The Model: Vehicle for Glory and Damage

By
Prof. Dr. Ir. K. van Breugel

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About the place of infrastructure in society and the influence of climate change on service life

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Valedictory address

Delivered at the farewell as professor in the field of
"Concrete Modelling and Material Behaviour"
at the Materials & Environment section of the Faculty of Civil Engineering and Geosciences of Delft University of Technology,
on Friday, September 27, 2019

by

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Preface

On Friday, September 27, 2019, I had the pleasure of delivering my valedictory address in the auditorium of Delft University of Technology. It was my intention to publish the speech in book form as well. Many other things got priority, with the result that the booklet* only appears now.

The text of the speech is generally followed in this booklet. However, in this written version extra attention is paid to the basic idea behind this speech. Briefly summarized, this basic idea is that people strive to control reality. To this end they have put almost all their bets on science and technology. To get a grip on reality, scientists and technicians in turn have used models. Via models, acquired insights and knowledge are made available to the manufacturing industry. The ability to control and shape reality is then put at the service of the pursuit of growth. Growth figures are impressive. This is illustrated in this speech by the infrastructure that has been built up over the years. However, the downside of this growth is becoming increasingly apparent. The construction of the infrastructure has an impact on the environment and on the climate. Climate change in turn affects the lifespan of the infrastructure. The lack of direction (Dutch: regie) is seen as one of the main causes of unbalanced, damaging growth. Direction is crucial if, on the one hand, growth is pursued, but on the other hand, the growth-related environmental impact must remain limited. The government's task to act in a directive manner is emphasized in this speech. The use of serious gaming is advocated as an instrument to support direction and good governance.

The beginning and end of this speech are more reflective. The central section delves deeper into the field of my chair. Both parts have models as the common and unifying element. If the reader is able to notice the latter, then writing this speech was not only a pleasure for myself, but I have also achieved at least one of my goals.

A word of thanks goes to my colleague prof. A.Q.C. van der Horst for reading through the original manuscript, and to Iris Batterham for designing the cover of this booklet.

Delft, October 2020

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*) The valedictory address has only been published in book form in Dutch. Digital versions are available both in Dutch and English.

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About the place of infrastructure in society and the influence of climate change on service life

Mr. Rector,
members of the Executive Board,
fellow professors and other members of the university community,
esteemed listeners,
ladies and gentlemen,

Introduction

On September 15, 1979, I joined the Concrete Structures Section of the Faculty of Civil Engineering[1] at TU Delft. A gentlemen's agreement had been made with the section head, Professor A.S.G. Bruggeling. Fifty percent of my time would be spent on teaching and fifty percent on research. That research should culminate in a doctorate. After four years I would leave the university and go to work. It all turned out differently. Not four, but forty years later I am leaving university. If my father had still been here, he would probably have said that it is nice that I am finally leaving the university, but that it is really not worth going to work anymore.

Still, I don't feel that I have done nothing in the past forty years. A lot has happened. Research has been done on bulk storage of hazardous bulk materials, behaviour of storage structures under extreme loads, liquid tightness of reservoirs, structural behaviour under imposed deformations, temperature development and cracking in hardening concrete, service life predictions and modelling of material and structural behaviour. Yet, to be fair, most of the research was done by others. And those others, fortunately, were many! Ninety percent of all scientists who have ever been active in science, or are still active, live today[2]. Enormous progress has been made in many areas. What do we not know yet? What has not yet been explained or solved? In the past, indeed, there used to be a lot of white spots and black holes in our knowledge. And when observed phenomena could not be explained, then the 'concept of God' was brought in to fill up the gaps in our knowledge. But that time is now really over. A probably untrue anecdote[3,4] tells us that emperor Napoleon once asked the scientist Laplace why God did not appear in his book on cosmology. Laplace is said to have

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[1] After the Civil Engineering and Mining Engineering faculties were merged in 2007, the name of the faculty was changed to Civil Engineering & Geosciences

[2] E. Guestfriend (2015) 90% of All the Scientists That Ever Lived Are Alive Today. https://futureoflife.org/2015/ 11/05/90-of-all-the-scientists-that-ever-lived-are-alive today /? 1 = cn-reloaded

[3] In: A. van den Beukel (1994) . *Met andere ogen* (*With different eyes.* (in Dutch)) Ten Have/Baarn 227 p.

[4] C. Jongeneel (2008) *It's in a lab and it's right*. (in Dutch) Veen Magazines BV 157 p

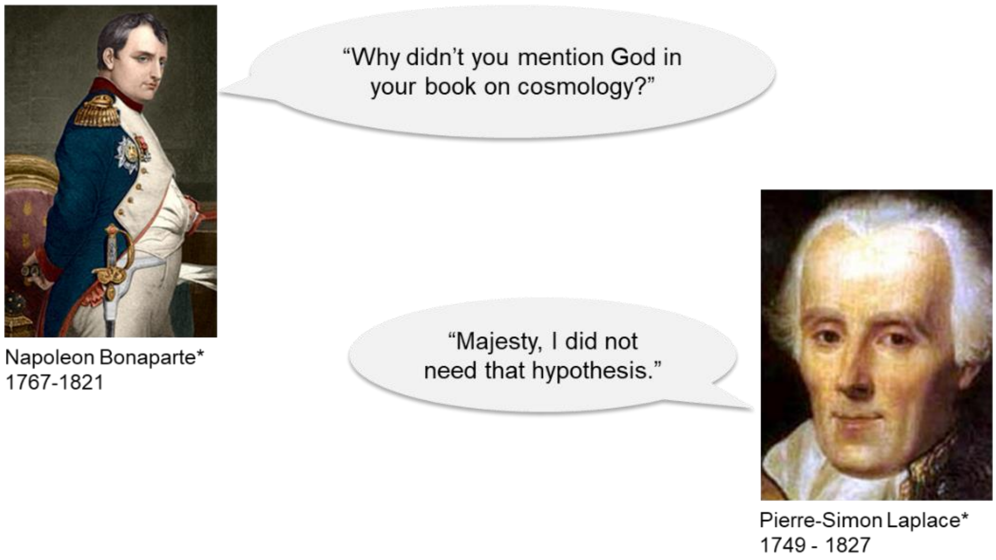

Fig. 1 Napoleon in conversation with Laplace (1749-1827) about his book on cosmology.

replied, "Sire, I did not need that hypothesis." The time when the concept of God was still necessary to make a scientific theory conclusive was passé for Laplace.

With his statement, Laplace may have been a little far ahead of the troops. But now, a few centuries later, we really do know much more. In their booklet *A Barrel of Fun* John & Stibbe[5] describe in a light-hearted way how a group of scientists had come to the conviction that the cosmos had gradually given up all its secrets. In order to fill in the gaps in knowledge, the concept of God had become definitively superfluous. For them the moment had come to inform God of this. A delegation travelled to the divine palace and knocked on the door. They were received with all respect and God listened attentively to their story. He was very impressed by their achievements. At the end of their talk, He suggested that they hold a contest. A 'people making' contest. That was right up their alley. They were allowed to start. One of the delegates bent down and scooped up a handful of soil. "No, no", God said, "you must bring your own soil." Then there was silence. Disillusioned, the delegation left the heavenly realms to return to earth, where they found themselves once again with both feet on the ground.

Scientists have to make do with what is available. They investigate *what is*. In this context, Einstein says that science can determine what is, but not what it should be. For the question why things are as they are, why there are things at all, for that you have

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[5] J. John, M. Stibbe (2009) *Weer en wind*. (in Dutch) Ark Media. 190 p. (Original: *A Barrel of Fun*)

* Pictures: Wikipedia

to go to religion. The philosopher Wittgenstein[6] would say: "What can be said at all can be said clearly, and what we cannot talk about we must pass over in silence."

What John & Stibbe, Einstein and Wittgenstein have in common is, that they call for modesty. We must make do with what is available. Why something is there, and why we are there, are questions to which the answer cannot be found behind a carbon atom or a distant celestial body. Carbon atoms and celestial bodies, and everything in between, in short, for everything that is available, we have our hands more than full! This also applies to concrete scientists. A handful of soil, if taken selectively, contains all the ingredients for making concrete. From that concrete he builds locks, roads, bridges, dams and skyscrapers. That looks glorious. But all these achievements also have their shadow sides. In recent years, the shadow sides have increasingly come into the spotlight. In the remainder of this speech we will look at this in more detail. We do this based on the idea that anyone who is bothered by the shadow, and who wants to change that, will have to focus on the object that causes the shadow. Running away from the shadow does not change the shadow. Intervening on the shadow-giving object, in order to change its shadow, does require knowledge of that object. The object which is the subject of this speech is the infrastructure. How did it come about and what determines its shadow. I would like to introduce further consideration of these questions with a story, with which I have started many of my lectures in recent years. The story of 'the treasure'.

Infrastructure as a product of science and technology

The Treasure

A father had three sons. Shortly before his death he called them to him. He told them that in the piece of land by the sea a treasure was hidden. After saying this he died. The sons went to the indicated location by the sea and began to dig. First, clearing stones. After removing the stones, a layer of fertile soil remained. They began to grow vegetables, and from the stones they built a shed. But they had not yet found the treasure. They dug deeper. The layer of fertile soil was now thick enough to plant large bushes and create a vineyard. From the stones they built a few houses where they could stay. They no longer had to return to the village every day to spend the night there. But they had not yet found the treasure. They dug deeper. They planted a forest and built up a herd of cattle. From the stones they built a city. They built roads, bridges and tunnels. Yes, it became a bustling city where it was good to live. Only the treasure

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[6] L. Wittgenstein (1921) *Tractatus Logico-Philosophicus*

they had still not found. But the value of everything they had built was many times greater than the treasure they were looking for. Yes, all that was the treasure!

This story is based on a few short sentences from the book *The mechanization of the world picture* by E.J. Dijksterhuis[7], a great scientist from the last century. The story illustrates how operating from a certain ideal can ultimately yield something that far exceeds the value of the original ideal. Dijksterhuis refers in this context to the alchemists. For centuries they made frantic attempts to make gold, never succeeded, but did make an enormous contribution to the development of modern chemistry!

The control motive

The treasure for which attention is called in this speech is that of the physical infrastructure. We shall see in a moment that infrastructure represents enormous capital, and may rightly be called a treasure. But before we deal with the value of this treasure, let us first ask ourselves what ideal was ever envisioned that preceded the creation of the modern infrastructure. Of the possible answers to this question I choose for the motive 'control'. Control as an ideal and driving force behind developments in construction and, in a more general sense, in science and technology. The theme of control is addressed in a fascinating way by Staudinger and Behler[8] in their book *Chance und Risiko der Gegenwart*. There they outline how people have been trying to get a grip on the world around them for centuries. Behind phenomena in the real world the actions of ghosts and gods were assumed. That was their ‘model’ of reality. In order to influence the invisible world of ghosts and gods, people turned to shamans and witch doctors. Those were supposed to be able to penetrate the invisible reality behind the visible world with special spells and rituals, in order to influence and control this reality.

Modern man has long since said goodbye to this old, metaphysical concept. There are no ghosts or gods hidden behind every-day phenomena, but natural laws. Particularly during the Enlightenment, important steps were taken in the demythologizing of our world picture. The previously mentioned quote from Laplace, that for his cosmology he no longer needed the hypothesis of God, marked a new era. Reality is not governed by magic words and rituals, but follows laws of nature. Those who wanted to control reality and bend it to their will, should turn to science. Knowledge of fundamental natural laws gives us the possibility of manipulating reality and creating a new world.

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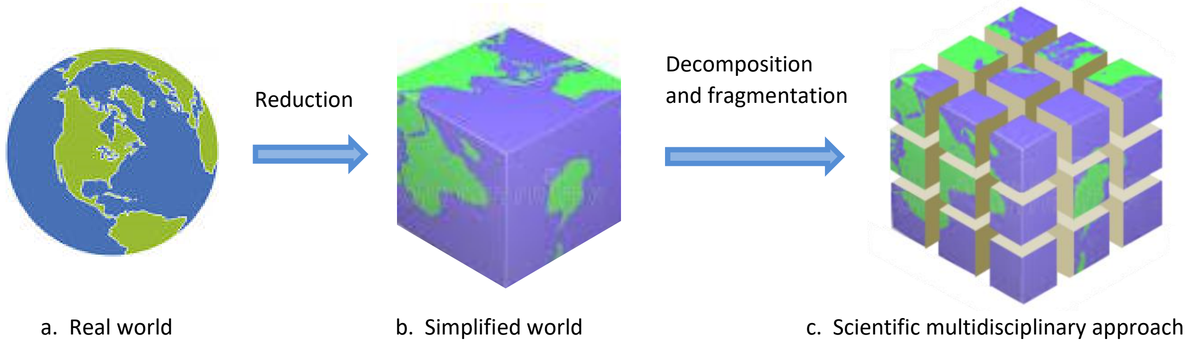
[7] E.J. Dijksterhuis (1950) *The mechanization of the world picture*. (Dutch and English) Meulenhoff. 594 p.

[8] H. Staudinger, W. Behler (1976) *Chance und Risiko der Gegenwart*. Deutsches Institut für Bildung und Wissen. Paderborn. F. Schöningh, 385 p.

Reduction and fragmentation

The method, used in science to achieve total control of reality, is that of reduction, decomposition and re-composition. The first stages of this method are shown schematically in Fig. 2. In the first reduction step the complex reality is reduced to a reality in which everything is measurable and weighable. This step is symbolized here by replacing a sphere with a cube. The cube now stands as a 'model' for the spherical reality. In a metaphorical way, the claim that the model is a one-to-one representation of reality is thus abandoned. The metaphorical element is in the special character of the number π, which is needed to determine the volume of a sphere. In his valedictory address in 2010 Roos[9] recalls that the number of known decimals of π is now 5,000,000,000,000. He notes that this number is still relatively small if we consider that the number of missing decimals is still infinitely large. Thus the number π reminds us of a world in which there was still room for the infinite and intangible, but which has been lost with the adoption of a reduced reality. In the cube, everything is exact. Only ...... a cube is not a sphere! Those who forget this, and hold the model up to the reality it represents, not only choose a form of voluntary poverty, but also overestimate the scope of the concept of 'model'.



a. Real world

b. Simplified world

c. Scientific multidisciplinary approach

Fig. 2 Schematic of the method of reduction and fragmentation in science.

To penetrate deeper into the reduced reality, the cube is further divided into smaller units (Fig. 2c). We speak of subject areas or disciplines. Within these subject areas, further reduction takes place. Reality is peeled off to the level of molecules and atoms, or even smaller. This is shown schematically in Fig. 3. The benefit of this method is that within individual fields great depth can be achieved. However, this benefit does not just fall to us easily. There is a hefty price to pay for it. The price is *fragmentation* of reality and the creation of a large number of *interfaces* between disciplines and scale

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[9] C. Roos (2010) *Does tireless work overcome everything*? (in Dutch) TU Delft. Valedictory address. MailSupport, 56 p.

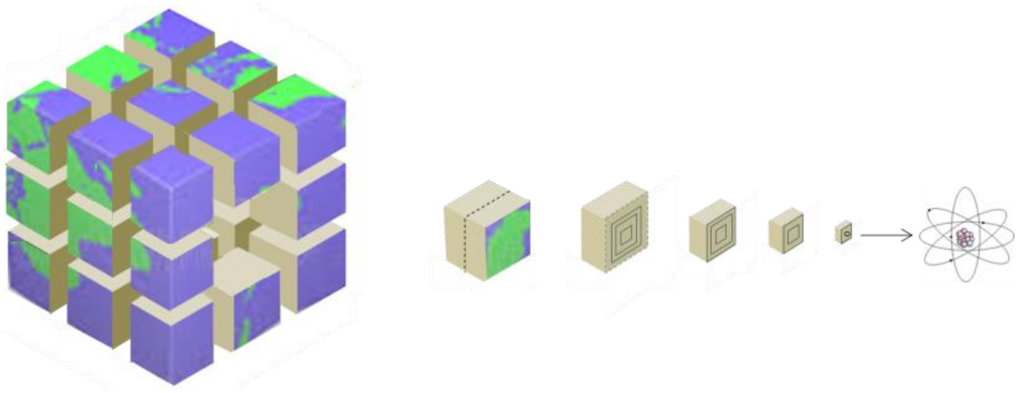

Fig. 3 Schematic representation of increasing reduction within one (mono) discipline.

levels. There is also the danger of *absolutizing* individual disciplines. This danger increases the more a particular discipline is deemed suitable to serve as a vehicle for realizing prosperity and growth. How excessive growth of individual disciplines can disrupt the harmony within reality as a whole will be discussed in detail later.

Fragmentation in construction

The construction sector has not proved immune to the fragmentation process outlined here. To illustrate this, we first look at an original definition of architecture:

> *'Architecture is the art and science of designing and constructing buildings and other physical structures for human shelter or use'.*

The strength of this definition lies in the connection between art and science on the one hand, and a clearly defined purpose on the other. The purpose of building is to provide facilities to protect people and make living together possible. Protection is needed from wind and weather, heat and cold, rising water, wild animals and hostile nations. Roads and bridges are needed for transportation of people and goods. In addition to knowledge, which is necessary for the realization of constructions, architecture also includes art. When construction projects were still manageable in size, both art and science were in the hands of one person, the builder. The builder knew everything, designed everything and oversaw everything. But those days are long gone. Already around the year zero, Vitruvius, the compiler of a classic ten-volume work on the art of building, sighed that structures had become so complex that it was impossible for one person to master all the disciplines of construction[10]. Fragmentation of construction came on the scene. The strong connection between art and science was in-

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[10] T. Peters (1999) Vitruvius , *Handboek Bouwkunde*. Anthenaeum – Polak & Van Gennip. 393 p.

creasingly lost. Interfaces arose between parties, with unavoidable obstacles and challenges for communication and collaboration. In spite of this development, which was in fact unfavourable for the building industry, a great deal has been achieved over the centuries. Construction, and the infrastructure it created, have often been crucial to developments in numerous sectors and to the growth of regional and national economies.

Infrastructure in a global perspective

Growth of the gross national product

Developments in science and technology are often seen as a precondition for growth. This growth can be expressed in the Gross Domestic Product (GDP). Roser[11] analysed the growth of the world GDP (WGDP) from the year 0 to the year 2000. In Fig. 4 this growth is shown with a green line. The growth of WGDP in the subsequent period 2000-2018 is shown with a red line[12]. The curve shows that in the first eighteen hundred years of the period under consideration, the growth of the WGDP is insignificant compared to the growth in the last two hundred years. The enormous growth starts at the time of the industrial revolution, around the end of the eighteenth and beginning of

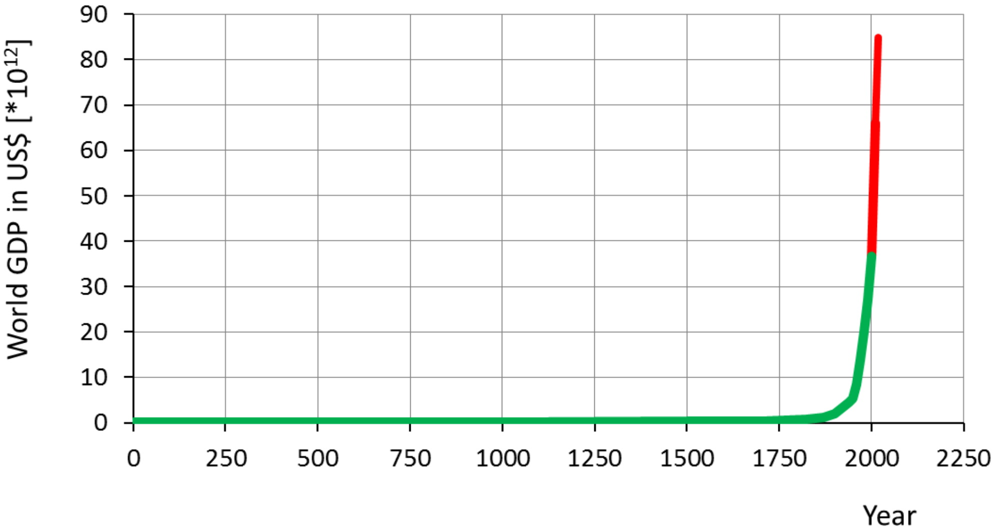

Fig. 4 Evolution of global GDP from 0 to 2018 (To Roser[11] (green curve) and World Bank[12] (red part of the curve)).

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[11] M. Roser (2017) Economic Growth. Our world in data. https://ourworldindata.org/economic-growth .
See also : The Maddison Project. http://www.ggdc.net/maddison/maddison-project/home.htm , 2013 version.

[12] Data from World Bank https://en.wikipedia.org/wiki/List_of_countries_by_total_wealth

the nineteenth century. In the sixties of the last century scientists started to worry about whether the earth could cope with this enormous growth. Warnings came, among others, from the Club of Rome with their well-known report "Limits to Growth[13]". There has certainly been reacted to that report, but it has not led to a slowdown in growth. On the contrary! As the curve in Fig. 4 shows, growth has continued unabated in recent decades.

Fig. 5 zooms in on the growth of the WGDP since 1950. This growth, indicated by the red line, can be explained by the growth of the world population (blue line), and an even stronger increase in per capita consumption (green line). In addition to the growth of the WGDP, the figure also shows the increase in cement production. We see that during the period under consideration, cement production grew even faster than the WGDP. This should not surprise us either. Growth of the WGDP requires good infrastructure, and for that a lot of concrete is needed. We can safely say that when it comes to prosperity and growth, the material concrete has mattered and still matters!

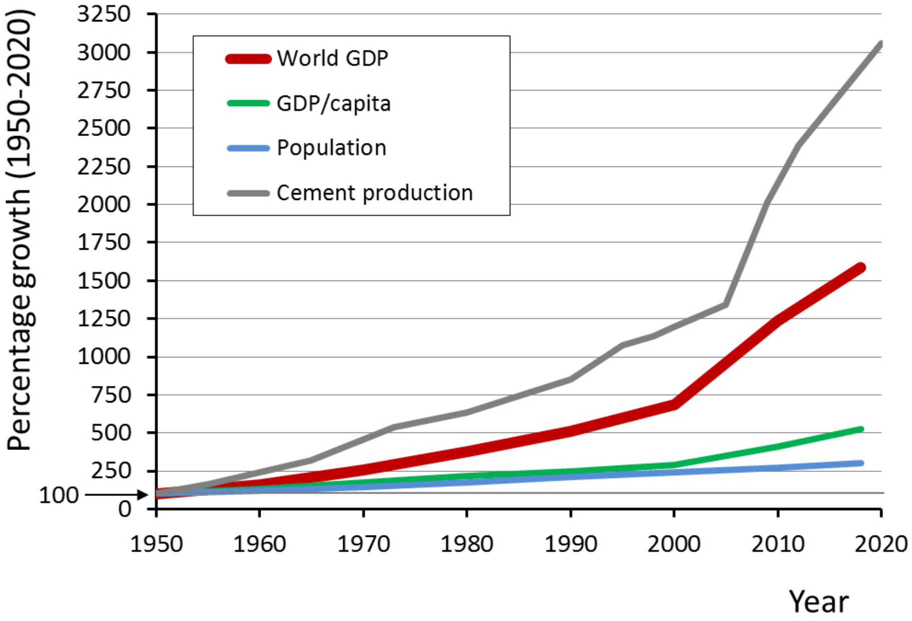

Fig. 5 Percentage growth of the World GDP, world population, GDP per person and cement production in the period 1950-2018 (see also Van Breugel[50]).

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[13] Club of Rome (1972). Limits to Growth (The Limits to Growth)

Value of infrastructure

The growth of the WGDP has been accompanied by an increase in national capital, i.e. wealth. Global Gross National Wealth (GNW) in 2018 has been estimated at US$ 320 trillion[12]. Of this, physical infrastructure makes up about half[14], i.e. US$ 160 trillion. Of this, US$ 90 trillion is in houses and US$ 70 trillion in civil infrastructure. By way of comparison: the total value of the infrastructure is about twenty times that of all the gold - about 190,000 tons - ever mined (price level 2019). Therefore, it is really not an exaggeration to see infrastructure as a treasure! A treasure that represents enormous capital. The latter determines us in our responsibility to handle this treasure with care. This care is especially necessary when we realize that this treasure is continuously subject to ageing.

Budgets for replacement and growth of infrastructure

As a result of ageing, the lifespan of infrastructure is limited. The design life of structures is between 50 and 100 years, with outliers to 150 and 200 years. In exceptional cases, a lifespan of up to 1000 years is required, for example for structures for the storage of radioactive waste. To maintain this infrastructure, assuming a value of US$ 160 trillion and an average lifespan of 50 years, an annual replacement budget of US$ 3.2 trillion will be required.

The replacement task is particularly important in industrialized countries with a more or less mature infrastructure. In emerging economies, investments are mainly made in infrastructure that is needed to realize growth. Over the period 2013-2030, global growth will require US$ 57 trillion[15]. That comes down to US$ 3.2 trillion per year. We saw earlier that an equally large amount is required annually to replace existing infrastructure. In the period up to 2030, therefore, growth and maintenance of global infrastructure will require US$ 6.4 trillion annually. To reduce this large sum to a human scale, we can divide it by the world population of 7.7 billion (2019). Then we see that a world citizen has to spend US$ 830 annually on maintenance and growth of the infrastructure. At first glance, this does not seem too bad. However, a few caveats are in order. First, an annual amount of US$ 830 per capita is indeed relatively small when compared to the gross national product per capita in the rich countries. In the world's ten richest countries, GDP per capita ranges between US$ 54000 and US$ 114000 per year[16,17] (Table 1). This is substantially more than in the ten poorest countries. There, GDP per capita ranges from US$ 303 to US$ 544 per year. It is clear that in the latter

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[14] AE Long, Sustainable bridges through innovative advances. Institution of Civil Engineers, presented at Joint ICE and TRF Fellows Lecture. 23, 2007.

[15] R. Dobbs, et al. (2013) Infrastructure productivity: How to save $1 trillion a year. McKinsey Global Inst. , 88 p.

[16] World Bank data. 2018

[17] The amounts shown here are mainly to illustrate the differences between poor and rich countries

Table 1 Gross Domestic Product (GDP) per capita in rich and poor countries[16]

Nations	Population	GDP/inhabitant/year US$
10 richest countries	49 billion	54000 – 114000
10 poorest countries	210 billion	303 - 544

countries an annual amount of US$830 per capita for infrastructure cannot be raised. However, it should be noted - and this is the second observation - that the per capita value of infrastructure in rich countries is many times greater than in poor countries. In the rich countries the amount that has to be paid annually to maintain the infrastructure is, therefore, a multiple of US$ 830 per capita.

The numbers and amounts mentioned here give us an impression of the value of our infrastructure. But they also confront us with the - worldwide - unequal distribution of capital assets. This, of course, is not a new fact. It does show that a consideration of infrastructure, and the associated budgets for replacement and growth, is not possible without facing the issue of equitable distribution of goods and property. In what follows, it will become apparent that this is a recurring theme as soon as the aspect of sustainability comes up for discussion.

Concrete under fire

Concrete is the most widely used building material on earth. Per capita, approximately 1.0 m^3 of concrete is produced annually[18]. Without concrete there is no infrastructure, and without a good infrastructure there is no flourishing economy. Yet the image of the material concrete is not good. Watts[19] even calls concrete the most destructive material on earth. Vidal[20] adds that concrete is plunging us into climate catastrophe. "Concrete fills our rubbish dumps, overheats our cities, causes floods that kills thousands of people - and fundamentally changes our relationship to the planet." Now it is known that there are people who do not like concrete. But what Vidal is saying here goes a long way. Nevertheless, we cannot simply ignore these statements. They were

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[18] Meyer, C. (2020) Concrete Materials and Sustainable Development in the United States

[19] J. Watts (2019) Concrete: the most destructive material on earth. The Guardian Concrete Week. https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth

[20] J. Vidal (2019) Concrete is tipping us into climate catastrophe. It's payback time. The Guardian https://www.theguardian.com/cities/2019/feb/25/concrete-is-tipping-us-into-climate-catastrophe-its-payback-time-cement-tax

not made by professional complainers in some corner of the world. These statements were made during Guardian Concrete Week, a platform where people come together who really know what is going on. What Watts and Vidal claim, therefore, deserves a thorough evaluation. This involves both the content of their statements and the context in which they made them. Regarding the latter: the context was that of the current climate issue.

The negative image of concrete is mainly due to the CO_2 emissions associated with the production of cement. Cement production accounts for 5 to 8 percent of global CO_2 emissions. CO_2 emissions from the entire concrete sector amount to about 10% of global CO_2 emissions. Steel production is associated with similar emissions. Together, the production and application of concrete and steel account for the emission of 6.7 billion tons CO_2 per year[21]. The question now is what options the construction sector has to reduce CO_2 emissions and, more generally, to mitigate the environmental impact of the construction sector. In this speech I will limit myself to the options available to the concrete sector. We first look at the material concrete itself. How is it made? What is cement made of and how does concrete get its strength? Then we focus on the construction process. Where are the opportunities to reduce the environmental impact of construction, what does that bring us, and what is the role of models in all of this.

Building with concrete - An initial exploration *)

Concrete as a material

Concrete is a complex, heterogeneous material. The main constituents of concrete are cement, sand, gravel and water. Cement is a fine powder, with a grain size of 0.5 to 100 μm. When cement reacts with water, reaction products are formed. Together with unreacted cement grains, these reaction products form cement paste, with which sand and gravel particles are "cemented" together. During the reaction of cement with water, heat is released and the temperature of the concrete rises. Gradually, as the reaction proceeds, the concrete becomes stiffer and stronger. The strength class of concrete is characterized by its compressive strength after 28 days, reached after hardening at a temperature of about 20°C. Eighty to ninety percent of the concrete used in

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[21] K. van Breugel (2017) Aging infrastructure and circular economy: challenges and risks Proceedings of the 2nd World Congress on Civil, Structural, and Environmental Engineering (CSEE'17) , Barcelona, 12p.

*) The following text is more technical in nature. The more contemplative part of this lecture will be resumed with the paragraph "Saving on infrastructure in the Netherlands - The new natural gas" on p. 26.

The Netherlands falls in the strength class 25 to 45 N/mm^2. The tensile strength of concrete is much lower than the compressive strength, usually only 10% of it. Because of the relatively low tensile strength, concrete elements are provided with reinforcement. If the tensile strength of the concrete is locally exceeded upon loading, the reinforcement takes over the role of the concrete. The concrete is then cracked. The trick of designing reinforced concrete structures is to dimension the reinforcement so that the crack width remains within acceptable limits. As long as crack width criteria can be met, cracks are not seen as damage, but are part of a sound design in reinforced concrete.

Large-scale application of concrete dates back to the early twentieth century. Impressive structures were built such as dams, bridges and viaducts. This type of construction often involved large sizes and large volumes. We then speak of mass concrete. In these large concrete volumes, the temperature can rise considerably during the hardening process. When cooling down later, this can lead to crack formation. Severe cracking is undesirable from a durability point of view and for decades an important reason for intensive research into factors that influence the curing process and the probability of cracking. To get a good picture of these factors, we have to descend to the level of atoms and molecules. Then we can make the figurative bridge to the behaviour of concrete structures, with dimensions from tens to hundreds of meters.

Length scales and the role of models

Fig. 6 shows the length scales that come into the picture when studying and making concrete and concrete structures. Materials scientists and concrete technologists study the behaviour of concrete at length scales from 10^{-10} m (1 Angstrom) to 10^{-2} m (1 cm). That is a range of eight orders of magnitude. Structural engineers focus on the behaviour of concrete structures with dimensions up to hundreds of meters, while looking at crack widths down to tenths of millimetres. That is a range of six orders of magnitude. Over the years, an enormous amount of knowledge has been developed at all these scale levels and is incorporated into the design and construction process. Models played a crucial role in this. Models make it possible to link knowledge on successive scales and to make all this accessible for practice. Practical applications include constructions for 'human shelter or use', but also many other structures. These structures will appeal more to the imagination if they are the result of a harmonious interaction of scientific knowledge and art. An example of a constructively and architecturally challenging creation is the apartment complex Habitat 67 in Montreal (Fig. 7a). This complex was built in the 1970s. It is appealing because of its architecture and the choice to keep the concrete completely in view. The apartments are placed as separate units and then connected to each other. From a constructive point of view, the connections between the cubic units are a major challenge. It would have been have much

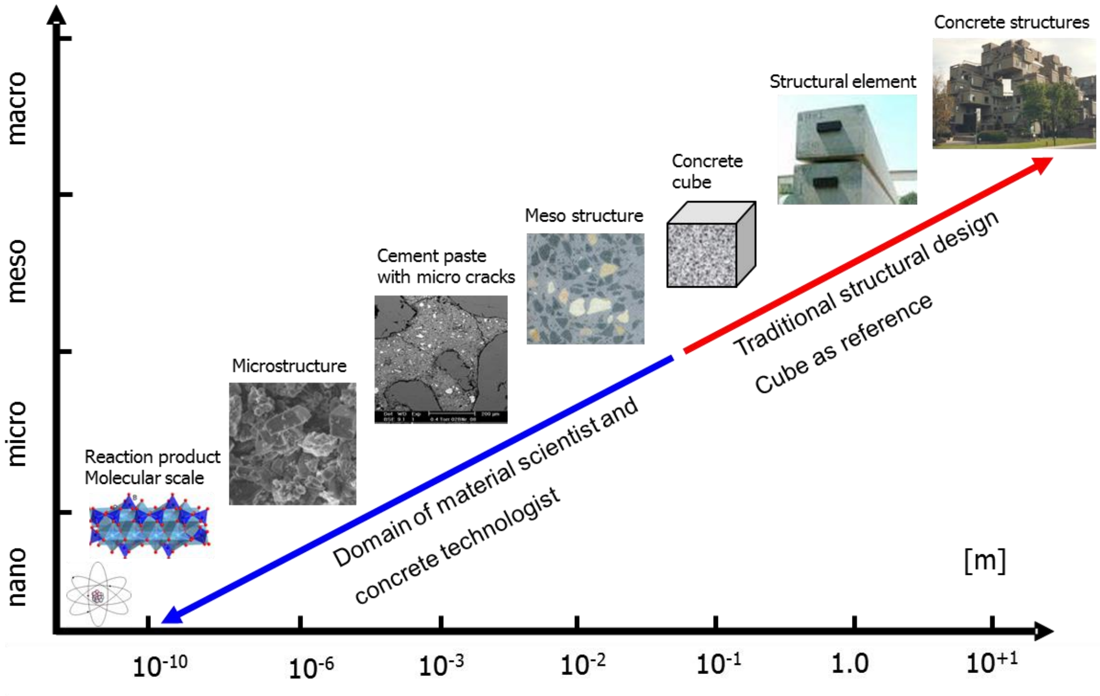


Fig. 6 Schematic representation of multiscale approach in materials and construction domain.

easier to place the units in a regular grid, as outlined in Fig. 7b. But that is emphatically not chosen in this complex. In a figurative sense, you could see the whole apartment complex as the result of decomposition of a composite cube, followed by a creative process of re-composing and connecting the individual units. The strong deviation

a. Architecture = Science + Art

b. Only science

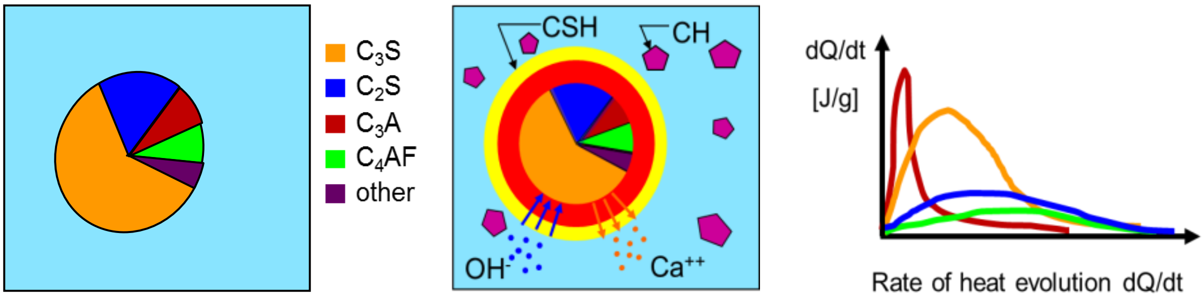
Fig. 7 Apartment complex Habitat 67, Montreal, Canada.

from a simple composite cube has resulted in an appealing structure. But a high price has been paid for this! The connections, i.e. interfaces, between the cubic units are complicated. Consider that this complex is exposed to large temperature differences: in winter to -30°C and in summer +30°C. Large temperature differences lead to large forces in the construction. All in all, it is an enormous task for structural engineers to control cracking as a result of the imposed temperature and shrinkage differences!

More about concrete

The reaction of cement with water

The hardening process of concrete is a complex physicochemical process. It has already been mentioned that the reaction of cement with water, called hydration, releases heat. The amount of heat produced and the rate of heat release depend on the chemical composition and fineness of the cement. These are also the factors that the concrete technologist can play with to control the curing process. To make this clear, we will look in more detail at the composition of a classic Portland cement. Fig. 8a shows - schematically - a cement particle with the four main constituents of cement: di- and tricalcium silicate (C_2S and C_3S), tricalcium alumunate (C_3A) and tetracalcium aluminate ferrite (C_4AF). The main reaction products formed when cement reacts with water are calcium silicate hydrate (CSH) and calcium hydroxide (CH). The volume of the reaction products is larger than that of the original cement. This means that a reacting cement particle ‘grows’, as it were. An outward growing shell of reaction products forms around the cement particle (Fig. 8b). Reaction products that are formed within the original contours of the cement particle are called ‘inner product’ (Fig. 8b, red shell). Reaction products outside these contours are referred to as 'outer product' (Fig. 8b, yellow shell).



a. Cement grain in water

b. Hydrating cement grain

c. Rate of heat liberation

Fig. 8 Schematic representation of a stages in the reaction process and rate of heat liberation.

The rate at which individual cement constituents react with water is different. C_3A and C_3S react relatively quickly. The rate of heat release, dQ/dt, is shown graphically in Fig. 8c. The fineness of the cement also affects the reaction rate. A finely ground cement has a large surface area that can react with water. The reaction then proceeds rapidly, and the rate of heat release and development of concrete properties also increases.

Optimizing the mixture composition - Reduction of CO_2 emission

When choosing a particular chemical composition and fineness of cement, the concrete technologist may have several goals in mind. He may want to keep the temperature of the concrete low during curing. He can then opt for a coarse cement with a low C_3S and C_3A content. This will result in a slow strength development. It is also possible that he wants a fast strength development. In that case he will choose a fine cement with a high C_3S and C_3A content. Today he would probably also strive for the lowest possible CO_2 emission per cubic meter of concrete. How this can be achieved will be illustrated by examining three mixtures in more detail. The mixtures are shown schematically in Fig. 9. Mixture A is made with a coarse cement, mixture B with a fine cement, and mixture C with a fine cement, part of which is replaced with an inert filler.

The coarse mixture A, because of the small specific surface area of the cement, will react slowly. Slowly, sand grains will be cemented together by the ‘growing’ cement particle. The coarse cement particle will be left partially unhydrated (Fig. 9d).

The fine cement B has a large specific surface area and will react quickly, which results in rapid strength development. All the cement reacts (Fig. 9e), which will lead to a significant heat release. The release of a lot of heat means a high temperature of the concrete and, on subsequent cooling, a significant probability of cracking. Moreover, a high reaction temperature will produce a cement paste with a relatively coarse pore system and lower final strength. A somewhat lower final strength is usually not a problem, but a coarse pore system can certainly cause problems. The resistance of the concrete to penetration of aggressive substances then decreases, and the structure will be less durable. So there is a price to pay if we want rapid strength development in order to build quickly!

From the concrete technology point of view the answer to the disadvantages of mixture B is, at least in part, to optimize the particle packing of the cement and aggregate. With a high packing density of the aggregate, a smaller volume remains that still needs to be filled with cement paste. Consequently, a lower cement content will suffice (mixture C, Fig. 9c). Good strength can still be achieved with less cement because the ‘growing’ cement particles have to bridge shorter distances between the aggregate particles (Fig. 9f). Thus, two birds with one stone are killed. Less cement means less CO_2 emis-

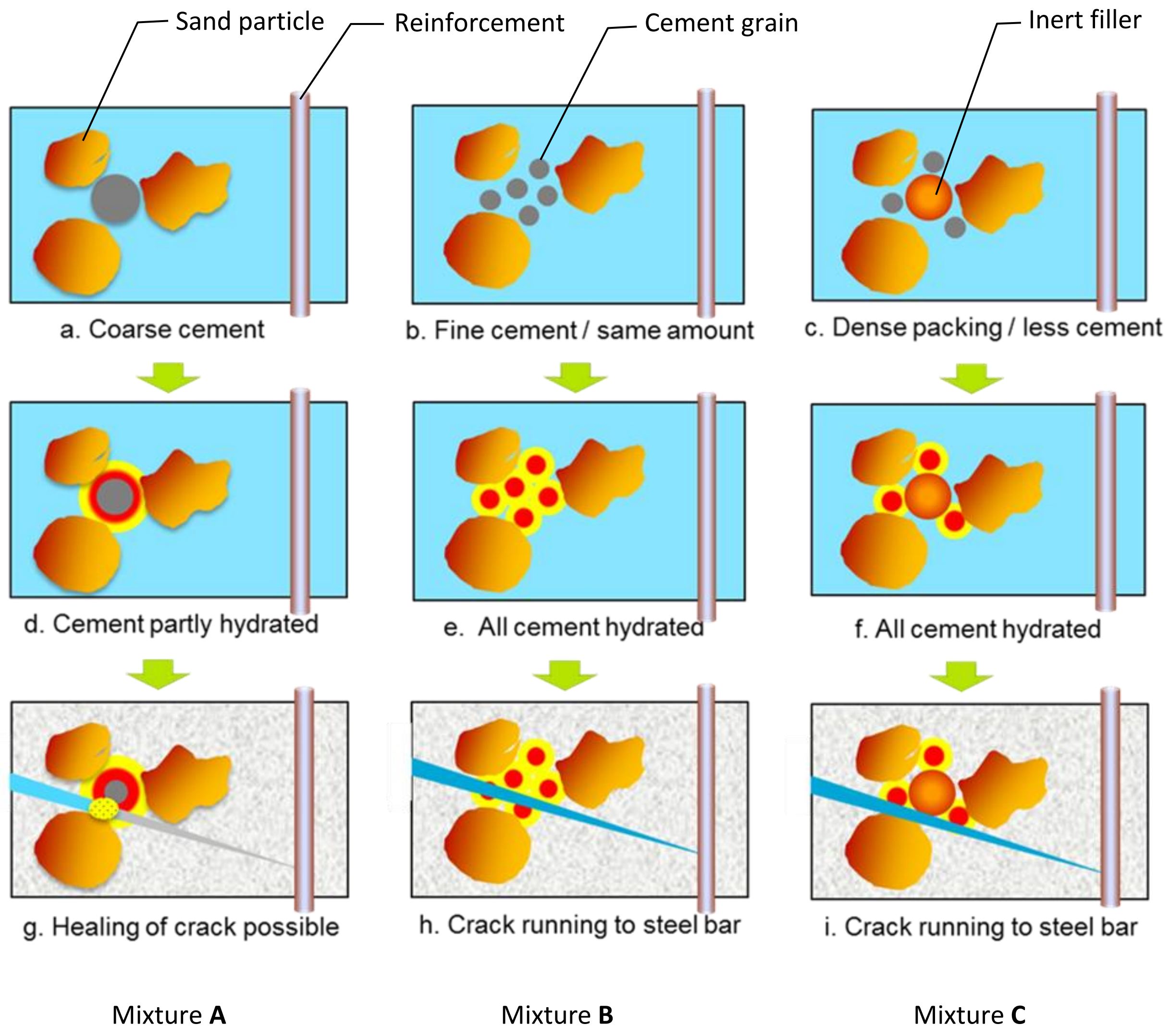


Fig. 9 Characteristics of concrete mixtures. A) Mixture with coarse cement; B) Mixture with fine cement; C) Fine cement with dense granular packing of aggregate and/or inert filler (e.g. very fine sand). (● cement; ● inner product; ● outer product; ◢ crack)

sions per cubic meter of concrete, and thus a lower environmental impact. At the same time, less cement also means less heat generation and a lower probability of cracking in the cooling phase of the hardening process.

If we now compare the mixtures A, B and C, mixture C tends towards the ideal mixture. Less cement, less heat development, a relatively fast strength development and also a good, sometimes even very high final strength. Because cement is much more expensive than sand and gravel, a high packing density also provides an economic advantage. But still a side note. Concrete is a brittle material and is, therefore, susceptible to cracking. If a crack develops in the concrete, mixture A has an advantage over mixtures B and C. After all, in the coarse mixture A there is still an amount of non-hydrated cement present (Fig. 9d). When water penetrates a crack, it can react with the remaining cement and the crack can close again (Fig. 9g). The concrete repairs itself! Mixtures B and C no longer have this self-healing ability (Figs. 9h and 9i). In other words, the slow mixture A is more robust than the faster mixtures B and C.

Long-term behaviour of bridge decks with old and modern concrete mixtures

The suspicion that the coarse and slow mixture A is more robust than the faster mixtures B and C finds support in an extensive study in the United States on the behaviour of concrete bridge decks. Mehta et al.[22] examined the long-term behaviour of bridge decks manufactured during four consecutive periods in the last century. The periods are shown in Fig. 10 on the horizontal axis. Mehta found that old bridge decks made before 1930 exhibited fewer problems than bridge decks made with more modern concrete mixtures. The durability problems increased with increasing cement fineness, higher contents of the more rapidly reacting C_3A and C_3S, and a low water-cement factor (applied to achieve high strengths). This development in concrete mixtures was the answer to the desire to build faster, bigger, stronger and higher. Or in other words, the driving force behind this development was the economy! Today, the environmental requirement to reduce CO_2 emissions is added to this wish list. Reducing the amount of cement in the concrete seems a logic shortcut to meet both the economic and en-

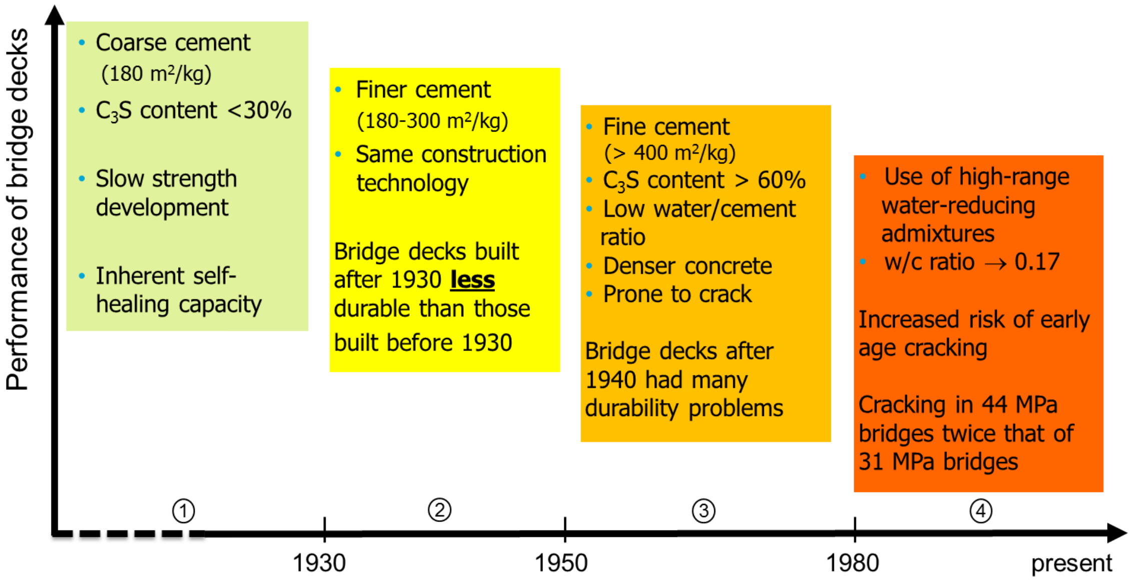


Fig. 10 Ranking of long-term behaviour of concrete bridge decks built in the period before 1930 up to the early 21st century. Vertical axis: performance (after Mehta et al[22]).

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[22] K. Mehta et al. (2001) Building Durable Structures in the 21st Century. Concrete Int., Vol. 23 (3) pp. 57-63

vironmental requirements. But when this short stroke leads to crack-prone structure with less self-healing capacity, and therefore a shorter life span, the intended economic and environmental benefit can eventually evaporate completely and even, as shown in the example of the bridge decks, turn into its opposite!

Models for concrete

Numerical models for hardening processes and microstructure development

In the foregoing we dwelt on the reaction of only a few individual cement particles with water. In reality, concrete contains millions of cement particles. When they all start to react, they come into contact with each other and together they form hardened cement paste. A number of numerical models have been proposed in the past to simulate the formation of cement paste. One of these models is the so-called pixel model[23], shown in Fig. 11a. In that model, cement particles are considered to consist of small cubes, called voxels, with a typical size of 1 μm^3. To these voxels certain properties are assigned. They make random walks through the cement paste, react with other voxels and thus form a microstructure. Another model is known as HYMOSTRUC[24], and was developed at Delft University of Technology. In that model, cement particles are represented as small spheres that grow slowly and thus come into contact with each other. This model dates back from the early 1980s, and was further developed by Koenders[25], Ye[26] and Peng[27]. Fig. 11b shows a virtual microstructure generated with the program HYMOSTRUC3D.EXD[27]. Such a virtual microstructure can be used to describe, for example, the development of material properties of hardening concrete[24], or for investigating microcracking in cement paste loaded by an external tensile force or an imposed strain[28] (Fig. 11c). Advanced hydration and microstructure models are also used as the basis for computer programs used to simulate the behaviour of complete concrete structures in the curing phase. Let’s have a look at those programs in the next paragraph.

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[23] Bentz, D.P., Garboczi E.J. (1989) A digitized simulation model for microstructural development. Advances in Cementitious Materials, Ed. S. Mindess, Westerville, Ohio, USA, Am. Ceramic Society, pp. 211-226.

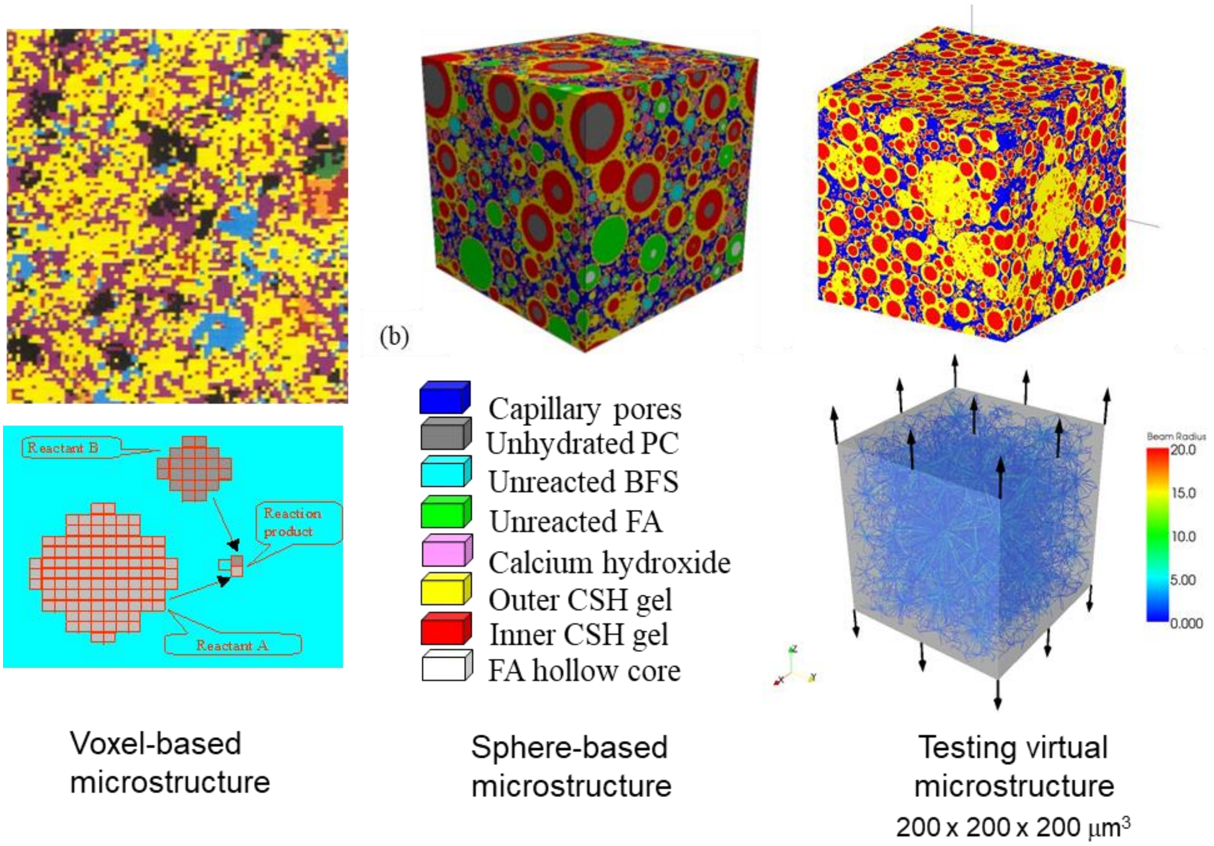
[24] K. van Breugel (1991) Simulation of hydration and formation of microstructure in hardening cement-based materials. PhD Thesis, TU Delft, 305 p.

[25] E.A.B. Koenders (1997) Simulation of volume changes in hardening cement-based materials. PhD Thesis, TU Delft, 171 p.

[26] G. Ye. (2003) The Microstructure and Permeability of Cementitious Materials. PhD Thesis, TU Delft, 186 p.

[27] G. Peng (2018) Simulation of hydration and microstructure development of blended cement. PhD Thesis, TU Delft, 223 p.

[28] Z. Qian (2012) Multiscale modelling of fracture processes in cementitious materials. PhD Thesis. TU Delft, 151 p.



a. NIST model[23] b. HYMOSTRUC3D-EXD[27] c. Testing virtual microstructure[28]

Fig. 11 Examples of numerically generated virtual microstructures of cement paste.

Models for cracking in hardening concrete structures

Advanced numerical models for describing the hardening process in concrete find their way to the practice through so-called Concrete Curing Control Systems. These systems are used to simulate the curing process in concrete structures as a function of the concrete mixture composition, structure dimensions, formwork type, pouring sequence and weather conditions. An example of a practical application of a Concrete Curing Control System concerns the simulation of the temperature and stress development in a hardening concrete wall that is poured on a rigid foundation slab. Such a situation is shown schematically in Fig. 12. In the wall cracks may occur at the surface when the wall cools down at the outside while the core of the wall is still warm. These surface cracks can be detrimental to the durability of the structure. In addition to surface cracks, so-called through-cracks can occur. These cracks are undesirable because they jeopardize the water tightness of the structure. Through-cracks occur when the core of the wall cools down over time. The wall as a whole then wants to shrink, but the rigid foundation slab will prevent this and the concrete wall might crack. By using a Concrete Curing Control System the hardening process can be controlled in such a way

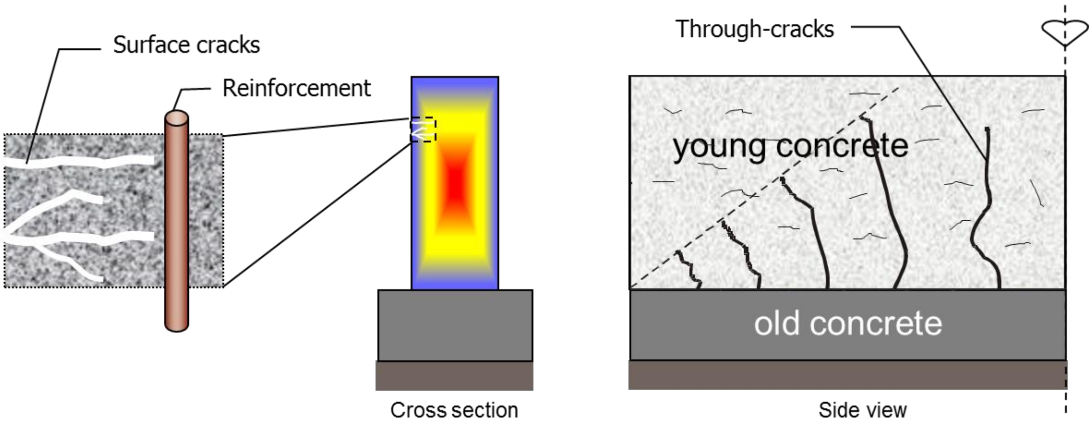


Fig. 12 Concrete wall poured on rigid foundation slab. Probability of formation of surface cracks and through-cracks (after Sule[29]).

that the probability of cracking is minimal. The concrete temperature plays a crucial role in this analysis. In view of what follows we shall have to dwell a little longer on the influence of temperature on the curing process. In particular, the rate at which the curing process takes place deserves our attention.

Effect of temperature on the length the construction phase

The rate of the hardening process determines, at least in part, the duration of the construction phase of a concrete structure. The construction phase includes making the formwork, placing the reinforcement, making and pouring the concrete, the hardening process, demoulding of the structure and finishing of the concrete surface. The upper part of Fig. 13 shows some illustrations of these operations. The lower part of the figure shows the so-called ‘performance curve’ of a structure. This curve shows, in addition to the construction phase, also the subsequent operation phase and the degradation phase. For economic reasons the construction phase should be kept as short as possible. The rate at which the concrete hardens plays an important role in this. The rate of hardening depends on the reaction temperature. The effect of temperature on the rate of hardening can be described by an Arrhenius function[30]. This formula describes the rate S(T) of physicochemical processes as a function of an experimentally determinable constant A, the temperature T [K], the activation energy E_A [J/mol] and the universal gas constant R [J/mol.K]. In formula form:

$$S(T) = A \cdot e^{-\frac{E_A}{RT}}$$

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[29] M. Sule (2003) Effect of reinforcement on early-age cracking in high strength concrete, PhD Thesis, TU Delft, 143 p.
[30] S. Glasstone et al. (1941) The theory of rate processes. McGraw Hill Book Comp. NY.

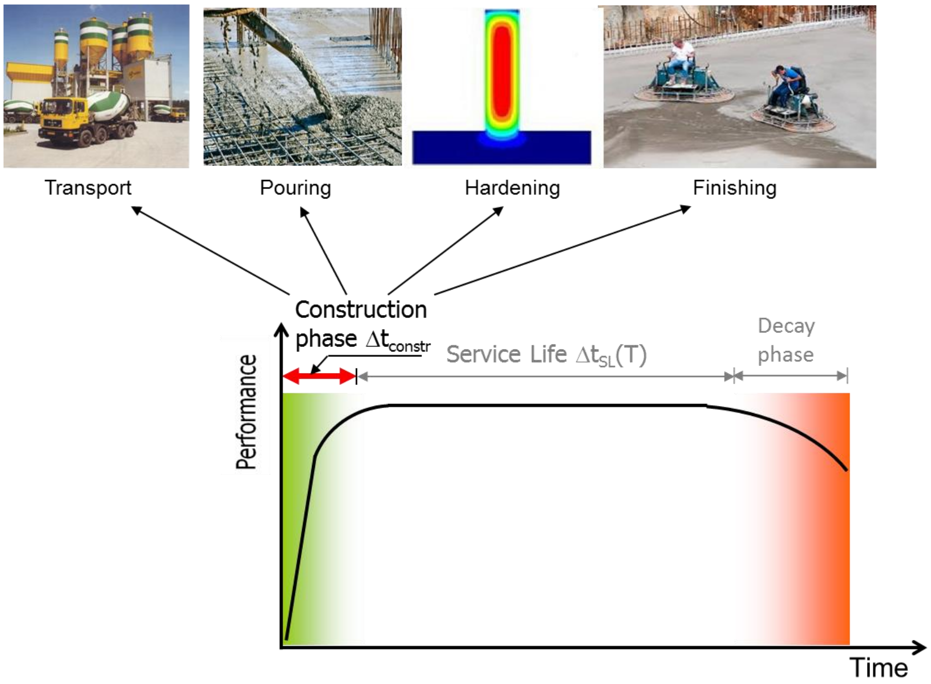

Fig. 13 Performance curve of a concrete structure, showing successive stages in the lifetime of a structure, with focus on the construction phase.

For the duration of the hardening process Δt_{constr}, counted from the time of pouring the concrete until reaching the required strength, it can be derived based on the Arrhenius function:

$$\Delta t_{constr}(T_{real}) = \Delta t_{constr}(T_{ref}) \cdot e^{-\frac{E_A}{R} \cdot \left(\frac{T_{real} - T_{ref}}{T_{real} \cdot T_{ref}}\right)}$$

where Δt_{constr} (T_{real}) is the hardening time at the real temperature of the concrete T_{real} [K], and Δt_{constr} (T_{ref}) is the hardening time at a reference temperature T_{ref} [K] (often 20°C, 293 K)[31]. Values for the activation energy E_A depend on the type of cement and the concrete composition. Common values are between 20 and 60 kJ/mol.

Although the hardening of concrete is an extremely complex process, the effect of temperature on the hardening time appears to be well described with this relatively simple Arrhenius formula. For common values of the activation energy a 10°C higher reaction temperature will almost halve the hardening time, resulting in a much shorter construction time. Economically this is beneficial, at least in the short term. However, as

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[31] The actual temperature T_{real}, and the reference temperature T_{ref} may also be functions of time, i.e. $T_{real}(t)$ and $T_{ref}(t)$

we have seen before, a high concrete temperature during hardening will result in a more porous concrete, while also increasing the probability of cracking on cooling, which in turn is unfavourable for the quality of the concrete. With the help of an advanced Concrete Curing Control System the hardening process can be controlled in such a way that an optimum is achieved between the construction speed on the one hand and the quality of the structure on the other. To achieve a high initial quality, a relatively low hardening temperature is often advantageous. The construction time will then be slightly longer (in the order of days), but the increase in life span can be many years! So the builder really has something to choose from!

Climate change and the service life of infrastructure

Effect of temperature on the service life of infrastructure

We have just seen that the length of the construction phase of a structure is partly determined by the temperature of the concrete during hardening. We now wonder whether there is also something to be said about the effect of temperature on the duration of the phase that follows the construction phase, namely the service life of a structure. In the past, this was almost never considered. However, the current discussion on climate change and global warming makes this question topical.

To be able to say something about the effect of temperature on the structure’s service life, we must first know which factors determine the end of this phase. Processes and mechanisms that should be mentioned in this context are penetration of chloride into the concrete, carbonation of concrete and degradation due to micro-cracking caused by temperature and moisture changes. Schematically, this is shown with the cartoons in the upper part of Fig. 14. When chloride ions, originating from, for example, de-icing salts or seawater, reach the reinforcement it can start to corrode. Corrosion of the reinforcement can also result from carbonation of the concrete. Carbonation is the reaction of CO_2 from the air with reaction products in the concrete. This increases the acidity of the concrete and lowers the pH from about 13 to values below 9. At a pH below 9, the risk of corrosion of the reinforcement increases significantly. With a high CO_2 content in the air – an issue today! - , the carbonation process proceeds more quickly, and the critical pH value at the location of the reinforcement will be reached sooner. Often, the onset of corrosion of the reinforcement is referred to as "end of service life".

The deterioration mechanisms of concrete mentioned here all concern physicochemical processes. With an increase in temperature, the rate of these processes will in-

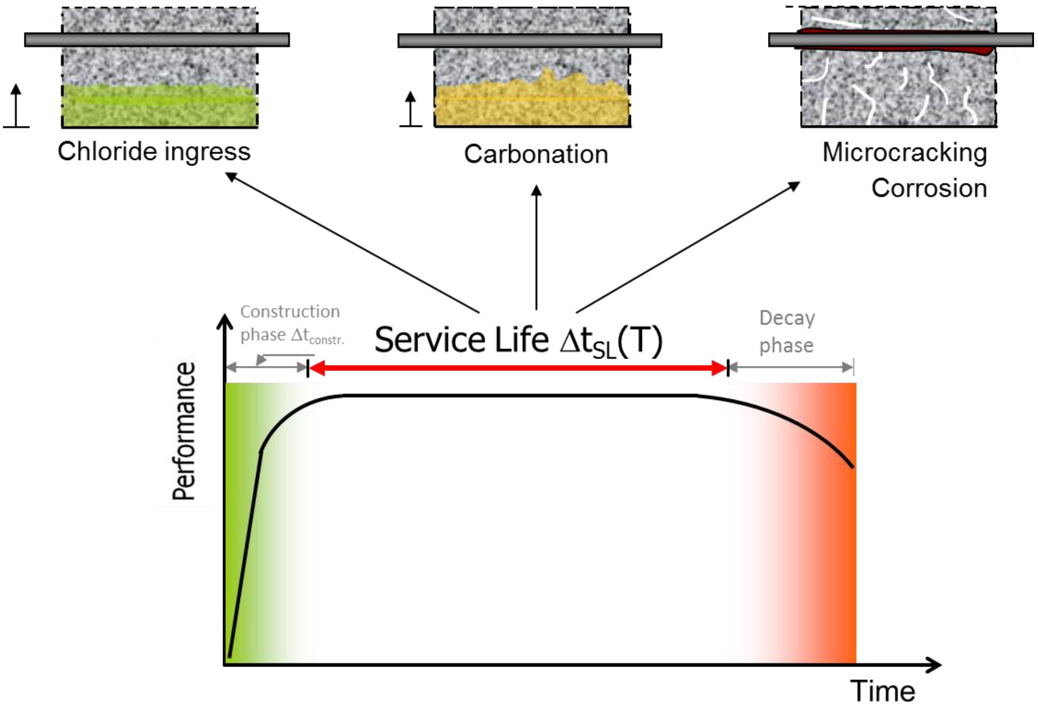

Fig. 14 Performance curve of a concrete structure, showing various degradation mechanisms which determine the service life of a structure.

crease. In principle, the Arrhenius function can also be applied here. For the service life of a structure as function of the average temperature it then holds:

$$\Delta t_{SL}(T_{climate}) = \Delta t_{SL}(T_{ref}) \cdot e^{-\frac{E_A}{R} \cdot \left(\frac{T_{climate} - T_{ref}}{T_{climate} \cdot T_{ref}}\right)}$$

where $\Delta t_{SL}(T_{climate})$ is the lifetime at the actual average ambient temperature $T_{climate}$, and $\Delta t_{SL}(T_{Ref})$ is the lifetime at the reference temperature T_{Ref}. As a reference temperature the average annual temperature can be used[32].

The question now is what the increase of the average temperature due to global warming means for the service life of our infrastructure. The IPCC (International Panel on Climate Change) calculates an expected temperature increase of 2.5°C. In addition, it also considers a pessimistic scenario with a temperature increase of 6.5°C. Fig. 15 graphically depicts the effect of temperature rise on the infrastructure's lifetime. The

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[32] The average annual temperature in the Netherlands is between 10°C and 12C. In the period 2010-2018, the average temperature by continent was: Europe 8.6°C; North America 12.2°C; Asia 16.6°C; Africa 21.9°C; Australia 14.9°C; Oceania 23.9°C. Source: World Data Info - https://www.worlddata.info/global-warming.php

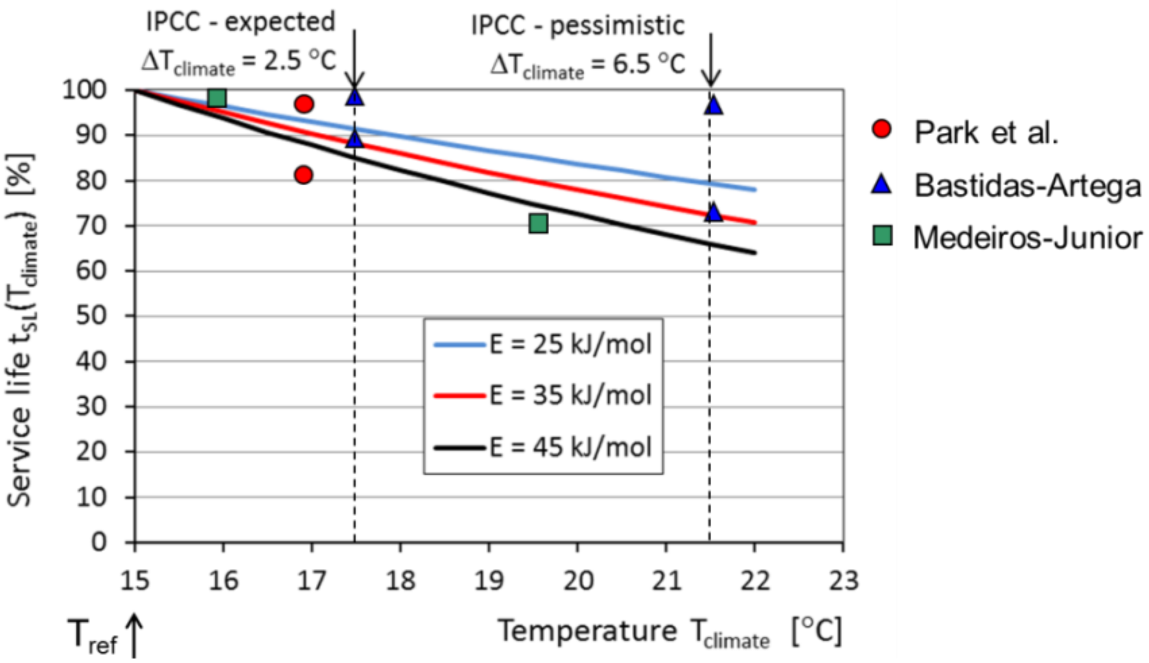

Fig. 15 Decrease in lifetime of (global) infrastructure with increase in average temperature.

horizontal axis shows the temperature, and the vertical axis the lifetime as percentage of the lifetime at the reference temperature. Calculations have been performed for a reference temperature of 15°C and activation energies of 25, 35 and 45 kJ/mol. A temperature increase of 2.5°C will cause a decrease of the lifetime by 9% to 15%. In a pessimistic scenario the decrease of service life will be 20% to as much as 30%. For comparison the figure also shows results from other researchers. They examined the effect of a temperature increase and an increase in the CO_2 content in the air on the lifespan of specific concrete structures. Their results differ slightly from the values calculated with the formula used here, but the trend is the same. This is not surprising. The basis for these calculations are formulas from reaction kinetics. These formulas have proven to be applicable thousands of times for describing temperature effects on the rate of physicochemical processes. The shortening of the lifespan of infrastructure as a result of global warming calculated here is, therefore, not the result of doom-mongering, but of the application of basic principles of reaction kinetics!

It should be noted that Fig. 15 shows the effect of the average global temperature rise on the lifetime of global infrastructure. It is quite possible that the effect will be different locally. For example, an average global temperature rise will cause zones with a lot of frost-thaw cycles to move north and south. This means that there will be areas where frost damage will decrease and the lifespan of structures will increase rather than decrease. On the other hand, there will also be areas where frost damage will increase. Here we see the importance of considering phenomena at different scales and defining suitable boundary conditions. At different scales the response to one and the same cause, i.e. a rise in temperature, may show opposite trends!

Effect of temperature on infrastructure replacement costs

As temperatures rise, as we have seen, the lifespan of infrastructure will decrease. Shortening the lifespan will lead to an increase in annual replacement costs. In Fig. 16 the additional replacement costs are plotted against the average temperature increase. The starting points for the calculation of the extra replacement costs are the value of the global infrastructure of US$ 160 trillion, a reference lifetime of 50 years and an activation energy of 35 kJ/mol. An increase in the average temperature of 2.5°C results in an increase in replacement costs of US$ 430 billion per year. In the extreme scenario, with a temperature increase of 6.5°C, this increase amounts to US$ 1220 billion per year. By way of comparison: in the period 2010-2015 natural disaster damages due to climate change ranged between US$ 100 and US$ 300 billion per year[33]. Thus, the projected additional infrastructure replacement costs from a 2.5°C temperature increase are significantly higher than the damages from climate-related natural disasters!

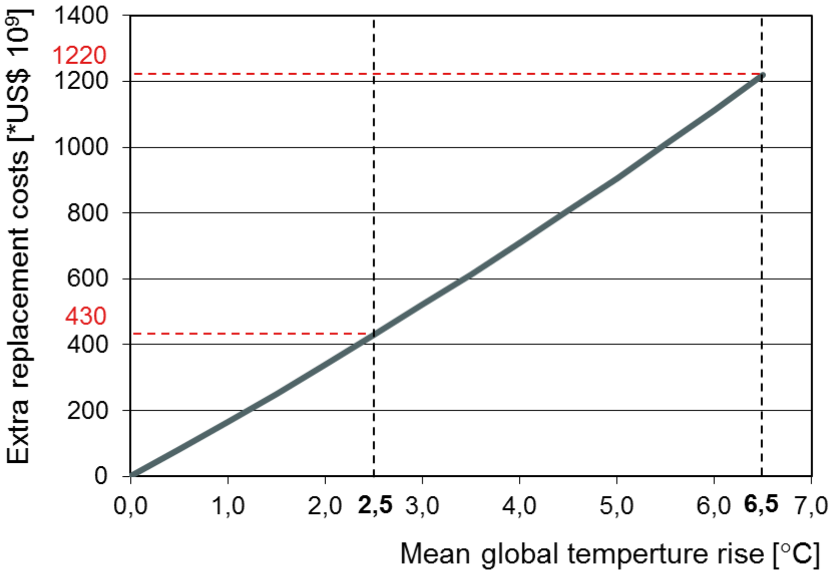

Fig. 16 Increase in annual replacement costs of global infrastructure as a function of increase of the mean global temperature.

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[33] W.J.J. Botzen (2017) Economics of Climate Change and Natural Disasters. Inaugural lecture Free University, Amsterdam, 28p.

Table 2 Additional replacement costs as a percentage of GDP**)/cap. in rich and poor countries.

		Extra replacement costs/cap. for IPCC climate scenarios	
		Temperature rise (expected) 2.5 °C	Temperature rise (pessimistic) 6.5 °C
		Costs: 56 US$/cap/yr	Costs: 158 US$/cap/yr
Category	GDP/cap/yr	Percentage of GDP/cap/yr	
Rich countries*)	114,000	0.05%	0.14%
	54,000	0.10%	0.29%
Poor countries*)	544	10.1%	29.0%
	303	18.5%	52.2%

*) 10 rich and 10 poor countries, according to World Bank (2018) **) GPD: Gross Domestic Product

For a world population of 7.7 billion people and a projected temperature increase of 2.5°C, the additional per capita replacement costs amount to US$ 56 per year. In the ten richest countries this corresponds to 0.05% to 0.10% of GDP per capita (Table 2). For residents of the ten poorest countries this is 10.1% to 18.5% of GDP per capita. Looking at these figures, it is clear that the impact of climate change on the lifespan of the infrastructure cannot be borne by inhabitants of the poor countries. It is mainly the rich countries that will have to pay for these extra replacement costs.

Saving on infrastructure in the Netherlands - The ‘new natural gas’

Savings by extending the service life of infrastructure

We have just seen that global warming will inevitably lead to a shortening of the service life of infrastructure and an increase in replacement costs. This is for sure a realistic, but also a somewhat gloomy way of looking at reality. We can also reason the other way round. We then ask ourselves what we could *save* on replacement costs if we succeeded in extending the service life of infrastructure. To illustrate this approach, we will now focus on the Dutch situation.

We saw earlier that the physical infrastructure makes up about 50% of a country's national capital. For the Netherlands, this rule of thumb holds quite true as well. Table 3 shows for various infrastructure components what proportion they make up of the national capital. The figures in the table relate to the situation in 2009. According to the Dutch Central Agency for Statistics, the national wealth at that time was € 3800 billion[34]. The value of infrastructure was € 1825 billion[35]. That is 47% of the Dutch national

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[34] Source: CBS, 2009 Centraal Bureau voor de Statistiek (*Central Agency for Statistics)*

[35] Note: For 2015, Statistics Netherlands estimates a value for the infrastructure of € 2001 billion.

Table 3 Value infrastructure of The Netherlands[36]

Fixed capital goods	Value [× € 1.000.000.000]	Percentage of national wealth [%]
Infrastructure	312	8
Houses	975	25
Industrial building	382	10
Permanent capital goods	156	4
Total	1825	47

capital. Now suppose that the design reference lifetime of our infrastructure is on average 50 years, and that we can extend it by 10% or 20% to 55 or 60 years, respectively. Fig. 17 shows how extending the lifespan will reduce the annual replacement costs. Extending the life span from 50 to 55 or 60 years results in annual savings of € 3.3 billion and € 6.1 billion, respectively. An amount of € 3.3 billion per year corresponds to the Dutch natural gas revenues in the 1990s[37]. The Dutch infrastructure could, therefore, be regarded as an enormous gas field, that could save us billions of euros if we would handle it more carefully!

It must be emphasized that it is certainly not easy to extend the average lifespan of infrastructure by, say, 10%. The billions that can be saved here are really not to be

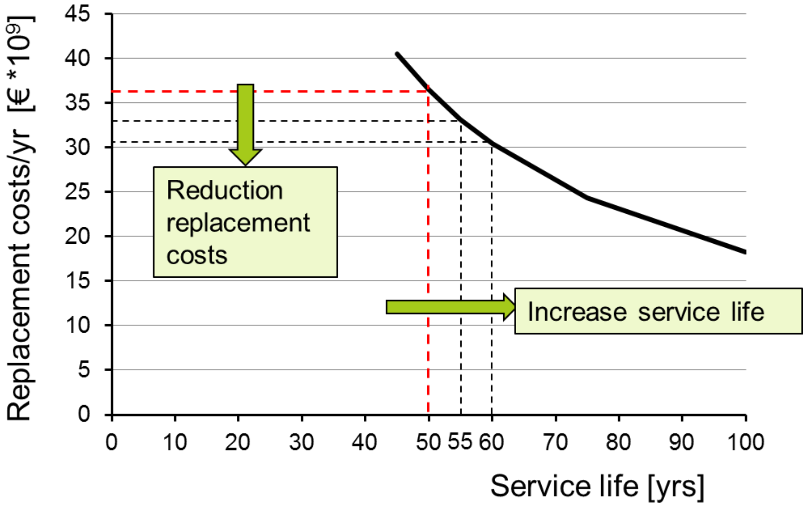

Fig. 17 Replacement costs of the Dutch infrastructure as function of service life.

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[36] De Haan, M. et al. (2009) Het nationaal vermogen van Nederland. In De Nederlandse economie 2009, pp. 129-140 (in Dutch).

[37] Natural gas revenues in the 1990s : €2 - €4 billion per year. Source : https://nl.wikipedia.org/wiki/-Aardgasbaten

picked as low-hanging fruit. The Dutch natural gas didn't just come out of the ground either. For that, there had to be a firm investment first. Similarly, achieving savings on replacement costs will also require a substantial investment. An investment of 20% to 30% of the intended savings seems realistic[38]. For annual savings of € 3.3 billion, this means an investment of € 0.7 to € 1.0 billion per year. That in itself is a large sum. But this amount must be judged against the background of the value of the infrastructure and the budgets involved in construction sector. We already mentioned the value of the Dutch infrastructure above. A number of key figures for the construction sector are given below.

Key figures for the construction sector

The turnover in the Dutch construction sector is approximately € 60 billion per year[39]. This turnover is realized with approximately 300,000 employees[40]. For the coming years a labour shortage of 30,000 employees is foreseen. That is 10% of the available potential. Almost 20% of the workers come from abroad[41]. Failure costs in construction sector amount to € 3 to € 6 billion per year[42]. That is 5% to 10% of the turnover in the sector. The number of companies active in the construction sector is 169,000[40].

Let us now look at these key figures against the background of the desire to save on replacement costs by extending the service life of the infrastructure by 10%. We then note a few things.

- Extending the service life of the infrastructure by 10% will not only lead to a reduction in replacement costs, but also to a reduction in the number of employees needed to carry out the replacement. Part of the anticipated shortage of workers can be met in this way.
- In addition to extending the service life, reducing failure costs is also an option for realizing savings. Failure costs often have a non-technical cause. These include poor communication, insufficient supervision during construction and inadequate execution. The increase in the number of employees who don’t speak Dutch increases the communication problem and the probability of failures. The human factor plays a key-role here.

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[38] K. van Breugel (2016) Societal burden and engineering challenges of ageing infrastructure. Proc. SCESCM 2016, Bali, 12 p.

[39] Average: €60 billion/year. In 2018: €70 billion. https : //www. bouwdnederland.nl/service/feiten-en-waarden

[40] Construction Fact sheet Labor Market. https://www.cdho.nl/assets/uploads/2018/02/UWV-Factsheet-Bouw-april-017.pdf

[41] C. Molijn (2019) One in five construction workers comes from abroad. NRC, 11.6.2019.

[42] P. van Heel et al. (2019) Failure costs in construction amount to billions of euros annually. https://insights.abnamro.nl/ 2019/04/faalkosten-in-de-bouw-lopen-jaarlijks-op-tot-miljarden-euros/

– A large number of companies are often involved in the realization of construction projects. In this respect the construction industry is clearly different from other industries. The turnover in the chemical industry is comparable in size to that in the construction industry: € 50 billion in the chemical industry compared with € 60 billion in the construction industry. But in the chemical sector the turnover is realized by 400 companies[43], compared to 169,000 companies in the construction industry. The involvement of many companies in the realization of construction projects implies many 'interfaces', and a great deal of pressure on communication and project management. On balance, this places a heavy burden on the quality and lifespan of the infrastructure.

Direction required

This brief overview shows that when looking for possibilities to extend the lifetime of the infrastructure and realize savings, both technical and non-technical aspects of the construction process must be taken into account. This calls for *interdisciplinary direction** of the construction process. In a moment we will discuss the question of how to meet the need for interdisciplinary direction. First, we will look at two more engineering and technology-oriented options to extend the service life of infrastructure and reduce its environmental impact. These two options are the use of self-healing concrete and circularity. After that, the subject *direction* will be discussed in detail.

Options for lifetime extension and reducing environmental impact

Self-healing concrete

With the passage of time materials can crack, embrittle or degrade due to material-inherent ageing processes. It would be nice if a material would repair itself at the first sign of degradation. This would be in the interest of the service life of structures and would reduce the impact of construction on the environment.

The search for self-healing materials is a form of treasure hunting. It is a search for materials that probably never existed, and perhaps never will exist, but the search for which can nevertheless provide us with a smart material that comes close to is. Now, in a sense, concrete can already be called a smart material[44]. After all, we saw earlier

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[43] Chemical industry –7-9-2019 https://nl.wikipedia.org/wiki/Chemische_industrie

*) The term 'direction' is used here as the translation of the Dutch term 'regie'. This Dutch term regie includes aspects of coordination, control, management, leadership and governance.

[44] K. van Breugel (2018) Smart materials for social infrastructure: Past, Present and Future. Int. Workshop on Structural Life Management for Eco-Power Structures. Deajeon, Korea. 12 p.

that concrete has a certain self-healing capacity by nature. If water manages to reach non-hydrated cement through a crack, then that cement can still start to react and the crack can repair itself (Fig. 9g). However, we also saw that for various reasons the self-healing capacity of modern concrete mixtures is under pressure. In recent years, this has prompted intensive research into ways of significantly improving the self-healing capacity of concrete. The research of Jonkers et al.[45] into self-repairing 'bio-concrete' is challenging and promising in this respect. Jonkers added specially selected bacteria to the concrete that have the ability to seal cracks. Fig. 18 shows the result of water permeability tests with cracked traditional concrete and bio-concrete. Cracks in specimens to which bacteria had been added were found to be completely sealed after only a few days. This in contrast to cracks in specimens to which no bacteria were added. Good results in various pilot projects have shown that self-healing of bio-concrete works not only in the laboratory but also in practice, and can thus contribute to extending the lifespan of the infrastructure.

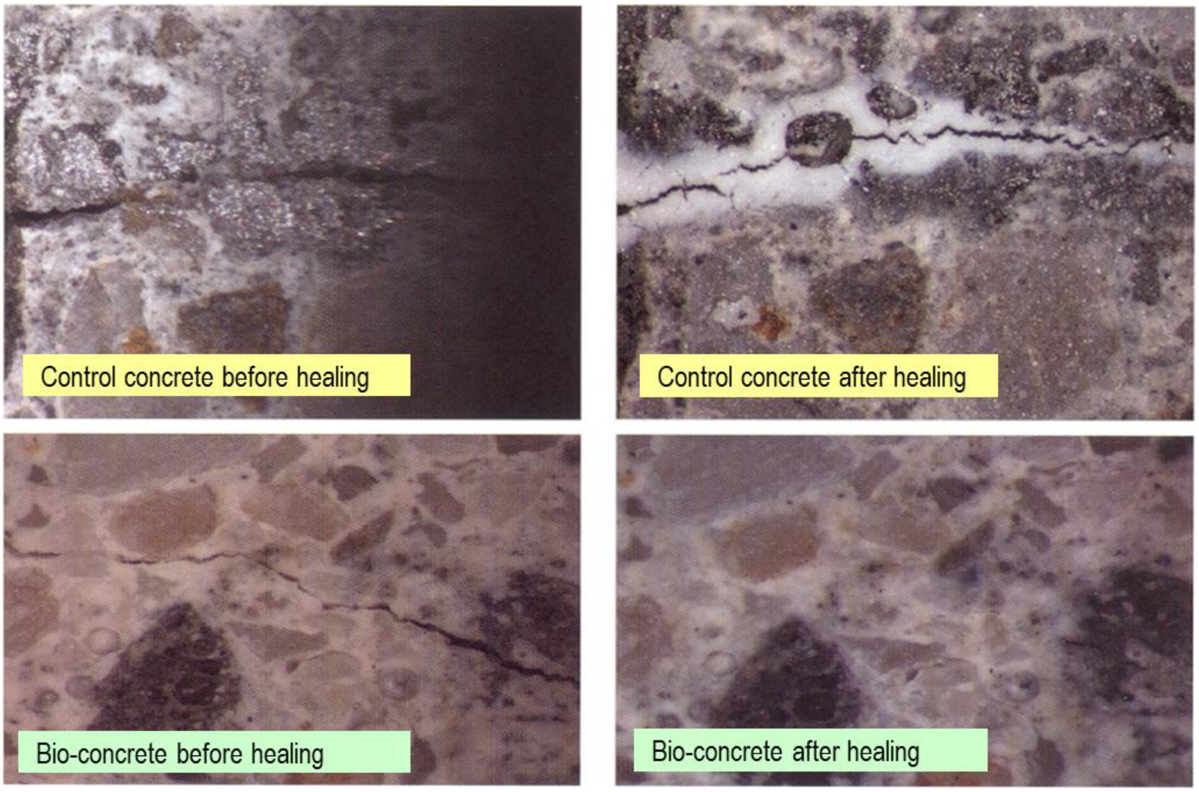

Fig. 18 Self-healing bioconcrete. Top: reference concrete without bacteria. Bottom: concrete with bacteria. Left samples at the beginning of a water permeability test and right after the test. The bottom-right picture shows complete healing of the crack[45].

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[45] H.M. Jonkers , A. Thijssen , G. Muyzer , O. Copuroglu , E. Schlangen (2010) Application of bacteria as self-healing agent for the development of sustainable concrete. Ecological Engineering 36(2). pp 230-235 .

Circularity

A different route to reduce the environmental impact of construction activities is that of circular construction. Professor Ch.F. Hendriks, former head of the Materials Science Section at the TU-Delft, already had the theme of circularity firmly in mind. His book *The Building Cycle* from 2000 bears witness to this[46]. Since 2006 the Materials & Environment Section has embraced the materials cycle and adopted it as the starting point for teaching and research. Meanwhile, thinking in terms of circularity has taken a big flight.

How circularity works in the construction sector is illustrated by the diagram in Fig. 19. In this diagram we distinguish two concepts. The first concept is represented by the dark blue outer circle of the figure. This circle relates to the materials cycle in traditional construction. Raw materials and energy are required to produce building materials. These materials are then used for the realization of construction elements and

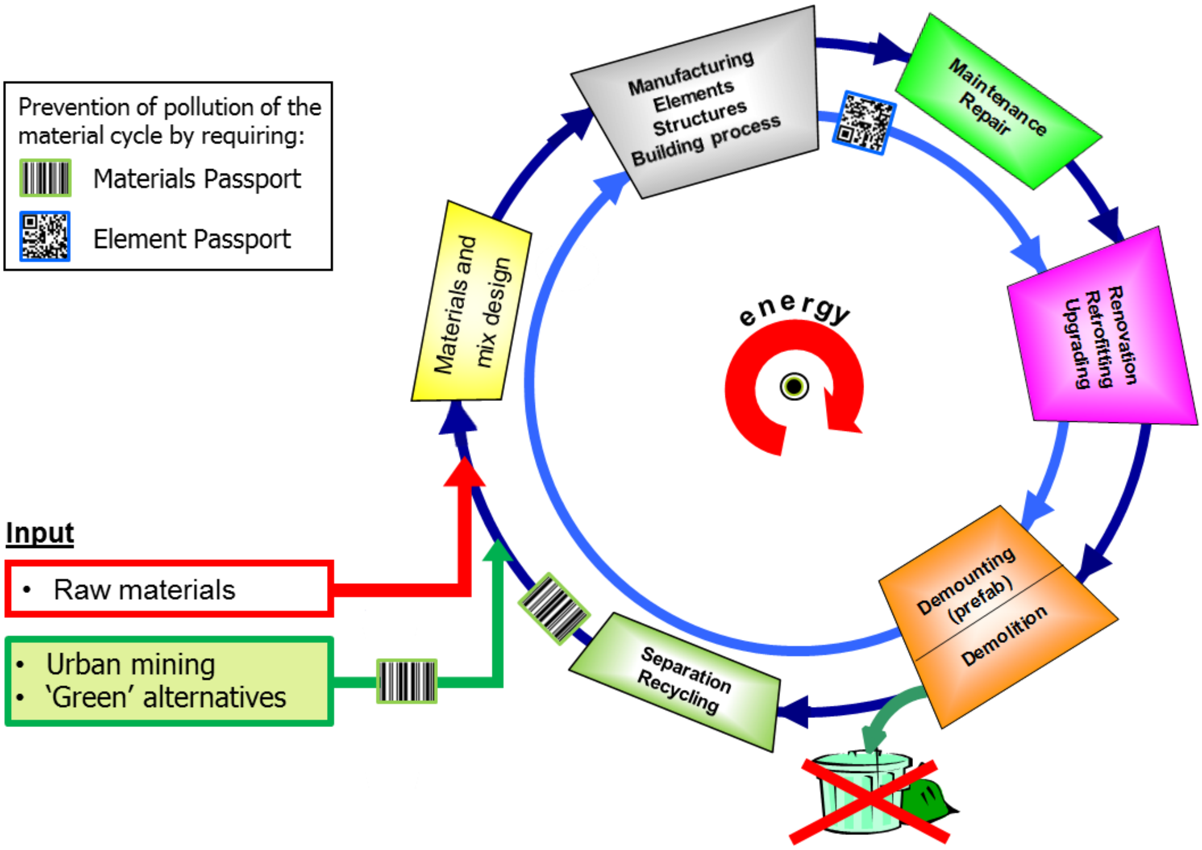

Fig. 19 The building and materials cycle in view of circularity[21,47].

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[46] Ch. F. Hendriks (2000) The Building Cycle . Aeneas Technical Publications, 233 p.

[47] K. v an Breugel K. (2017) Circularity: A new avenue for mitigating the footprint of ageing infrastructure ? The 9th International Symposium on Cement and Concrete (ISCC 2017), Wuhan . 12 p.m.

complete structures. This is followed by the operation phase. In this phase maintenance of structures takes place and repairs are carried out, possibly followed by upgrading and retrofitting. At a certain point, keeping a structure in operation will cost so much money and energy that the decision is made to demolish it. All the material released in the demolition process is then recycled and reused. That completes and closes the circle.

The light blue inner circle of Fig. 19 represents the precast construction. Prefabricated building elements are manufactured in the factory under strictly controlled conditions and are of high quality. At the end of a structure's lifetime, the prefabricated building elements can be disassembled and reused to create new buildings.

Much is expected of this circular concept. The pressure on scarce raw materials decreases and construction-related CO_2 emissions are reduced. Those are the benefits. But these benefits are not just there for the taking. Without being exhaustive, the following points are mentioned here for careful consideration when working out and evaluating a circular concept[47].

- A fully circular concept assumes the availability of *donor buildings*, which can provide a sufficient quantity of suitable material to realize the desired new building. However, it is virtually inconceivable that a single donor building can provide all the materials needed for a comparable new building. A *regional policy* is needed to set up a database in which all buildings in a region are registered that qualify for recycling, including data on material quantities, nature and quality of the materials, age, repair records, etc. (so-called 'urban mining').
- The inclusion of different materials in the material cycle requires careful registration of the characteristics of these materials. Alternative materials, applied to replace traditional ingredients of concrete mixtures, often with the aim of 'greening' the concrete, should be tested for their effect on the short- and long-term behaviour of the concrete. Any negative effect on the long-term behaviour will by definition only manifest itself after years. Harmful 'pollution' of the materials chain can thus continue unnoticed for years. To prevent the latter, it is important to keep track of materials on their way through the construction and materials cycle. An electronic materials and/or elements passport (Fig. 19) offers the possibility of monitoring and/or separating material flows. A materials passport can be seen as a logical sequel to the 'birth certificate' for concrete structures advocated by Rostam[48] in the 1990s.

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[48] S. Rostam (2005) Service life design of concrete structures – A challenge to designers as well as to owners. Asian Journal of Civil Engineering (Building and Housing) Vol. 6, no. 5, pp. 423-445.

- Circularity in construction presupposes the presence and availability of structures that are eligible for recycling. It was pointed out earlier that, globally, half of the construction task in the coming years will be dominated by growth. Where construction is dominated by growth, circular construction can hardly be an option, simply because there are not enough structures available that can serve as donor buildings[47,49]. In areas where the absence of donor buildings implies that urban mining is not yet an option, new construction will still have to rely on new raw materials. In order to limit construction-related CO_2 emissions and reduce the environmental impact, consideration will then have to be given to the application of new (smart) materials, smart use of materials and extending the lifespan of structures.

Even a superficial assessment of these points of interest reveals the need of *direction*! Direction is needed to set up a database of donor buildings and to register and monitor materials and material flows, respectively. All the more reason to return to the previously identified need for direction in the construction industry.

Serious gaming for interdisciplinary direction in construction

The earlier discussion of the possibilities to extend the service life of infrastructure and to save on replacement costs ended with the question of disciplinary direction of the construction process (p. 29). A tool that could facilitate and support this inter-disciplinary direction and coordination is serious gaming. A serious game offers a platform where bridges can be built between different disciplines, communication can be optimized, the balance between different sustainability parameters can be made visible and which can subsequently be acted upon.

The playing field of a serious game is schematically shown in Fig. 20. As a platform, a serious game can host advanced simulation models. For example, within a serious game the previously discussed Concrete Curing Control Systems can be active for optimizing the execution process. Research on the use of simulation models in the manufacturing industry has revealed that companies that use simulation models actively perform significantly better than companies that do not[50]. This not only illustrates the usefulness of simulation models in the manufacturing industry, but also challenges the development of a serious game for the construction industry in which the entire design and construction process is simulated integrally.

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[49] K. van Breugel (2018) Modelling in the service of sustainable construction. RILEM Pro. 126 Proc. of the Workshop on Modelling and Concrete Materials Behaviour. Ed. Guang Ye, pp. 3-14 .

[50] M. Boucher (2010) Cost saving strategies for engineering: Using simulation to make better decisions. Aberdeen Group. 24 p.

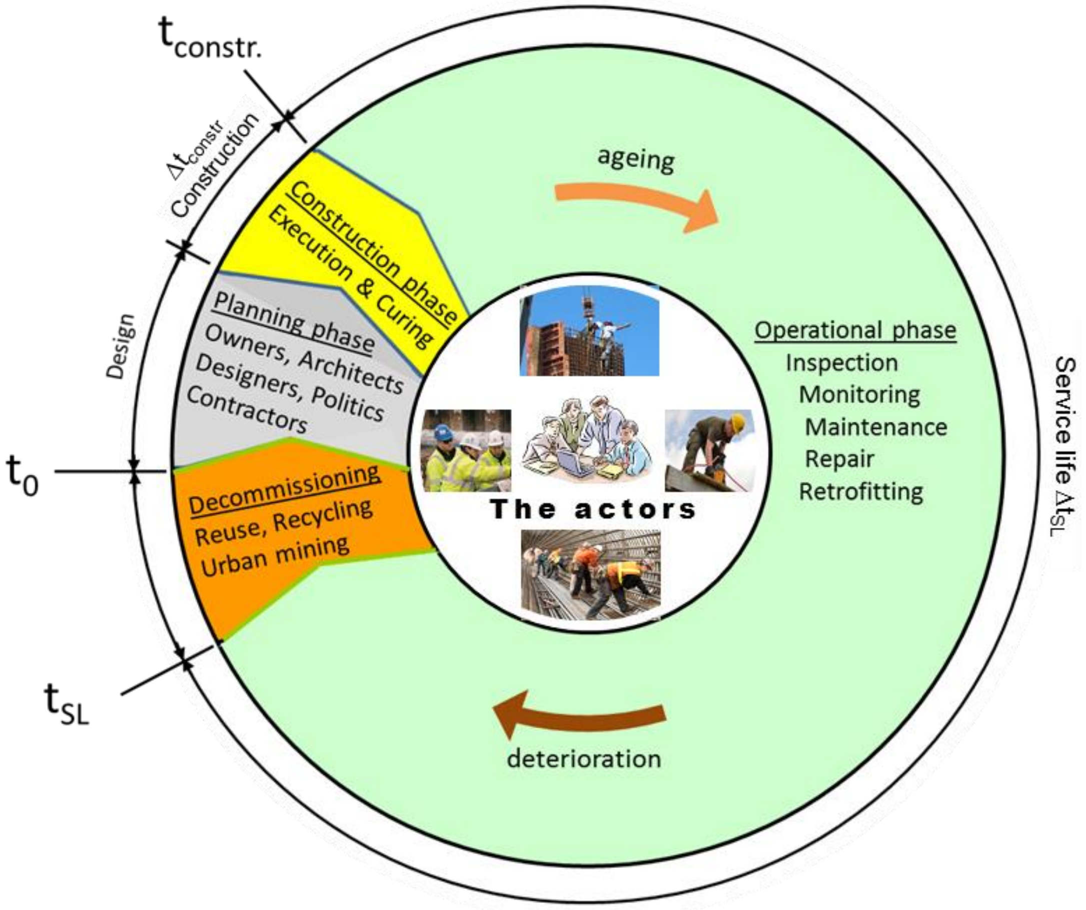

Fig. 20 Serious game as a platform for (interdisciplinary) management within a (circular) construction process.

For a complex and fragmented sector like the construction industry, there are enormous challenges and opportunities here. An important question is who will take the lead in developing a serious game for the construction sector. Here too, direction is needed, i.e. leadership! Now that the question of direction has been raised so emphatically again, we will have to dwell on this in more detail. When doing this I will not restrict this discussion to direction for the development of a serious game, but broaden this discussion to direction in developments in science and technology in general. Within the framework of this speech this should be, of course, in a very concise manner. The focus will, therefore, remain on the construction industry. For what follows, I now return to the beginning of this speech, namely the explanation of how science and technology work.

On direction and leadership

What if there is no direction?

Great successes in science and technology are often due to far-reaching specialization. Models play a key-role in this. Models are used to apply newly acquired insights and knowledge to realize people's wishes and dreams. In industrialized countries, these wishes and dreams have long since left the stage of 'providing shelter for people'. It is now about consumption and growth. As long as consumption increases and the economy grows, all signs will be green. But if this growth has to be assessed in the light of the Earth's sustainability, the signs are red. Science and technology have enabled us to consume the annual ration of raw materials and energy at an unprecedented rate*. In 2019, Earth Overshoot Day[51] fell on July 29. On that day, the world's population had used up its ration for 2019 and the cookie jar was empty for the rest of the year. Schematically, this is shown in Fig. 21.

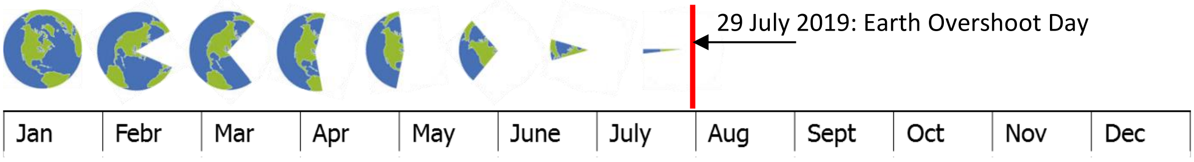

Fig. 21 Schematic representation of the rate at which the annual ration of raw material was consumed in 2019. By July 29, 2019, the ration for that year was completely consumed.

Anyone who continued to consume or had something to hand out after the end of July 2019 could only do so if they had increased their share of the pie earlier that year at the expense of others, or if they had advanced their share for next year. The former is a form of injustice, and the latter is contrary to the sustainability principle as expressed in the Brundtland report[52] that underlies current sustainability thinking. In fact, for years we have seen that mankind fails to balance consumption and growth on the one hand with the possibilities that the earth - at the current state of science and technology – offers us at the other. This also points to an imbalance between technical possibilities and our ambitions on one hand, and responsible stewardship of the earth on the other. Fig. 22 illustrates this unbalance. In Fig. 22a reality, reduced to a cube, is

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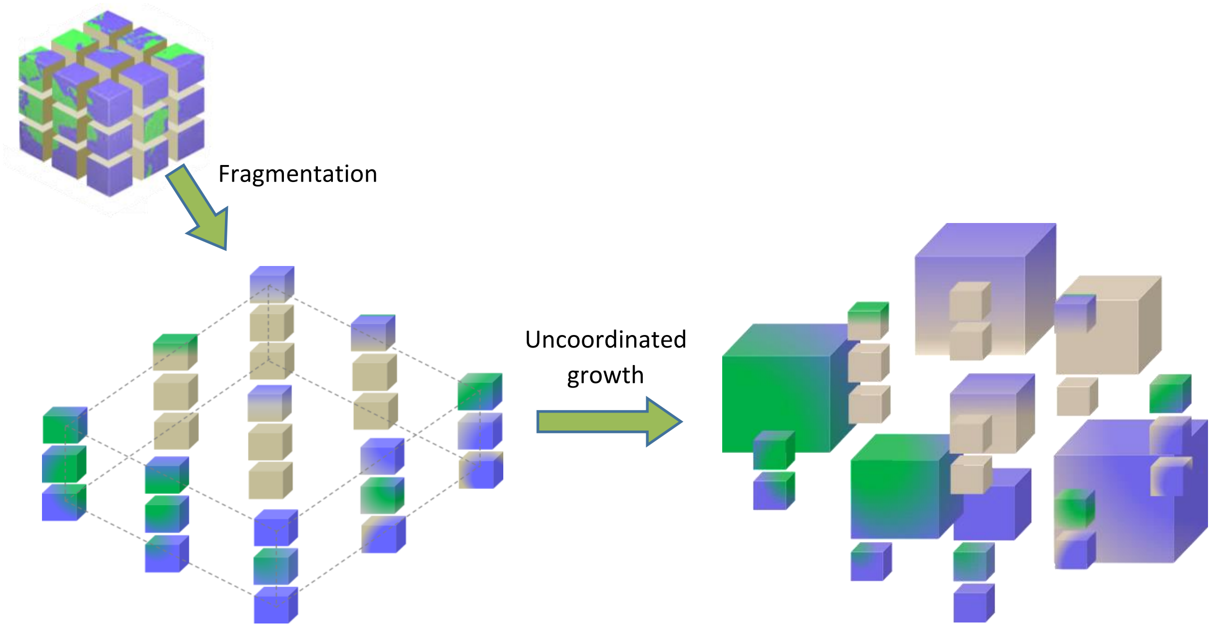
*) Indicative for the increase in consumption of raw materials and energy is the growth curve in Fig. 4.

[51] L. Mead (2019) 2019 Earth Overshoot Day Reaches Earliest Date Ever. SDG Knowledge Hub. https://sdg.iisd. org/ news/2019-earth-overshoot-day-reaches-earliest-date-ever/

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



a. Decomposition and fragmentation

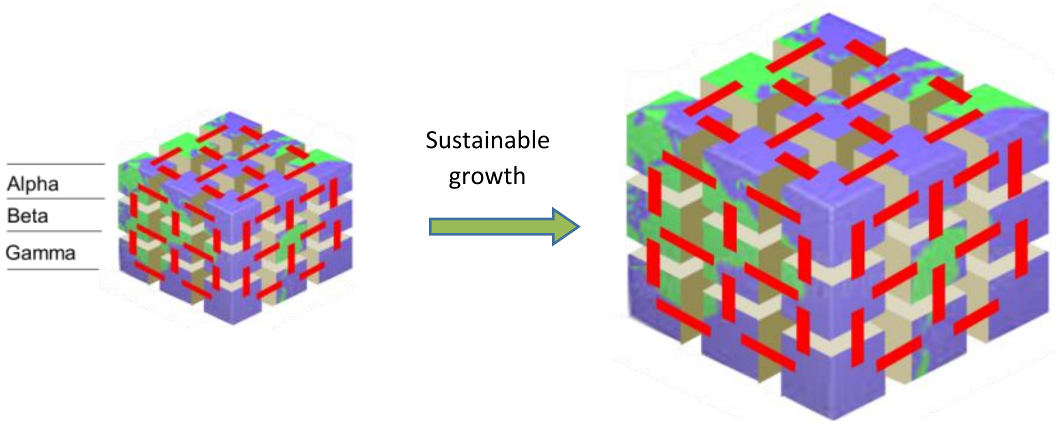
b. Result of uncoordinated growth

Fig. 22 Schematic representation of growth of individual sectors without consideration of mutual coherence and harmony.

divided into twenty-seven sectors, all of equal weight. When especially sectors that offer the prospect of great prosperity and pleasure are given the opportunity to grow, a picture emerges as shown in Fig. 22b. Some sectors have grown enormously, while others have remained the same. In no way these twenty-seven cubes can now be made into something that has the contours of the original cube. Reality has been violated. Disproportionate growth produces a monstrosity! This is not to say that growth should always be avoided. But growth of individual sectors should be proportional, and aimed at harmony and maturity. If after reaching the stage of maturity the growth does not stop, a medically undesirable situation or a disease arises! To cure from such a disease not only surgery is needed, but also and especially a change of behaviour. Without a change in behaviour a harsh intervention will soon lose its effect. Nature teaches us that.

Towards sustainable growth

If the purpose of construction is to provide "shelter for people", and if everyone is provided with shelter, then further growth will have to be preceded by the question of what its purpose is. Engineering and technology will not provide an answer to this question. Neither will science. In the words of Einstein, science and technology are concerned with how things are, not how they ought to be. The question of how things should be is beyond the scope of this speech. Here I limit myself to the comment that sustainable growth requires a balance in growth of all sectors that together represent



a. Alfa’s, bèta’s and gamma’s ‘connected’

b. Balance as precondition for sustainable growth

Fig. 23 Sustainable growth: Balance between alpha, beta and gamma aspects.

reality. The three Ps, that are central to sustainability thinking, People–Planet–Profit, presuppose mutual interaction, coordination and harmony. Harmonious growth assumes that the growth of one sector is accompanied by a corresponding growth of other sectors *and* of our ability to oversee the short- and long-term consequences of implementing new techniques and technologies needed to achieve this growth. Schematically, this is shown in Fig. 23. The composite cube in Fig. 23a is now divided into alpha, beta and gamma sectors[53]. Horizontal and vertical connections between individual sectors should prevent unbridled growth of one sector from disrupting the balance within the composite cube. Focusing on the construction sector, the question is how alpha’s, beta’s and gamma’s can be brought to their full potential within the construction process, and how together they can ensure that the growth of the infrastructure can take place in a responsible and sustainable manner. This will certainly not happen automatically. Here too, there is a need for direction and an authority that can manage this well and with authority.

The government as director

The reason for considering the theme 'direction' in detail was the question of who should take the lead in developing a serious game for construction (p. 34). It is not realistic to assume that one individual party in the construction industry will develop a serious game for the entire sector. If sustainable development is the primary goal of using a serious game here, then the direction for the development of a serious game will also have to lie with the body that is responsible for this primary goal. The Dutch

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[53] In the Netherlands is discerned between alpha, beta and gamma sciences. Alpha refers to spiritual sciences, beta to natural sciences and gamma to social sciences.
Source: https://www.arvindus.com/publications/201704162.html

constitution shows us the way here. Article 21 of the Dutch constitution states this as follows:

> "The government's concern is focused on the habitability of the country and the protection and improvement of the living environment."

When it comes to the earth, and caring for the earth, the government is in charge. It is fair to say here, that the Dutch government in particular is doing a great deal to make and keep our country habitable. Guaranteeing that seventeen million people can live and work safely in a delta area is a big challenge and requires a huge effort from the government. In line with the Constitution, however, ensuring the habitability of the country should also go hand in hand with *protection* and *improvement* of the environment. We see that this is increasingly becoming a problem, also in construction. The previously mentioned quotes - however one-sided(!) - from Watts[19] and Vidal[20], but also the discussions about particulate matter, nitrogen, pfas, etc., are illustrative in this regard. We see ourselves faced with the consequences of unbalanced growth.

In 1987 the booklet *Can we manage the earth* was published by the Dutch economist and Nobel Prize winner Jan Tinbergen[54]. The title of his booklet is already revealing. Tinbergen does not speak of controlling, but managing. He is sharp when he says that the gluttony of our generation can mean lack for future generations. He continues by saying that creativity and frugality together will have to become our life's advice. For responsible stewardship of the earth, Tinbergen advocated direction, c.q. management and leadership, on a broad international level. Managing the earth requires thinking big and then acting locally, i.e. nationally. Construction has the potential to make a substantial contribution to the responsible stewardship of our planet. But without direction, cashing in on this potential remains an illusion. The government must make its appearance here. An advanced, multidisciplinary serious game can be an instrument that benefits the entire construction sector as well as Dutch society and the environment.

Direction and leadership are crucial for the development of a serious game for the construction sector. Not only because of the complexity of the construction sector, but also in view of recruiting experts from all disciplines involved to design a serious game. Direction is also indispensable for generating and managing the resources needed for the development and implementation of a serious game for the construction industry. It was indicated earlier that for realizing an annual saving on infrastructure of € 3.3

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[54] J. Tinbergen (1987) Can we manage the earth? (Dutch: Kunnen wij de aarde beheren?) Uitg. Kok/Agora. 172 p.

billion, an investment of about € 1 billion per year is needed. A substantial part of this amount should be spent on developing a serious game for construction. Further breakdown and allocation of this budget is beyond the scope of this speech. What is important, however, is that the budget is distributed among all disciplines - alpha, beta, gamma - that are involved in the initiation, realization and management of the infrastructure.

The Model: Vehicle for Glory and Damage

The time has come to ask the question whether all of the foregoing has now given us insight into the theme of this speech: 'The model: vehicle for glory and damage'. In order to answer this question, we first briefly summarize the foregoing. We have seen that science focuses on understanding reality, with the ultimate goal of being able to control this reality. Then we saw that doing science is an activity characterized by a continuous ‘reduction’ of reality. The path of reduction has been chosen because reality is too complex to understand all its facets in their mutual coherence and to capture all these facets in one all-encompassing model. Gradually, during the process of reduction, individual disciplines developed that focused on sub-areas of reality. The knowledge acquired in these areas was then used to develop models to describe phenomena within and interactions between sub-areas. The acquired knowledge is then made operational in the manufacturing industry via models.

If we now look at the products that the manufacturing industry has produced, we see impressive achievements. Much has been done, built and enjoyed. We also see that science and technology, as well as models, have been and are used to achieve growth. Economic growth and growth in prosperity. To make this growth possible, a reliable infrastructure is essential. This infrastructure now accounts for about 50% of the world's national capital. To refer to all this with the term glory is not out of place. But for this glory and growth a high price is paid. Growth that continues after reaching maturity is harmful growth. The generated damage can be very local, but can also manifests itself as global environmental damage and climate change. The infrastructure also suffers. Thus we see that science and engineering, and also models developed and applied in science and engineering, are vehicles, that can lead to both glory and damage. However, ... they are and will remain vehicles! Nothing more than that. The *driver* determines where the vehicle will take him! Neither science, nor technology, nor any model will move society forward or sideways, if there is no driver setting the course and operating the accelerator. It is not science and technology that leave their mark on society, but it is *people* who leave the mark of science and technology on society.

Science and technology have no fixed domicile or residence, nor can they be summoned when it comes to the question of who bears responsibility for the impact of man's actions on his fellow man and the environment. It is always people who make choices and set the course. People can choose to use science and technology for growth. But they can also make a choice for sustainable growth. Sustainable growth is growth that aims to develop and sustain a mature economy. For construction, this means developing and realizing constructive concepts for ‘human shelter and use’, i.e. an infrastructure necessary for a society to function safely and in harmony with its environment. For now and for the near future, defining what is really necessary - what are really our 'needs' – should have top priority. New products or services that become available today, possibly at the expense of other people or of the earth, should not immediately be added to the list of 'needs', let alone that the access to these products or services should immediately be given the status of a (human) right. Here too, neither science, nor technology, nor scientific models will provide an answer to the question of what our needs really are and what goes beyond them. It is people who make choices here. In making those choices, models can, however, help us to assess whether our choices will lead to glory or damage.

Education

I would like to briefly discuss one aspect of education. In the period 2005-2009 I had the pleasure of serving as Program Director of the Faculty of Civil Engineering & Geosciences. In that capacity I experienced the change culture in education up close. The introduction of the BaMa-structure was just behind us, but the change virus was still active. The reason for making changes was that - in my opinion - too often a stand still was judged to be going backwards. Mathematically expressed: $0 = -1$. A peculiar equation, which involuntarily reminds one of Escher's drawings in which water flows upwards instead of downwards. At first glance everything in his pictures seems to add up, but on closer inspection nothing is right. Nevertheless, Escher became world famous with it. In the same way, change agents almost always draw the longest straw. If a proposed change works out well, then the official who proposed the change is soon instructed to prepare the next change. If the change turns out to be wrong, then another official is given the task of rectifying the failed change. In this way, the change virus continues to run rampant.

I prefer to see education as a tree. For a tree, standstill = growth! Occasionally dead wood has to be sawn away. But if see dead wood, you should not immediately pull the entire tree out of the ground to see if the roots are still healthy. Then the tree will die!

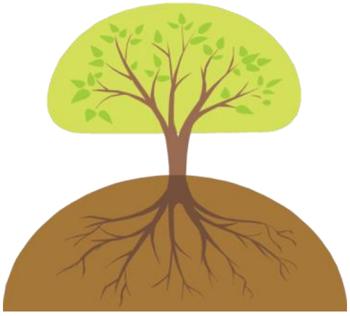

Fig. 25 The tree as metaphor for development of education: Standstill = Growth!

If there is dead wood, then cut it down where necessary. Encourage where possible, correct where necessary and have a bad-news interview if unavoidable, but don't bother everyone with generic measures that cost a lot of money and cause a lot of frustration, but which most likely leave the dead wood untouched.

Word of thanks

It has been more privilege than merit that I have been able to spend my entire active career at TU Delft. I have enjoyed the freedom you have in this institution as a scientist, lecturer and manager, and I am deeply indebted to this university. Thanks for the great contacts with colleagues of the section, department, faculty and university. In particular, I would like to mention the cooperation with the Department of Education & Research in the period 2005-2009, during which I was allowed to serve as Program Director of the faculty. The contacts with colleagues from other departments and faculties are among my best memories. Special thanks also go to colleagues with whom I was able to contribute to the realization and implementation of the IOP program 'Self-Repairing Materials' under the expert guidance of prof. Sybrand van der Zwaag. Thanks are also due to the colleagues with whom the initial impetus was given for the formation of an Expert Centre on the ageing of materials and structures.

Without exception the contacts with the industry, the Dutch Concrete Association, CUR, CROW, NEN, KIVI, Rijkswaterstaat, the Concrete Repair Board of Experts, STW, M2i, Stufib and Stutech were extremely valuable.

During the international farewell symposium in Delft in 2018, I already had the opportunity to reflect on the value of international contacts[55]. The collaboration with col-

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[55] G. Ye (Ed.) (2018) RILEM Workshop on Concrete Modelling and Materials Behaviour. RILEM PRO 126. Delft.

leagues from foreign universities in European research projects has brought me a lot academically and socially, as well as lasting friendships. There were numerous contacts with colleagues from universities outside Europe, i.c. Canada, USA, China, Vietnam, South Korea, Indonesia, Russia, Israel, India, Japan, South Africa and Brazil, to mention just a few. All these contacts with colleagues from universities, research institutes and international organizations such as fib, IABSE, IALCCE and RILEM are oxygen for a scientist. You can't do without it. Thank you all for that.

At the end of my inaugural lecture[56] in 2000 I had ample opportunity to thank colleagues in the Concrete Structures Section for their collegiality and cooperation, not least with the intention of continuing this fruitful cooperation. Of my professorship I eventually spent only the initial period with that section. Even though it was much shorter than planned, many thanks for the cooperation in that period and for its continuation in lectures and in the jointly conducted postgraduate courses on temperature and shrinkage effects in concrete structures.

I owe a lot to colleagues with whom I had the pleasure to work from 2003 onwards on the continuation and further design of the Microlab and the Materials & Environment section. In doing so, I could count on the critical but benevolent support of the Dean, prof. Louis de Quelerij, and the Department Chair, prof. Frans Bijlaard. Their support was indispensable. Thank you for that! It was a challenge to position the section together with the scientific staff, the technicians, secretaries, students, student assistants and researchers. Without their efforts it would have been impossible to get where we are today. Many thanks for that.

I look back with great satisfaction at the international conferences, workshops and courses which were initiated and organized by the section over the past years. Some of these international events were organized in collaboration with colleagues from Ghent University, Southeast University*) (Nanjing/Cn), Lehigh University (Bethlehem/USA) and Tongji University (Shanghai/Cn). It was great to work on these co-productions. Thanks for that! I would like to thank Iris Batterham for her part in the design and organization of these events. Without her efforts, not much would have happened.

The growth of the Section and the organization of events required a lot of secretarial support. Iris Batterham, Marijke van der Veen, Claudia Baltussen, Melanie Holtzapfel, Ingrid van Wingerden, Nynke Verhulst, Claire de Bruin and Jacqueline van Unen-Ber-

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[56] K. van Breugel (2000) From Vitruvius towards Virtual Lab (in Dutch). Inaugural speech TU Delft. 50 p.

*) The cooperation with Southeast University was expanded with the support of prof. Changwen Miao’s Sobute New Materials Company, for which our gratitude.

genhenegouwen were never called upon in vain. Thank you for your dedication and the pleasant manner in which you did your work.

Special mention should be made of Nynke Verhulst's support around my unexpected stay in Daejeon hospital in Korea in October 2015. She took care of the communication between me and the home front, maintained the contacts with the insurance company, arranged the repatriation and acted as non-medical escort on the return flight. I will never forget her care and dedication. Thank you!

During my unplanned stay in Korea in 2015, and in the months that followed, colleagues in the Section showed that without me, the work could continue as usual. I did not have any worries about that either. Erik Schlangen, Ye Guang, Ton van Beek and René Braam, thank you for the extra efforts you made to take over the lectures. You inadvertently showed then that I could work towards leaving the university without worrying about the future of the Section.

This farewell speech was preceded by a special farewell symposium. I would like to thank the organizers of this event, and in particular dr. Carola Edvardsen from COWI Consult and prof. David Lange from the University of Illinois for their inspiring lectures.

A farewell address is the moment to reflect on all that I have been allowed to do over the past four decades, the health I have enjoyed all those years and the people with whom I have worked more or less intensively. Nothing about all that has been was taken for granted. You don’t ask me, at least not today, but now is also the time for me to give an account. To account for published articles and books, for lectures and committee work, for conferences and courses, for performance and appraisal interviews, for policy decisions and management style, in short for everything I have done. All in all, it's quite a lot. No, not everything was perfect, but it does represent something. I’m not claiming that I can make life, or even that I know everything about concrete. But I would still like to know if it was, broadly speaking, up to par. I update my resume and submit it all to God. He takes it in hand. He looks. He browses. He weighs. I wait and see. Maybe then He'll say, "Nice. Yes, that's a good way to go". Then He shoves my resume aside and continues: "You could have left your CV at home. I already knew it. But I have something better for you. And the best is yet to come!" I would like to echo Laplace when he says that he does not need God as a hypothesis. Indeed, not as a hypothesis, but as a Father.

I did say.

Valedictory address, delivered at the farewell as professor in the field of
"Concrete Modeling and Material Behavior"
at the Materials & Environment section of the Faculty of Civil Engineering and
Geosciences of Delft University of Technology,
on Friday, September 27, 2019
by Prof.Dr.Ir. K. van Breugel