Modelling in the service of sustainable construction

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The world's infrastructure is vital for providing accommodation and mobility for people. Although it is obvious that the construction industry has been crucial for realizing building and civil infrastructures, it is also clear that building activities have a big impact on the environment. Still growing and developing societies and economies do need even more buildings, more roads etc. The question is how all these needs can be accomplished without compromising the ability of future generations to meet their needs (Brundtland Report).

In this contribution the urgency of a sustainable construction industry is explained. The need for a change from *building in the service of growth* to *building in the service of sustainability* is emphasized. Comprehensive models, with which the entire building cycle can be simulated, would enable engineers to analyse the building and construction process with respect to the demand for raw materials and energy, maintenance and repair, renovation and retrofitting and, finally, recycling and reuse of materials and/or structural components. The option of developing a serious game for sustainable construction is discussed and recommended. With such a game the whole building cycle is simulated, ranging from decision making by stakeholders to execution on the site, curing, maintenance and repair in the service life phase, decommissioning, recycling and reuse.

Keywords: Modelling, microstructure, ageing, quality, sustainability, serious gaming

1 Introduction

Since ancient times people have been in the need of shelter. Protection was needed against harsh climate conditions, flooding, wild animals and hostile tribes. However primitive these shelters were, they had to meet basic criteria of functionality, strength and stiffness. Shelters were built from locally available materials, like mud, mud-bricks, wood, straw and organic cloth. In the absence of good roads the use of local materials was obvious. The limited possibilities to transport bulk materials over long distances – maybe with the exception of transport via water -, forced people to maintain a balance between the consumption of local materials and their availability. Violating this balance would deprive them, at least on the long term, from the possibility to provide appropriate shelter and, finally, to survive.

A big jump in time brings us to modern societies. Buildings still provide shelter and are still designed for strength, stiffness and functionality. But now extensive transport networks have made it possible to transport building materials over long distances. Huge metropoles were built, with a demand for building materials often far beyond what local resources could provide. The economic and infrastructural boundary conditions, together with the modern means of transport, have set the conditions for unprecedented growth. This is convincingly shown in Figure 1, where the evolution of the World Gross Domestic Product over the past two millennia is presented (based on Roser [1] and Maddison [2]).

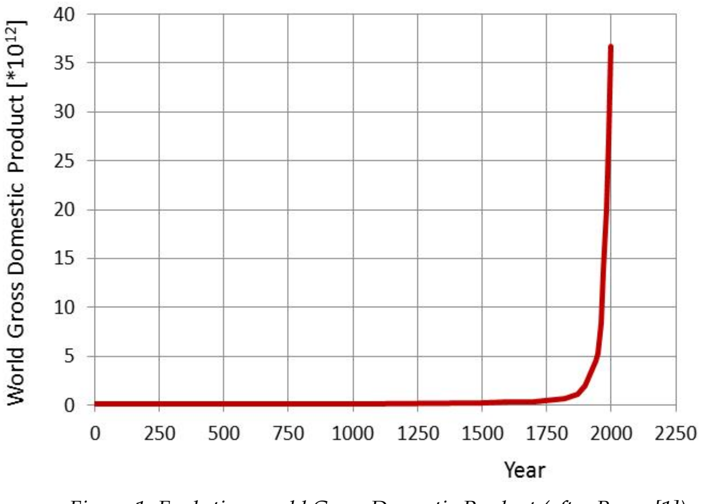

Figure 1: Evolution world Gross Domestic Product (after Roser [1])

The process of unprecedented growth started slowly in the second half of the nineteenth century during the industrial revolution. It is not by accident that this growth coincides with the emerge of concrete as a building material. The availability of cement and concrete stimulated and enabled the design and construction of huge civil infrastructures and the development of our modern road and railway networks. This infrastructure facilitated further growth in the twentieth century at an absolutely unprecedented rate.

A more detailed analysis of the growth figures shows that in the second half of the 20th century the percentage growth of cement consumption was even larger than the percentage growth of the world's GPD (see Figure 2). The increase in cement consumption indicates a corresponding increase in building activities and of the value of the global infrastructure stock. In industrialised countries the infrastructure stock accounts for about 50% of the country's national wealth [3, 4].

There is no doubt that in this period of unprecedented growth science and engineering have substantially contributed to this growth, or have even enabled it. In summary we may safely say that for many decades science and engineering developed in the service of growth. The role of models and modelling in this process of growth can hardly been overestimated. At the same time, however, we can say that it was the modellers who have pointed to the negative side-effects of growth [5]. Growth has a price! Models have convincingly shown that unlimited growth is unstainable. Today modellers – and many others - are challenged to use their knowledge, skills and models *in the service of sustainable development*. This does not unconditionally mean that we have to refrain from growth completely. The focus and challenge should be, however, whether and how we can realise growth in a sustainable way.

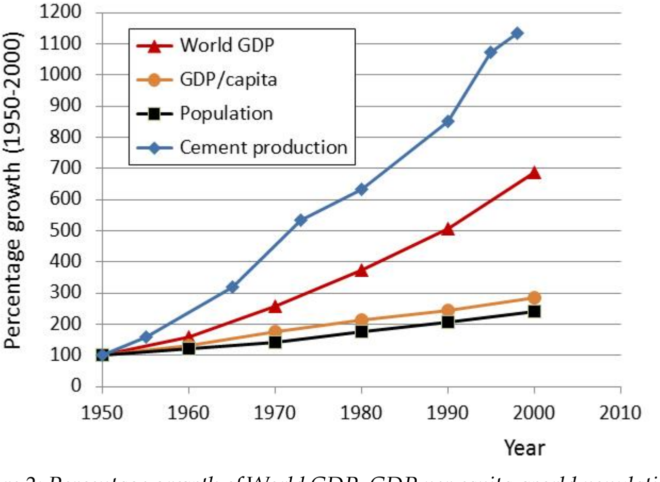

Figure 2: Percentage growth of World GDP, GDP per capita, world population and cement production in the second half of the 20th century [3]

2 Modelling in science and engineering

2.1 *Some general features of models and modelling*

Science and engineering are hardly conceivable without models and modelling. Yet, we cannot say that there is something like a general theory of modelling [6]. Nevertheless there is a basic notion of what a model is: "A model is a simplified version of something that is real" [7]. That 'something' can be small or big, simple or complex. A model tries to represent the real thing and its performance under prevailing exposure conditions. Models enable us to make fundamental knowledge and theories operational for engineering purposes. Models enable us to bridge length scales and, reversely, challenge researchers to systemize science through multi-scale modelling [8]. Besides *bridging* of length scale models also can also *connect* different disciplines, i.e. physics, chemistry and mechanics [9].

There is no doubt that the introduction of powerful computers has been crucial for the rapid growth of the modelling community. Huge computation power and parallel computing has made it possible to simulate the performance of complex systems. In fact, the performance of materials is increasingly considered as the performance of complex multi-scale *systems* [10]. From the modelling point of view considering the reality as a system, and this at subsequent length-scales, is challenging. Many algorithms do apply at different length scales. We have to bear in mind, however, that a phenomenon that is decisive for the performance of a system at a certain length scale might have negligible effect at other length scales. Each length scale has its relevant set of mechanisms and laws, which dominate the performance of a system at that particular scale. Ignoring this will undoubtedly lead to unbalanced models. Particularly when dealing with complex multi-scale and multi-disciplinary systems this can be a 'pitfall' for researchers.

2.2 *Modelling sustainability*

On the scale of complexity the physical world around us, including the man-made built environment, is by far the most complex system we can imagine. It is just this system that reveals signs of instability. The construction industry is said to be a serious contributor to this instability. For example: the production of steel and concrete is responsible for 20% of the worldwide CO_2 emission [11]. In past decades both the steel and cement industry have made big steps towards cleaner production processes. In the near future further dramatic reductions are hardly conceivable. Moreover, the effect of reducing the production-related CO_2-emissions per ton steel or cement will soon be cancelled out by the *increase* in the prognosticated worldwide growth of consumption of steel and concrete, particularly in countries with a rapidly growing economy. Figure 3 shows the expected increase in cement production from about 1.5 billion tons in 2000 to 3.5 billion tons in 2015 and 4.4 billion tons in 2030. In the first three decades of the 21st century the cement production is expected to increase even faster than in the second half of the 20th century!

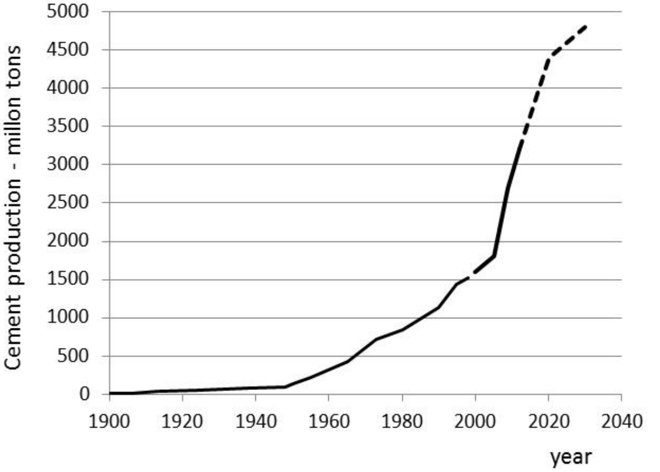

Figure 3: Evolution of cement production, worldwide [3,12]

Today mitigating CO_2 emissions and reducing the use of raw materials are among the most frequently mentioned goals of sustainable development of the construction industry. These goals force us to develop building materials using locally available resources and to optimize traditional concrete mixtures in terms of CO_2 emissions. At the same time these mixtures should meet durability requirements in order to ensure the required service life of structures. For developing new mixtures and for service life predictions, models are indispensable.

Before continuing the discussion on modelling opportunities in the context of sustainable development, a few comments will be made regarding two tedious modelling issues at the materials level. The first issue is that of modelling of autogenous deformations in hardening concrete. The second is that of the simultaneous occurrence of autogenous shrinkage and drying shrinkage. The potential of models and modelling in this discussion will be emphasized.

3 Modelling complex materials behaviour

3.1 Early-age hydration-induced deformations

The hydration process of cement-based materials is accompanied by volume changes. These volume changes can be expansion or shrinkage. The type of binder and the water-binder (w/b) ratio of the mixture dominate the hydration-induced deformations. Mixtures with a relatively high w/b ratio often start with some swelling, followed by shrinkage. For systems with a low w/b ratio swelling is generally negligible. Shrinkage of low w/b ratio systems, however, may result in high tensile stresses and cracking (if restrained). A lot of research has been devoted, therefore, to modelling of early-age shrinkage of low w/b ratio mixtures. Several mechanisms have been proposed that can *explain* shrinkage and can subsequently be used as a basis for *modelling* shrinkage. Depending on the magnitude of the relative humidity in the hardening systems *disjoining pressure* and *capillary tension* are the most often used mechanisms for modelling early-age (autogenous) shrinkage. These two (different) mechanisms have in common that a decrease of the relative humidity of the system will result in shrinkage. Swelling, however, cannot be explained by these mechanisms, at least not as the result of a drop of the relative humidity. This leaves us with the question, firstly, where de swelling comes from and, secondly, how to model it. And, more importantly, can a model that accurately describes the shrinkage behaviour (maybe after adjusting some model parameters), be considered correct if *any* effect of swelling is ignored?

The problem in view is schematically shown in Figure 4. The figure shows a measured deformation curve of a high w/b ratio system. In the first stage of hydration the system swells. This swelling is followed by continuous shrinkage. When it comes to modelling of the measured autogenous deformation it is too simple to assume that *first* only a swelling mechanism is active and that *after* swelling only a shrinkage mechanism is active. Given the complexity of hydrating systems it might well be that swelling and shrinkage mechanisms are active *simultaneously*. The measured autogenous deformation will then be the result of, for example, simultaneously active *swelling* mechanism I and *shrinkage* mechanism I. It can also be, however, the result of *swelling* mechanism II and *shrinkage* mechanism II (Figure 4).

In fact numerous combinations of swelling and shrinkage curves are conceivable that produce the measured deformation curve. From the measured autogenous deformation alone the individual contributions of swelling and shrinkage mechanisms cannot be inferred. Quantitative modelling of conceivable swelling and shrinkage mechanisms is an appropriate way to tackle this problem. This, however, requires comprehensive and advanced modelling with input from different disciplines.

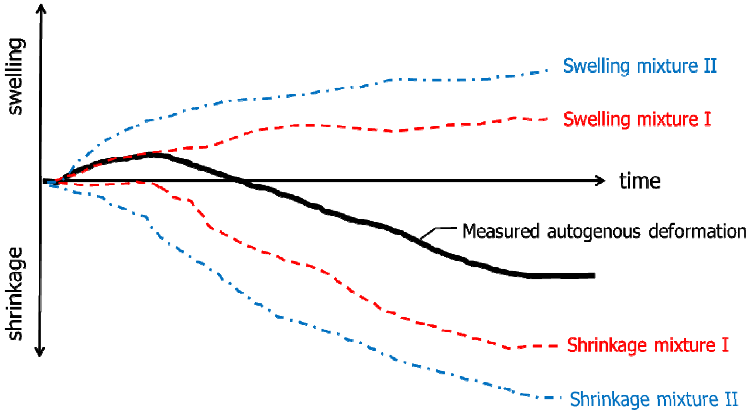

Figure 4: Schematic representation of measured autogenous deformation as result of simultaneous swelling and shrinkage mechanisms

3.2 *On the role of creep in autogenous deformation – Implications for the practice*

The drop of the relative humidity in hardening cement paste – a key-parameter in models for autogenous shrinkage -, is caused by self-desiccation of the paste. The drop in relative humidity results in capillary tension in the pore water. The tensile stresses are equilibrated by compressive stresses in the solid skeleton of hydration products [13]. The compressive stresses cause deformations of the skeleton, known as autogenous shrinkage. Assuming that this mechanism is indeed the one that is responsible for autogenous shrinkage – opinions still differ [14,15] – one would expect that autogenous shrinkage will cease as soon as the hydration-induced self-desiccation process stops. Although it is true that most of the autogenous shrinkage is observed in the early stage of the hydration process, numerous tests have shown that autogenous shrinkage continues to increase even after the hydration process has virtually stopped. From this observation it has been concluded that autogenous shrinkage consists of an elastic part and a time-dependent part [16,17]. The existence of a creep component is conceivable: a material under constant load will first deform elastically, followed by a time-dependent creep part. In more recent studies the creep part of autogenous deformation has been studied in more detail [18,19] and numerical models are being developed in which the elastic and creep part are separated [20].

So far the focus of these modelling activities has been on improving the predictions of autogenous shrinkage, particularly the long-term shrinkage when the hydration process has virtually stopped. Little or no attention has been paid yet to the implications for the engineering practice. In the design practice it is well-known that it makes a big difference whether an imposed strain is an elastic strain or a creep strain. Stresses exerted by a restrained creep strain will be compensated by relaxation (depending on the rate of creep). Analogously, the creep part of autogenous shrinkage, if restrained, will be compensated by relaxation. Ignoring the fact that a part of the autogenous shrinkage is a creep strain can result in a not justified conservative design!

*3.3 **Combination of autogenous shrinkage and drying shrinkage***

Since the use of concrete drying shrinkage of the material has been studied. One of the issues was the role of stresses is the cross section of drying specimens caused by the moisture gradients [21]. With the use of low w/b ratio concretes another issue has drawn the attention of researches, i.e. the combined occurrence of autogenous and drying shrinkage. For concrete mixtures with w/b ratio between 0.35-0.39 (grade C55/65), it has been found that in the period between 28 days until 91 days the autogenous shrinkage of concrete prisms (100×100×400 mm^3) was as high as 40% to 50% of the drying shrinkage of prisms exposed to a RH of 50% at 20°C [22]. Similar studies were performed by Mors [22, 23] on concrete mixtures with w/b ratio 0.44 - 0.50. A typical example of Mors' results is shown in Figure 5. The shrinkage curves represent autogenous shrinkage and drying shrinkage of specimen that were unsealed after 3 and 28 days, respectively. Two types of aggregate were used; gravel and limestone.

Sealed specimens showed a steadily increasing shrinkage, even at an age of 91 days. After 28 days the autogenous shrinkage increased by another 60% at 91 days and almost doubled at 196 days (not shown in the figure). Similar results have been reported by Lee et al. [25]. It was noticed that, in spite of double sealing of the prisms for autogenous shrinkage, some moisture loss did occur. After correction for this moisture loss the resulting autogenous shrinkage still exhibited a trend to increase substantially and remained similar to those found by Lee et al., and also in line with earlier results of Van Cappellen [26].

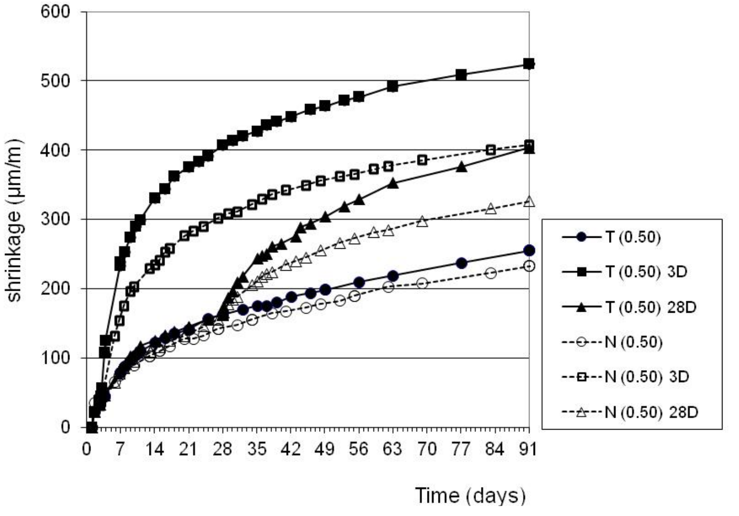

Figure 5: Combinations of autogenous shrinkage and drying shrinkage of traditional mixture T (0.50) and a mixture with limestone aggregate N (0.50). BFS cement CEMIII/B. Drying tests: RH = 50% after 3 d and 28 d, respectively [23,24]

The relative large autogenous shrinkage after 28 days, shown in Figure 5, deserves attention. Following the discussion in the previous section, part of the autogenous shrinkage has to be assigned to creep. If in a real structure these slowly generated creep strains are restrained, they will hardly generate stresses (because of relaxation). Another reason why the origin of these long-term shrinkage strains deserve attention concerns the contribution of these strains to the proneness to microcracking. More research is needed to clarify this issue.

4 Sustainability-inspired modelling tasks

4.1 Mitigation of the CO_2 footprint

Among the strategies to reduce the CO_2 emissions associated with the production of Portland cement, the use blended cement is often recommended. The use of slag, fly-ash and limestone powder are the most frequently used cement replacements. The effect of blending of powders on CO_2 emissions can easily be assessed as long as only the *production process* of the blended binders is considered. For an integral judgment of the effect on CO_2 emissions the total lifetime of structures made with these blended cements should be considered. The challenging question is then how different mixtures perform on the long term. In other words, how these materials age [3]. Today our knowledge on ageing of cement-based materials (and of many other materials) is far from mature. Hence, there is a huge market for models for simulating the long-term performance of materials and structures. To say it differently; reliable quantitative ageing models are vital for integral judgment of new binder concepts (see also section 4.3).

Extension of the service life of concrete structures is another option to reduce the environmental impact of building activities. It reduces the CO_2 emission in all subsequent stages of the structure's lifetime. A next and logic step after extension of the lifetime of structures is that of complete *circularity*, as will be discussed in the next section.

4.2 ***Circularity in the building industry – The concept***

Today circularity is a key-issue in many sectors, also in the building industry. In fact the reuse of materials of demolished buildings for making new structures is not new. Hendriks [27] memorized that waste materials, such as metals, wood, and paper, have been reused for centuries already and he mentioned a few examples to illustrate this. Although it is hard to believe that 100% circularity is possible, it is at least a concept that generates the badly needed awareness of the environmental impact of the construction industry, and it forces us to think about alternative concepts. The search for full circularity will certainly generate new and unprecedented solutions, most probably as a result of multidisciplinary collaboration.

Figure 6 shows the building cycle with its subsequent stages of a structure's life cycle. It starts with the design and production of building materials. In this phase raw materials and energy are needed for the production of building materials. In the next phase construction elements and/or complete structures are produced. The outer circle of Figure 6 represents the materials cycle of the so-called *monolithic* design concept. The inner circle refers to the concept of *demountable* design. After having passed all subsequent stages of repair, renovation, retrofitting and upgrading, structures built according to the monolithic design concept have to be demolished. In a circularity concept the demolition waste will be reused for production of new building materials. The inner circle (demountable design) will require less energy for a complete loop compared to the outer circle (monolithic design) and is, therefore, preferable from the sustainability point of view. Of course, the reuse of construction elements cannot go on forever, but will be limited. Ageing of the material and degradation processes dictate the number of life cycles of building elements.

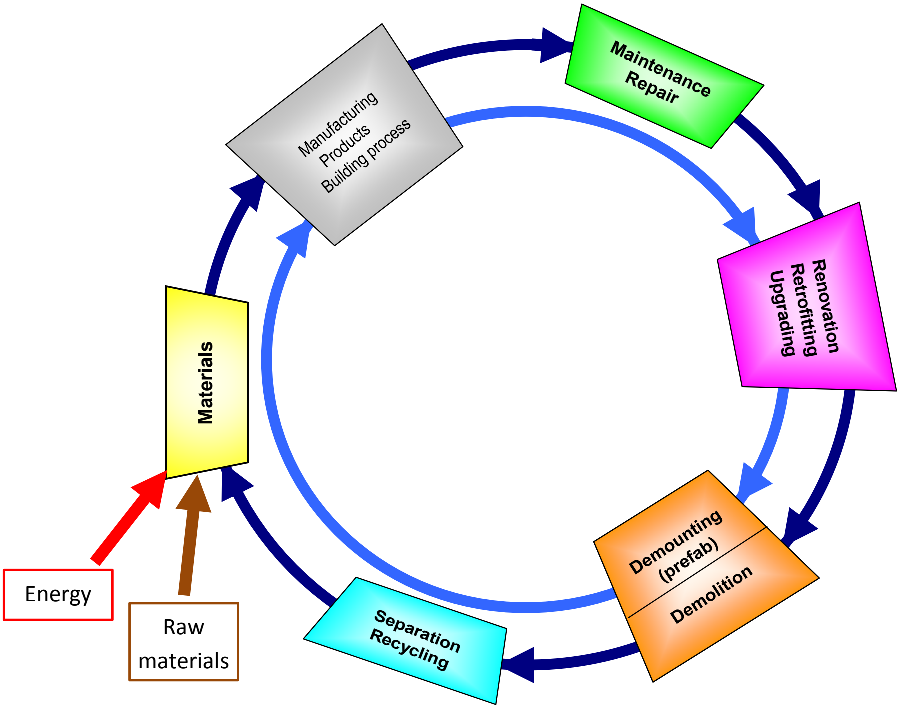

Figure 6: Building cycle. Outer circle: monolithic design concept. Inner circle: demountable design concept [3,28]

In a discussion of the circularity concept the question has been put forward for which problem this concept can be considered a solution [3]. In that discussion it was remarked that in the coming years, globally, less than *one third* of the investment of building industry is expected to be spent on replacement of existing structures, whereas more than *two third* of the investment will be needed for realizing prognosticated *growth*. The estimated growth of the use of concrete, and hence of raw materials, can certainly *not* be accomplished completely by demolition of structures that are nominated for being recycled. Growth implies a demand for extra raw materials and an associated, and unavoidable, *increase* in CO_2 emission, unless production or construction technologies will dramatically change. For realizing growth *extra* materials will be needed. Growth will predominantly take place in countries where *not* many buildings are available for providing 'second-life' material. In most situations where growth is needed there is simply (almost) nothing to recycle yet! It was concluded [3] that in a situation of growth the role of recycling can only be marginal and that circularity cannot be expected to contribute much to mitigation of the environmental footprint on short term.

4.3 Ageing of materials and structures

The rate at which materials and structures go through the building cycle depends on the service life of structures. The service life, on its turn, is determined by the quality of the structures. Irrespective of how good the initial quality of a structure has been, with elapse of time its performance will change. This change of performance with time is called *ageing*. The driving force for ageing of materials is, among other things, the presence of internal gradients. Examples are moisture gradients, density gradient, charge gradients, chemical gradients, etc. Even though gradient-induced changes may occur extremely slow, on the long term they do affect the performance of the material. For modelling of ageing processes the relevant ageing mechanisms must be known. Concrete, with its numerous internal interfaces and associated gradients at nano, micro and meso scale, is prone to ageing. At the same time it is also a material with an inherent self-healing potential. It can heal its microcracks autogenously, depending on the type of binder used. In this respect it is remarked that reducing the cement content in concrete mixtures, in order to meet sustainability goals, might result in less robust and ageing-prone mixtures! Moreover, numerical simulations by Huang [29] have shown that coarse cements have a higher self-healing potential than fine cements. More research on the effect of replacing Portland cement by other binders on the resulting proneness to ageing of these modified materials is strongly recommended.

4.4 Serious gaming of a sustainable construction cycle

As mentioned in section 2.1, a model is a simplified version of something that is real. The real thing can be a material, a structure or even the entire building stock, but also the *process* to realise all this. The ultimate goal of modelling the entire building stock is two-fold. The first goal is to provide appropriate, comfortable and affordable shelter, i.e. accommodation, for people. The second goal is to realise all this without compromising the ability of future generations to meet their own needs. The latter goal is the well-known sustainability goal formulated in the Brundtland Report [30]. It is not easy to break down this overarching sustainability goal in sub-goals for the construction industry without losing the connection with the overall goal. An appropriate vehicle to accomplish these goals is that of serious gaming. The term gaming in the context of sustainability might sound, on first hearing, inopportune. Sustainability is a serious topic, whereas gaming is often associated with amusement. Games, however, can be developed for *any* platform [31], also that of sustainable development. In her review paper on serious games on sustainable development Katsiliaki et al [32] presented a nice inventory of sub-goals of serious games. These goals include all aspects of education, like teaching, training and communication. They allow learners to experience situations that are impossible in the real world for reasons of safety, costs and time. Games stimulate the user's engagement in an activity and can have a positive impact on a variety of the player's personal skills. Serious games can also improve self-monitoring, problem recognition and problem solving, decision making, collaboration and negotiation. All these characteristics, features and goals of serious games make them a perfect platform for a serious game on sustainable construction.

As mentioned in foregoing sections already, one way to mitigate the environmental impact of the construction industry is extending the service life of concrete structures [33]. Extending the service life of structures presupposes, among other things, high quality of design and execution, appropriate choice of materials, good management and transparent communication. Figure 7 shows a schematic representation of a series of aspects involved

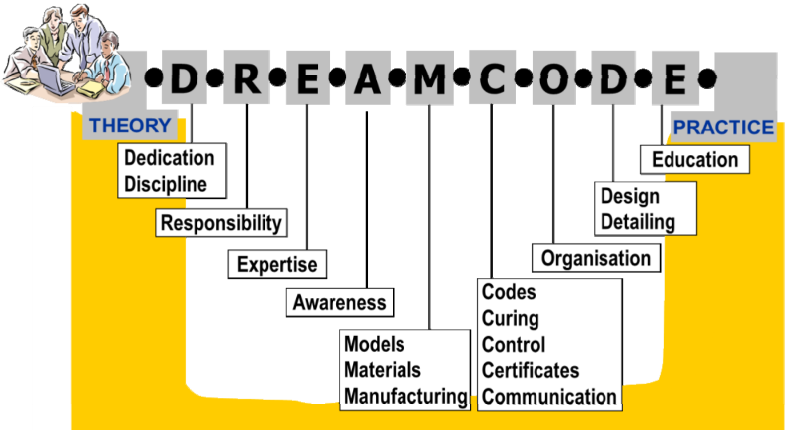

Figure 7: Cartoon representing the multi-disciplinarity of quality parameters (after [34])

in the building process. Together these aspects from a chain that bridges the gap between theory and practice. This chain is called the DREAMCODE [34]. This is a virtual code that identifies the variety of aspects that are considered crucial for realising good quality structures. A serious game would be an excellent vehicle to make this code operational in the practice. In this game each stakeholder in the building process can play his particular role, viz. as owner, decision maker, designer, craftsman, manager, initiator, supervisor, etc. In its capacity as education tool the DREAMCODE illustrates that the strength of the chain is as strong as the weakest link. This helps individual stakeholders to put the relevance of their own contribution to the success of the entire building process in perspective. For example, the benefits of advanced numerical simulations of materials behaviour with the aim to realise a top-quality structure with minimal environmental impact will be lost completely by poor execution on the building site. Reversely, the dedication of the craftsman will be fruitless if he has to do his job with inferior material or if the detailing of the reinforcement is such that pouring of the concrete is virtually impossible. And the use of more and thicker codes will not result in higher quality if there is no adequate understanding and education of these codes. A serious game, if loaded with adequate content and models for individual aspects of the DREAMCODE, can make designers, technologists and craftsmen aware of the impact of their choices, decisions and skills on the quality of the end product and on the resulting environmental impact of the building process.

5 Concluding remarks

The enormous impact of the construction industry on the environment on the one hand, and the increasing demand for buildings and infrastructure on the other hand, have revealed the need for an alternative approach of this industry in order to accomplish sustainability goals. One of the possible routes to sustainable development is to save energy and raw materials by increasing the service life of concrete structures. Extending the service life of structures, however, is not an easy task. The building industry is very complex, tradition plays an important role and concrete structures are often one-of-a-kind products. Even if the building process is sub-divided in smaller parts, these parts still exhibit a high complexity. This complexity has stimulated efforts to simplify reality in order to make things manageable. Simplifications, resulting in simple models, certainly have a right of existence. As long as the outcome of simple models meet the expectations of the user, also simple models can be judged good models! The range of application of simple models, however, is generally limited. For reliable simulation of complex materials issues, like that of creep and shrinkage, simple models do not apply and more advanced models are needed.

When it comes to an assessment of the environmental impact of the construction industry, the capacity and use of models should be placed in a wider, multi-disciplinary context. In this paper such a wider context has been framed by referring to a DREAMCODE. This virtual code stands for a variety of aspects involved in the realization of any (concrete) structure. A serious game of the building process was mentioned as a platform for making this DREAM-CODE operational. Developing such a game is a huge challenge and will cost hundreds of man-years. These efforts and costs, however, should be put in the perspective sketched in the Introduction. The infrastructure of industrialized countries accounts for about fifty percent of their national wealth. On a global scale this value has been estimated at US$ 51 to 125 trillion dollars [3]. Huge amounts of energy and raw materials were needed to realise this infra-structure and huge amounts are needed to maintain, repair and replace it. On top of that there is a high demand for new-built. Scientists and engineers are, for their share, responsible for the environmental impact of existing assets and of those yet to be built. Enormous savings for the environment and the society can be realized by extending the service life of the infrastructure stock by, for example, ten percent. Assuming, conservatively, a value of the global infrastructure stock of US$ 51 trillion and an average service life of 50 years, an increase of the service life by 10% would reduce the annual replacement costs by US$ 90 billion per year [3]. Amounts of this order of magnitude should be born in mind when judging the (global) efforts needed to realize such savings. Investments needed to realize such savings will finally pay off [3]!

References

[1] Roser, M., ‘Economic Growth. Our world in data.’ https://ourworldindata.org/economic-growth (consulted in 2017).

[2] The Maddison Project. http://www.ggdc.net/maddison/maddison-project/home.htm (2013).

[3] Van Breugel, K., ‘Circularity: A new avenue for mitigating the footprint of ageing infra-structure?’ Proc. 9th International Symposium on Cement and Concrete (ISCC 2017). Wuhan (2017) 12.

[4] Long, A.E., ‘Sustainable bridges through innovative advances’. Institution of Civil Engineers, presented at Joint ICE and TRF Fellows Lecture (2007) 23.

[5] The Club of Rome: ‘The Predicament of Mankind – Quest for Structured Responses to Growing World-wide Complexity and Uncertainties’ (1970) 31.

[6] Ritchey, T., ‘Outline for a morphology of modelling methods – Contribution to a General Theory of Modelling’. *Acta Morphologica Generalis*. AMG (2012) 120.

[7] Schichl, H., 'Models and the History of Modelling'. In: Kallrath J. (eds) *Modelling Languages in Mathematical Optimization. Applied Optimization*, Springer, Boston **88** (2004) 25-36.

[8] Wittmann, F.H., 'Shrinkage and creep of concrete: Mechanisms as described on different structural levels'. Proc. Conf. on Systemization of Concrete Science and Technology through Multi-scale Modelling. Tokyo. (2015) 11.

[9] Van Breugel, K., Ye, G., 'Multi-scale modelling: The vehicle for progress in fundamental and practice-oriented research'. Proc. Sec. Int. Conf. on Nanotechnology in Construction, Bilbao, RILEM publ. S.A.R.L. (2005) 10.

[10] Van Breugel, K., 'Concrete : A material that barely deserves that qualification'. Proc. Int. Conf. on Material Science. 64th Rilem week, Aachen – MATSCI (2010) 22.

[11] Netherlands Environmental Assessment Agency. CO_2 time series 1990-2014 per region/country. (2014).

[12] Aitcin, P.C., 'Cement of yesterday and today, Concrete of tomorrow'. *Cement & Concrete Research*, **30** (2000) 1349-1359.

[13] Acker, P., 'Swelling, shrinkage and creep : a mechanical approach to cement hydration'. *Mat. & Struct.*, **37** (2004) 237-243.

[14] Beltzung, F., 'Shrinkage mechanisms'. ASMES International Workshop, EPF Lausanne (2011).

[15] Wittmann, F.H., Beltzung, F., 'Fundamental aspects of the interaction between hardened cement paste and water applied to improve prediction of shrinkage and creep of concrete: A critical review. *Journal of Sustainable Cement-based materials*, Taylor & Francis (2015) 12.

[16] Powers, T.C., 'Mechanisms of shrinkage and reversible creep of hardening cement paste' in Proc. Int. Symp. "Structure of Concrete and its behaviour under load', London (Cem. & Concr. Ass., London (1965) 319-344.

[17] Person, B., 'Creep and shrinkage of young or mature HPC', in Proc. 5th Int. Symp. on Utilization of high strength/high performance concrete, Sandefjord (1999) 1272-1281.

[18] Lura P., '*Autogeneous deformation and internal curing of concrete*', PhD Thesis, Delft University, The Netherlands, 2003.

[19] Do, Q.H., '*Modelling Properties of Cement Paste from Microstructure: Porosity, Mechanical Properties, Creep and Shrinkage*'. PhD Thesis 5881, EPFL (2013) 183.

[20] Lu, T. '*Autogenous shrinkage of early age cement paste and mortar*' PhD Thesis, Delft University of Technology, The Netherlands, 2018. 160 p.

[21] Bazant, Z., '*Mathematical Modeling of Creep and Shrinkage of Concrete*'. Edited by Z. Bazant. John Wiley & Sons Ltd (1988).

[22] Van Breugel, K., Ouwerkerk, H., de Vries, J., 'Effect of mixture composition and size effect on shrinkage of high strength concrete'. Proc. Int. RILEM Workshop Shrinkage of concrete - Shrinkage 2000 (2000) 17.

[23] Mors, R.M., 'Autogenous shrinkage – Cementitious materials containing BFS'. MSc-thesis, TU Delft (2011) 63.

[24] Van Breugel, K., Mors, R., Bouwmeester, J.W., 'New insight in the combination of autogenous and drying shrinkage'. Proc. Fib symposium Engineering a Concrete Future: Technology, Modelling and Construction, Tel Aviv (2013) 8.

[25] Lee, K.M., Lee H.K., Lee, S.H., Kim, G.Y., 'Autogenous shrinkage of concrete containing gbfs', *Cement and Concrete Research* **36** (7) (2006) 1279-1285.

[26] Van Cappellen, J., 'Autogenous and drying shrinkage', MSc-thesis, Delft University of Technology, Delft, The Netherlands (2009) 95.

[27] Hendriks, Ch.F., '*The Building Cycle*'. Aeneas Technical Publications (2000) 233.

[28] Van Breugel, K., 'Ageing infrastructure and circular economy: challenges and risks'. Proc. of the 2nd World Congress on Civil, Structural, and Environmental Engineering (CSEE'17) (2017).

[29] Huang, H., '*Thermodynamics of autogenous self-healing in cementitious materials*'. PhD-Thesis, Delft (2014) 167.

[30] Brundtland commission, 'Our Common Future', Report World Commission on Environment and Development. Oxford University Press (1987).

[31] Zyda, M., 'From visual simulation to virtual reality to games'. IEEE Comp. Soc. (2005) 25-32.

[32] Katsaliaki, K., Mustafee, N., 'A survey on serious games on sustainable development'. Proceedings of the 2012 Winter Simulation Conference. C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, and A.M. Uhrmacher, eds. (2012) 1528-1540.

[33] Hendriks, C.F., Janssen, G.M.T., 'Does recycling fit with sustainable use?' Proc. Int. Conf. Achieving Sustainability in Construction, Dundee, Ed. Dhir et al., Thomas Telford (2005) 331-340.

[34] Van Breugel, K., 'Durability: key issues in perspective'. Proc. 1st Int. Conf. on Microstructure Related durability of cementitious composites. Nanjing. I (2008) 323-332.