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Ageing Infrastructure and Circular Economy: Challenges and Risks

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Abstract **–** A reliable infrastructure is crucial for proper functioning of a society. Apart from its crucial role in the functioning of a society, the infrastructure also represents a large share of a country's national wealth. Depending on what is considered as infrastructure, it represents up to 50% of the national wealth. For realizing this infrastructure huge amounts of raw materials and energy were needed. At the same time we have to realize that the infrastructure stock is ageing (average lifetime 30 to 80 years). Maintenance, repair, renovation and new-built are needed to ensure undisturbed use of our infrastructure. On top of that there is a demand for growth of the infrastructure stock, particularly in countries with booming economies as well as in countries that are in serious need of a good infrastructures to get their economy off the ground.

Growth of the infrastructure stock implies an increasing impact of building activities on the environment (demand for raw materials and energy). Today a circular economy is considered the appropriate concept for the future, also for the building industry. In this contribution the need for new strategies for mitigating the environmental burden, and hence societal burden of building activities will be discussed. On the one hand the potential, challenges and risks of a circular building industry are addressed. On the other hand the need for fundamental research on ageing of materials, structures and systems will be highlighted. It will be shown that more knowledge on ageing phenomena is of utmost importance for developing a circular economy that can really meet the expectations of all stakeholders, who too often seem to believe that adopting a new concept, i.e. circularity, will solve all our problems. The contribution ends with an estimation of societal savings that might be expected from investments in fundamental research.

Keywords**:** Ageing, Infrastructure, Concrete, Service Life, Economy, Durability, Modelling

1. Introduction

A modern society is inconceivable without a well-developed physical infrastructure. This infrastructure consists of networks for transportation of good and people, networks for transportation and distribution of energy, sewage systems, roads and railways, bridges and tunnels, airports, buildings, houses, factories, power stations and defence works. According to Long [1], the infrastructure accounts for about 50% of the country's national wealth. From different sources values of the world's infrastructure have been inferred between US$ 51 to 125 trillion [2].

In a recent study of the McKinsey Global Institute [3] estimates were published of future investments in infrastructure needed to ensure economic stability and growth. In order to catch up with the prognosticated economic growth an investment of more than € 41 trillion was considered necessary in the period 2013-2030. This figure includes the infrastructure for transport (roads, ports, rail, airports), water, telecommunications and power plants. This amount was based on an evaluation of money spent on infrastructure in 84 countries, accounting for more than 90% of the global gross domestic product (GDP). Table 1 gives the breakdown of investments over different categories.

The aforementioned figures illustrate the crucial importance of an appropriate and reliable infrastructure. Without this infrastructure the economy would come to a complete stop. The infrastructure, however, is subject to *ageing*. Our assets – roads, railways, energy infrastructure, etc. - are still in use, but many of them beyond their initially presumed lifetime of, let us say, 30 to 80 years. Ageing processes can go fast, slow or extremely slow, but are in fact an inherent property of materials and structures. For many structures, built in the after-war period between 1950-1970, the end of service life is immanent. In the coming decades not only new-built for accommodating growth, but also for replacing obsolete structures is needed. This new-built, however, has to be realized in a world in which the boundary conditions have dramatically changed since the fifties and seventies of the past century. The awareness of the environmental impact of the construction industry has resulted in more stringent boundary conditions than 50 to 80 years ago.

Table 1: Estimated needs for global infrastructure in different categories in the period 2013-2030 [3].

Category	Reference	Required investment [4] × € 1,000,000,000,000
Roads	OECD[1]	12.2
Rail	OECD	3.3
Ports	OECD	0.5
Airports	OECD	1.4
Power	IEA[2]	8.8
Water	GWI[3]	8.4
Telecommunication	OECD	6.8
Total		41.4

1) Organization for Economic Co-operation and Development; 2) International Energy Agency; 3) Global Water Intelligence; 4) Conversion rate 2013: 1 US$ = € 0.73

The discussions on man-induced global warming, emerging in the sixties of the past century, have meanwhile resulted in strategies for reduction of the amount of emissions of greenhouse gases. Shortage of raw materials is another aspect that threatens one of the pillars of the building industry. At the same time we have seen an enormous evolution in computation power and predictive tools that can support decision making processes aiming at a predictable and sustainable future. These changes will undoubtedly affect the way in which the building sector will respond on the demand for new-built in the future.

2. Environmental Impact

2.1. CO_2 emissions

The physical infrastructure is made of materials. Most often used building materials are concrete and steel. About 0.215 ton steel is used per capita per year [4]. The production of 1 ton of steel goes along with about 2 ton CO_2, which makes about 0.45 ton CO_2 per capita. For a world population of 7 billion this results in a CO_2 emission of 3.25 billion ton per year.

Regarding concrete: per capita about 1.2 m^3 concrete is produced per year. The production of 1 m^3 concrete goes along with the emission of about 0.4 ton CO_2. For a concrete consumption of 1.2 m^3 per capita this results in a worldwide concrete-related CO_2 emission of 3.44 billion tons per year. The production of steel and concrete together is responsible for a CO_2 emission of 6.6 billion ton per year. This is about 20% of the worldwide CO_2 emission of 36 billion tons per year [5].

The production of building materials by far accounts for the largest amount of emission of the construction process [6]. Even though the in-use building emissions are about 4 times! the manufacture emissions, the CO_2 emissions from the production of steel and concrete are huge and call for cleaner production processes. In the past decades both the steel and cement industries have been able to reduce the amount of emissions significantly. In the near future further dramatic reductions are hardly conceivable. Moreover, the effect of reducing the CO_2 emissions per ton produced steel or cement will be cancelled out by the *increase* in the prognosticated worldwide use of steel and concrete, particularly in countries with a rapidly growing economy. Note, for example, that in the period from 2006 to 2015 the cement production is expected to increase from 2.55 billion tons to 3.7 to 4.4 billion tons [7].

2.2. Raw materials

Besides CO_2 emissions associated with the production of building materials, the availability of raw materials is another point of concern. Even though the quantities of raw materials worldwide are huge, there can be a *local* shortage of them. A local shortage may stem from an absolute absence of raw materials in a certain district, but can also be the result of local restrictions to exploit available resources, for example because of expected disturbance of local ecological equilibria. Local shortages may lead to long distance transport of bulk materials. Because of the pollution associated with long-distance transport of bulk good this should be minimized as much as possible.

2.3. Mitigating emission of cement and concrete

Concrete-related CO_2 emissions come from the calcination process, i.e. the breaking down of limestone into calcium oxide and CO_2. The calcination process accounts for about 50% of the emission from cement production and are called the *direct* emissions. *Indirect* emissions come from the burning of fossil fuels (about 40%) and the electricity used for operating the plant machinery and transport of cement (10 to 15%) [7]. For reduction of the amount of concrete-related emissions several options have been, and still are, considered.

- The use of alternative fuels and optimization of kiln technology. The potential for reducing the amount of CO_2 emission by further optimization steps, however, have almost been exhausted [7].
- The use of *blended* cements, in order to reduce the amount of Portland cement (CEM I cement), has been considered since decades. In some countries the use of ground granulated blast furnace slag (CEM III cements) is popular, up to replacement percentages of 90%. Additional advantages of CEM III cement are its low heat production during hydration (lower risk of thermal cracking), and a denser microstructure, which has a positive effect on its resistance against chloride ingress. A higher autogenous shrinkage and higher proneness to freeze-thaw scaling have been mentioned as drawbacks of CEM III cements. The use of fly-ash for replacing cement is also popular for reducing CO_2 emissions, with an additional advantage of a positive effect on the workability and long-term resistance against chloride ingress.
- The amount of CO_2 emission per m^3 concrete is also possible by reducing the amount of cement per m^3 [8]. This can be achieved by optimizing the particle packing, often in combination with the use of admixtures to ensure the workability of the mixture in the fresh state. A positive side effect of reducing the amount of cement is the reduction of peak temperatures in the concrete in the hardening stage. In the hardened stage, however, a lower cement content means a reduced potential of the concrete to repair microcracks by self-healing. The quick win might be completely lost at the end of the (premature) end of service life!
- As long as concrete is used, we know that concrete will be carbonated under uptake of CO_2. Carbonation has always been considered as a degradation process, since it is associated with the drop of the pH of the concrete. A drop of the pH from 13 in healthy concrete down to 9 will cause depassivation of the reinforcing steel, resulting in corrosion. The lower the carbonation depth, the lower the risk of carbonation-induced corrosion. Eventually with the aim to improve the image of concrete carbonation has recently been mentioned as a significant CO_2 sink. However, aware of the enhanced risk of rebar corrosion due to carbonation of the concrete, carbon uptake of concrete structures should not be considered as a serious strategy for creating a CO_2 sink.
- Extension of the service life of concrete structures is one of the promising options to reduce the environmental impact of the construction industry. It reduces all activities of the construction process, from production of building materials, transport, labour etc., and hence the CO_2 emissions associated with these activities.
- The next step after extension of the service life is that towards circularity. In fact materials reuse and recycling are not new. Hendriks [9] memorises waste materials, such as metals, wood, and paper, to be reused since time immemorial. For example, a concrete structure used for transport of water from the Eiffel to Cologne (AD 80) contained a binder made with lime, dust from broken bricks and other pozzolanic materials. Today circularity is a key-issue in many sectors, and so in the building industry. It is high on the political agenda and deserves special attention (next section).

Chen et al [10] emphasizes that the effects of optimization steps anywhere in the production process in view of reduction of CO_2 emissions should be carefully checked for their effect on the *total* life cycle of a real structure. Also local circumstances, i.e. availability of raw materials and fuel, can have a substantial impact on the outcome of the optimization process.

2.4 Circularity

Although there will hardly be anyone who believes that 100% circularity is possible, it is at least a concept that generates and stimulates awareness of the environmental impact of the construction industry and forces us to think about the potential of new concepts. The way towards full circularity will certainly create unorthodox solutions, most probably as a result of multidisciplinary collaboration.

Figure 1 shows the building cycle with its subsequent stages of the life cycle of a structure. It starts with the production of building materials, requiring raw materials and energy. In the next phase construction elements and/or complete structures are realized, marking the start of the structure's life time. The outer circle of figure 1 represents the materials cycle for a so-called *monolithic* design concept, whereas the inner circle represents a *demountable* design concept. After having passed the stage of renovation, retrofitting and upgrading, structures built according to the monolithic design concept have to be demolished at the end of their service life. In a circular concept the demolition waste will be reused for producing new building materials, products or structures. Structures built according to the demountable concept will provide new elements for reuse in new buildings directly. The inner circle (demountable design) will require less energy for a complete loop compared to the outer circle (monolithic design) and is, therefore, preferable from the sustainability point of view.

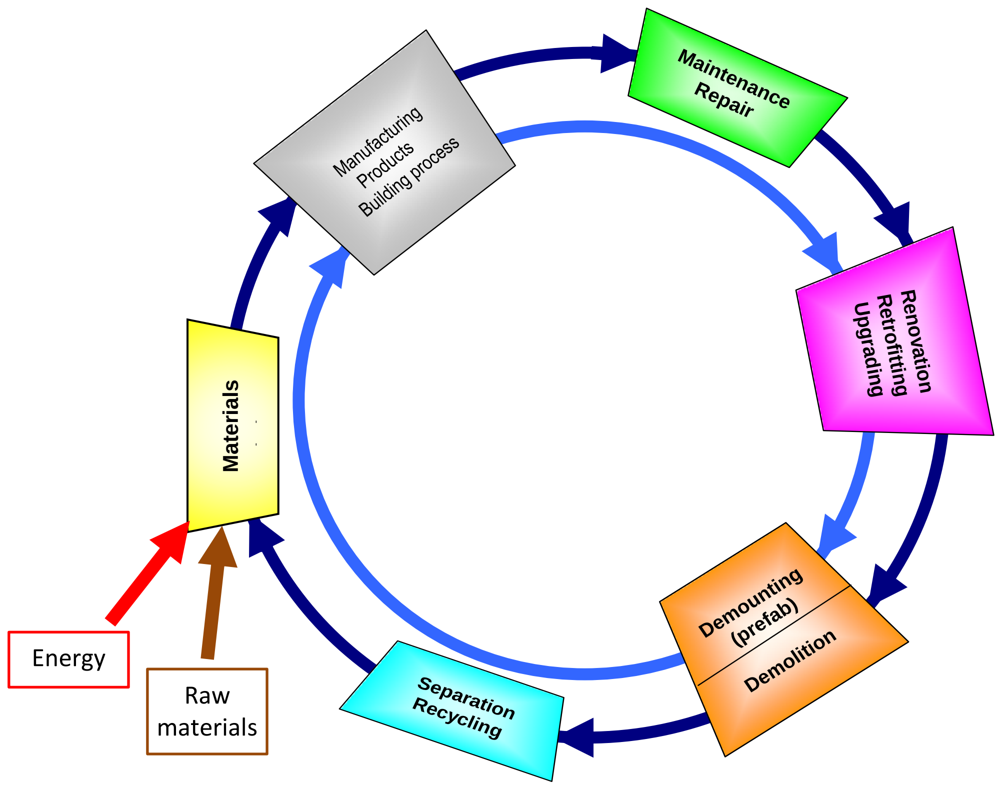


Fig. 1: Building cycle. Outer circle: monolithic design concept. Inner circle: demountable design concept. Consumption of energy and raw materials to be reduced as much as possible.

3. Ageing of Infrastructure Stock

The rate at which materials and structures go through the building cycle depends on the service life of the structures. The service life, on its turn, is determined by the quality of the structure. Irrespective of how good the initial quality of the structure has been, with elapse of time its performance will change. This change of performance with time is called ageing. In essence ageing is a 'natural law'. Bad design, poor workmanship, inadequate maintenance or overloading of a structure may indeed jeopardize a structures lifetime by enhancing the rate of ageing, but in the end ageing will continue anyway. For a proper estimation of the change of performance with time, one should be able to describe the rate of ageing processes accurately. This is only possible, however, if the driving forces of ageing are known. Yet, this is not always easy. Figure 2 may be helpful for understanding why predicting ageing processes is so difficult. The curve in this figure illustrates three subsequent stage of a structure. In the initial stage all components of which a structure will be made are assembled, resulting in a mature structure that meets the design criteria. Then a period follows of 'top level sport' for all elements of the structure, from the smallest (atoms, molecules) to the biggest ones (columns, slabs, walls). During this period - the service life -, the performance of the structure hardly changes. At the macroscale no changes of performance with time will be registered at all. But in fact, at lower length scales, ageing processes will have started, but still remain under the radar of currently used inspection techniques. However, it are just these very slow processes which determine the onset of the stage with decreasing performance of the structure. In other words, ageing does not start when the performance changes (the traditional perception), but when so called basic building blocks (atoms, molecules) start to change their position under prevailing load and exposure conditions, while the structure still meets all performance criteria!

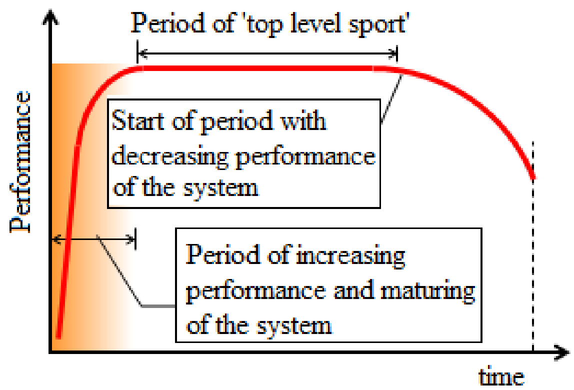


Fig. 2: Performance curve of concrete structures.

From the foregoing reasoning it can be inferred that ageing problems are, by nature, multi-scale problems. For this reason, and also because it is difficult to define the exposure and load conditions during the entire service life deterministically, ageing studies will inevitably be probabilistic in nature. Uncertainties in service life predictions will increase with increasing lack of knowledge of the materials from which structures are made. This is in fact the case with new materials, maybe recommended because of their low CO_2 emission during production, but with no data on their long-term performance. A few thoughts on dealing with this type of issues will be dealt with in what follows.

4. Dealing with uncertainties

Structural designers are used to cope with uncertainties, i.e. scatter in materials properties and loads. In probabilistic design codes these uncertainties are well considered. When the input parameters of a probabilistic analysis, i.e. their distribution curves (mean values and scatter), are known, the *probability of failure* of a material, structure or system can be predicted. For a complete evaluation of the *risk* not only the probability of failure, but also the *consequences* in case of failure must be known. For different activities figure 3 shows the risks spectra, with the probability of failure on the vertical axis and the damage potential, e.g. costs in case of failure, on the horizontal axis. Spectrum K_1 represents well-defined risks associated with, for example, current structural designs of houses. Spectrum K_2 represents the risk adopted in some branches of the process industry, where catastrophic accidents have turned out to be possible. Examples are the Bhopal accident in 1986 and the Mexico City LPG-disaster in 1984. Spectrum K_3 stands for activities of which the consequences in case of an accident are so high, or the probability even unpredictable, that it could hardly be justified to accept them. Examples are found in the waste management business, where the long-term consequences in case of a failing containment are largely unpredictable. Spectrum K_4 represents Low Probability/High Consequence Risks. In those cases the theoretical event probability is so low, that no statistical data is available to verify these figures. Core melt-down accidents in nuclear power plants are examples of K_4-events.

A large-scale use of new materials, of which the long-term properties are unknown, is a typical K3 issue. If the short-term performance meets the requirements, the entire period until a sudden emerge of an unpredicted deterioration mechanism will be available for the uptake of a substantial amount of these materials in the building cycle. A recent example of such a situation is the Canadian Pyrrhotite problem. Pyrrotite is a reactive iron sulfide mineral that has been found in the aggregates of concrete foundations of hundreds of residential buildings. If present beyond a certain threshold value, the Pyrrotite can completely destroy the concrete due to the formation of an expansive reaction product. This has actually happened. The total damage is now estimated at $ 75.000 to $ 145.000 per house. Total costs may rise up to $ 1 billion Canadian [13].

The large-scale use of concrete mixtures with cements blended with ‘new’ powders of which the effect on the long-term performance of the concrete is unknown, can also pose a certain risk. A too narrow focus on CO2 reductions for a quick win should not lead to carelessness with regard to checks of all other properties, particularly the long-term properties. For new man-made materials no information about their ageing properties is available yet. For a justified use of these new materials fundamental studies of ageing mechanisms are a prerequisite in order to prevent contamination of the building cycle as presented in figure 1 and proposed in a circular economy.

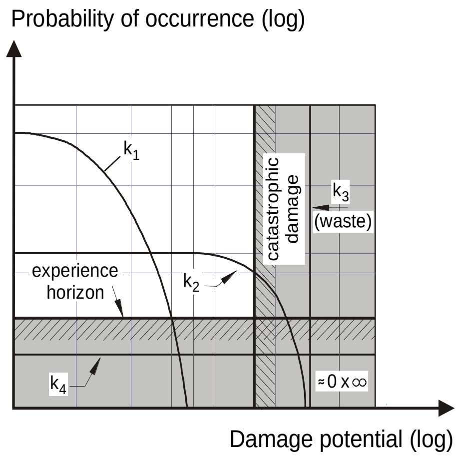
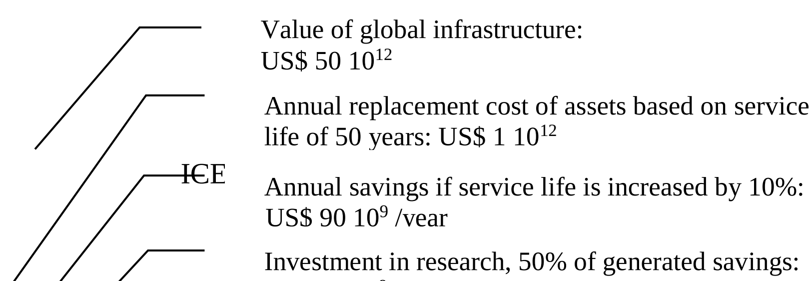


Fig. 3: Risk spectra (after [11,12]).

5. Research and Return on Investment

The concept of circularity is challenging and certainly the way forward, but it also contains risks. One of the risks is the contamination of the materials cycle, with potentially far reaching consequence on the long term. It is of crucial importance, therefore, to develop reliable models for prediction of both the short and long-term consequences of the use of new materials, material modifications and new design concepts. The development of such models presuppose that fundamental ageing mechanisms and processes are known and adequately addressed in these models. Most of the currently used models for long-term predictions are empiric formulae, which describe degradations processes as a function of time, but do not describe the degradation processes itself. More research is needed of the real driving forces and decisive preconditions of ageing processes to happen. This research requires quite substantial investments and the question is who will pay for this. In the search for research money it is worthwhile to look at the issue from the perspective of potential savings that can be achieved by extending the service life of our infrastructures (see also [2]). In the introduction the value of our infrastructure has been estimated between US$ 51 to 125 trillion. Let us, conservatively, assume US$ 50 trillion. Let us further assume an average lifetime of infrastructures of 50 years. This means that each year US$ 1 trillion has to be spent on replacement of obsolete structures. Let us further assume that, in order to mitigate the impact of building activities, the average lifetime of our infrastructures should be increased by 10%, i.e. from 50 to 55. This will reduce the yearly replacements cost from US$ 1 trillion to US$ 0.91 trillion, a reduction of US$ 90 billion per year. For realizing these savings we first have to invest! Let us assume that for saving these US$ 90 billion per year we have to invest 50% of this amount in research, i.e. US$ 45 billion per year. Assume that 50% of the required money, i.e. US$ 22.5 billion, has to be spent on management-oriented research and 50% on science-oriented research. A part of this science-oriented research should be devoted to ageing of materials and structure. Let us assume that 20% of science-oriented research, i.e. US$ 4.5 billion per year, should be spent on fundamental ageing studies. This US$ 4.5 billion is 10% of the required research budget for realizing the savings of yearly replacement costs and only 5% of the targeted savings. Schematically this is shown in figure 4.



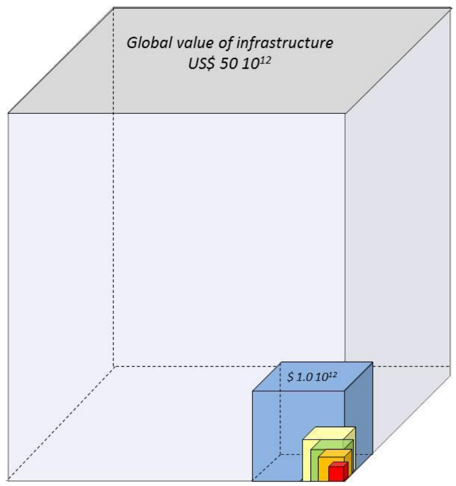


Fig. 4: Global value of infrastructure, replacement costs and research budgets for generating savings in replacement costs (interest / inflation not considered) (after [2]).

6. Concluding remarks

The value of the world's infrastructure has been estimated at more than US$ 50 trillion. This infrastructure is ageing! The costs associated with ageing infrastructures is a huge financial burden for the society and a burden for the environment as well. Controlling ageing-induced degradation processes, and hence reducing costs of new-built and of maintenance of existing infrastructure, contributes to lift this burden. It is simply a matter of *responsible stewardship* to mitigate the environmental impact that comes along with gradual ageing of our infrastructure assets.

Ageing is an *inherent* feature of materials. It finds its origin in the ever present *motion* and *gradients* at primary length scales. In heterogeneous materials, like concrete, many interfaces are present at which different types of gradients are likely to occur and which make this material prone to ageing. Dealing with ageing and solving ageing problems require a fundamental materials science oriented approach. Understanding ageing mechanisms is the key to design low-ageing materials, i.c. (s)low-ageing concretes. For developing (s)low-ageing materials and concepts, we have to invest in research. An example has been presented, illustrating how investments in research can result in savings for the society far beyond the investments needed to generate these savings. Setting clear targets for the magnitude of savings and for the required research budgets for accomplishing these savings is a challenge and stimulus for effective research and innovation. It is strongly believed that in the end the investment in research will pay off.

The intensive search for 'green' mixtures - generally defined as mixtures with a low CO_2-footprint - is understandable, but also needs to be considered with caution. It is not only the CO_2 footprint of 1 m^3 concrete that finally counts, but the CO_2 footprint 1 m^3 *during its total life cycle*. More generally speaking one could say that focusing on CO_2 reduction is *necessary, but not sufficient* for a comprehensive judgment of the environmental impact of concrete. Since sustainability is a more-dimensional issue, judgment of the environmental impact also requires a more-dimensional set of criteria for evaluating this impact [12].

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