to predict the time to failure at entering the third creep phase (with increasing strain rate leading to failure) [44].

Alarmed by the collapse of the bell tower of the church in Meldert on July 6, 2006 (Fig. 11) the stability of the tower of the Saint Eustachius church in Zichem (Fig. 12) was investigated, as this tower was built with the same sandstone material and showed a similar damage pattern at its base.

Fig. 11. Collapse of bell tower of St Willibrordus church at Meldert

Fig. 12. St Eustachius church in Zichem

With a probabilistic analysis, based on Monte Carlo sampling, the failure probability of the church in Zichem was estimated for the relative stress level, present in the interior pillars of the tower (55.4%) and for a time frame of 700 years, because the bell tower of the Saint Eustachius church in Zichem was constructed in the early 14th century. From this analysis, a resulting failure probability of 39 % was found. Although a deterministic calculation did not immediately predict failure for this bell tower, the probabilistic analysis estimated a very high failure probability for the preset time frame, due to possible fluctuations on material strength and coherence of the masonry.

Because the calculations did not guarantee the tower's structural safety, and having in mind the collapse in the year before of the tower in the nearby village, the risk was considered too high and strengthening measures were proposed and swiftly executed in 2007 [45]. The bases of the columns of the tower were strengthened by constraining the lateral deformations with epoxy bonded Carbon Fibre Reinforced Polymer sheets (CFRP), as shown in Fig. 14.

Fig. 13. Brick masonry infill in concave sections of column cross section

The constraining effect of the CFRP sheets increases the load bearing capacity of the pillars. The wrapping of the pillars was designed as a temporary measure, to ensure stability until an extensive strengthening and consolidation campaign could take place. This would include grout injections to increase the internal coherence of the pillars as well as the overall strength of the masonry.

In this case the general opinion of the public says that a building which was stable during the past 500 years, will also remain stable during the next 500 years. In this case this rule of thumb has been overruled.

The authors wish to believe that this was due to their probabilistic analysis. However, they are aware that the nearby collapse of a similar tower might have had a much greater impact on the decisions.

In the era of computer-aided design, CAD, and building information modelling, BIM, sometimes the rules of thumb are cited with some embarrassment. But there are many reasons to

Fig. 14. CFRP-constraining strips around column base during execution

believe that the significance of the rules of thumb should not decrease:

- widespread use of computer programmes often creates students and young engineers in the virtual world far away from the building site and construction. Then, the probably approximately correct value may perform the functions of a common-sense verification. Certainly, one cannot say that construction technology has already been developed to the limits of comprehension [41]. But for sure the rules of thumb are milestones in reality. Already at the very beginning of the virtual world in 1966, R. L'Hermite [42] stated about researchers and research publications: "Tout d'abord, aucune publication ne doit sortir d'un institut sans avoir été soumise à son directeur scientifique. … Au lieu de se hâter de publier, qu'ils prennent le temps de mûrir leur affaire. … Le défaut de la publication hâtive est celui des jeunes; lorsqu'on avance en âge et malgré que le temps presse apparemment il est courant de remarquer que l'on publie moins souvent et de meilleure façon". Reflections which are valid for researchers hold even more for civil engineering design engineers.
- rules of thumb help to preserve and even revive the engineering intuition and prevent "re-inventing of the wheel",
- rules of thumb help to keep the link between science and engineering, while the immersion of science and technology within civil engineering is becoming more and more obvious.

However, we should add three more rules of thumb for general use:

- in order to find accurate information on the Internet, at least nine irrelevant pieces of information must be rejected (a rule of 90:10 according to Banerjee);
- a rule of 80:20 according to Koch says that 20% of our efforts bring 80% of benefits, but it is believed that in structural design Hyde's rule of 5:90 is applicable [43] – the last 5% of the design takes 90% of the total time. But even the missing 5 % or 20 % of the design efforts are responsible of the vast majority of structural defects, and they provide the nutrient ground for a flourishing repair industry in construction.

And to conclude:

- the golden rule according to George Bernard Shaw says that there are no rules. However, he was not an engineer.

6. Summary

The statement in the introduction that "it is better to be roughly right than precisely wrong" (J.M. Keyness) makes us realise the dilemma of accuracy and simplification*,* of how our data and models are far from the truth and what consequences this might have for the field of safety and reliability. Estimating this "distance from truth" and its effects gradually progresses, based on scientific grounds. However, the significance of the rules of thumb and engineering intuition based on technical knowledge has also been presented. It is estimated that there are nearly 300 million websites of unstructured scientific reports available on the Internet; each year 5,000 publications on the subject of concrete alone are issued. On the other hand, in technology, and especially in construction, the improvement of professional skills only by practice is not sufficient and may even be dangerous. The very nice English phrase learning by doing may come down to risky actions in accordance with the trial and error method*.*

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