Sustainability

During the last 250 years, since the start of the Industrial Revolution, aspects of human activity is causing significant climate changes on our planet. Changes occurred also before humans started to create real damage, for instance due to volcano eruptions and asteroid impacts. And even today there may be aspects of climate change that are not influenced by humans. But make no mistake about it: emissions caused by human activity amplifies the greenhouse effect, causing the planet to warm. The Global Climate Change website maintained by NASA is one good place to learn more about it; visit https://climate.nasa.gov. The greenhouse gases we emit that cause our planet's atmosphere to warm include

- carbon dioxide (CO_2),
- methane (CH_4),
- nitrous oxide (N_2O), and
- chlorofluorocarbons (CFCs) and a group of fluorinated gases, i.e., F-gases.

Figures 1, 2, and 3 are taken from the NASA website mentioned above. Figure 1 shows how the global average temperature has increased by roughly one degree Celsius in the last 100 years.

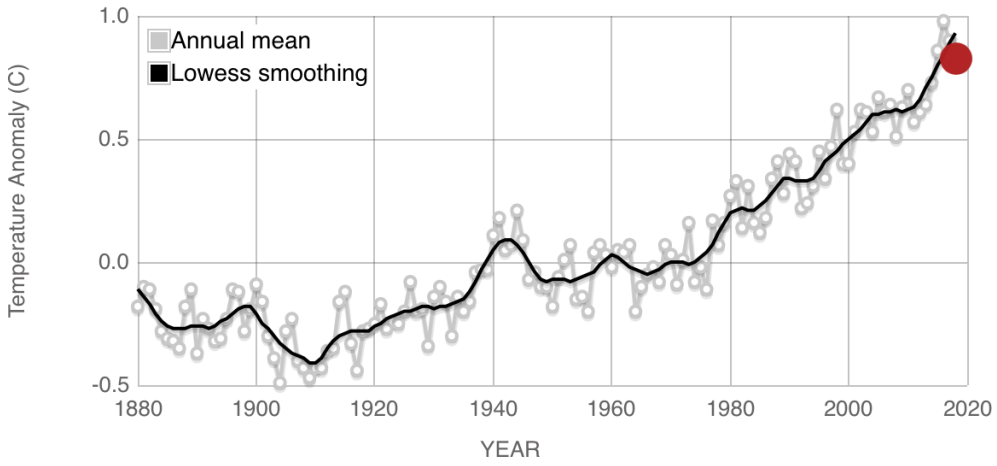

Figure 1: Recent development in the global temperature (https://climate.nasa.gov).

Figures 2 and 3 show the dramatically increase in CO_2 levels. To save the planet from potentially devastating climate change we need to reduce the emission of greenhouse gases and also increase sequestration. Another gas whose presence amplifies the greenhouse effect is water vapour, but that gas is not the concern for humans trying to limit harmful emissions. Rather, it is the following activities that are harmful:

- CO_2 emissions: Deforestation, burning of fossil fuels, cement production that thermally decomposes calcium carbonate
- CH_4 emissions: Decomposition of waste, digestion in livestock, rice cultivation

- N_2O emissions: Use of fertilizers and fossil fuels, production of nitric acid, burning of biomass
- CFC emission: Produced solely in industrial applications, but heavily regulated after it became known how damaging these gases are to the ozone layer

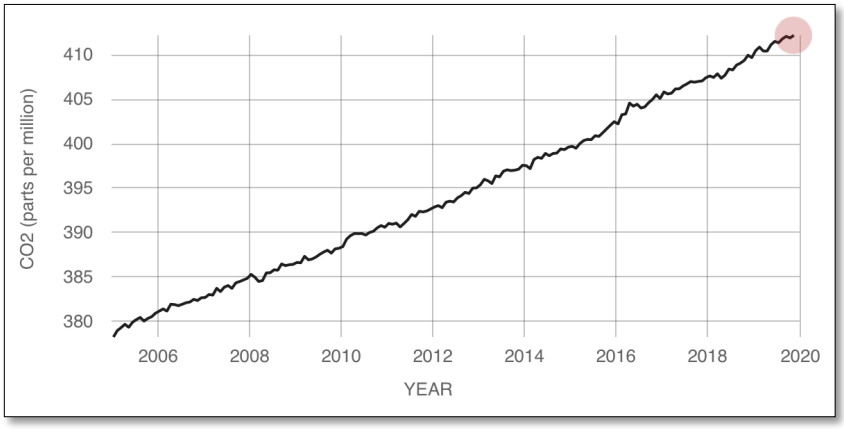

Figure 2: Recent CO_2 levels (https://climate.nasa.gov).

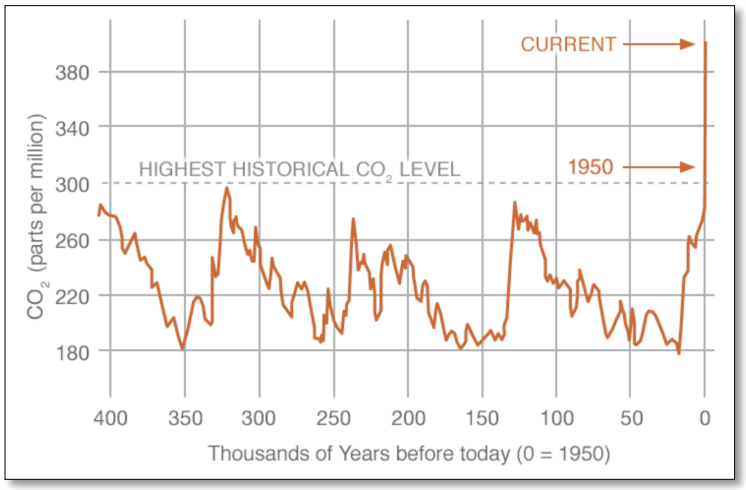

Figure 3: Historic CO_2 levels (https://climate.nasa.gov).

Several leadership figures have provided inspiration for us to address the challenge evident in Figures 1, 2, and 3. Former Vice President of the United States of America Al Gore stirred many with the movie entitled An Inconvenient Truth. The Nobel Peace Prize 2007 was awarded jointly to Al Gore and the Intergovernmental Panel on Climate Change, cited shortly. Al Gore's book Our Choice (Gore 2009) is an accessible guide to addressing the climate crisis. In Canada, David Suzuki has inspired many with his eponymous foundation and his book outlining the effects of human consumption (Suzuki et al. 1997).

Global Emissions

Considering total global emissions, the Intergovernmental Panel on Climate Change estimates that (IPCC 2014):

- 65% of greenhouse gases are emitted in the form of CO_2 from use of fossil fuel and industrial processes, including the production of construction materials,
- 11% is CO_2 emitted from forestry and other land use,
- 22% is methane and nitrous oxide emissions, and
- the last couple of percent are F-gases, such as CFC.

Attributing the emissions to various sectors the estimates are (IPCC 2014):

- 14% of greenhouse gas emissions is from transportation,
- 6.4% from operating buildings,
- 21% from industry activity, including the construction industry, and
- 24% from agriculture, forestry, and other land use, including forest fires.

The remaining 35% of greenhouse gas emissions is related to electricity, heat production, and other energy usage. Some of that is in turn labelled "indirect emissions" and attributed to the various sectors as follows (IPCC 2014):

- 12% from operating buildings,
- 11% from industry activity, including the construction industry, and
- 10% from other energy usage.

Emissions from Construction

As structural engineers we are particularly concerned with the emission of CO_2 and other greenhouse gases related to the construction, retrofit, and repair of buildings and other infrastructure. One source of data is the website entitled "Tracking Buildings" maintained by the International Energy Agency, IEA (https://www.iea.org/reports/tracking-buildings). However, similar to the challenge of fully understanding the source of the emissions quoted in the previous section, the IEA numbers include the operation of buildings, which requires a substantial amount of energy. IEA is naturally focused on energy usage; hence, transportation and the thermal properties of building envelopes are important concerns there. When quoting the IEA numbers in January 2019 in a piece entitled "Efforts to make buildings greener are not working" The Economist suggested that "putting up and running buildings consumes 36% of the world's energy and produces some 40% of energy-related carbon emissions. Five-sixths of that energy is used to light, heat, cool and run appliances." The piece continues by saying that more than 5 billion tonnes of cement is manufactured each year, causing 6% of emissions. In the same source the manufacturing of steel is said to cause 8% of emissions, with half of all steel going into construction.

Another interesting piece, entitled "Buildings are bad for the climate" is authored by Bill Gates in October 2019 and posted to https://www.gatesnotes.com. He quotes several interesting facts, some noted earlier in this document:

- 25% of greenhouse gas emissions is caused by electricity production,

- 24% is caused by agriculture,
- 21% is caused by manufacturing of materials, including emissions from the energy needed and also emissions from the chemical processes,
- 14% is caused by transportation,
- 6% is caused by energy usage in the operation of buildings, and
- 10% is caused by miscellaneous activities.

More specific to construction, Bill Gates points out that the manufacturing of steel and concrete causes 10% of all greenhouse gas emissions. He also talks about the energy required for the operation of buildings and the emission of F-gases by air conditioners. An important purpose of other documents posted on this website is to provide the details behind numbers such as those given above, allowing calculations for specific buildings and other civil infrastructure.

What to Do?

From the above, and from a structural engineering perspective, it is understood that the following actions are needed to save the planet from overheating:

- Reduce the use of steel and cement, for example using wood and other natural materials, or find ways to produce steel and cement without the emissions and energy use
- Reduce transportation of materials and workers and improve the energy efficiency in all aspects of the construction and operation of buildings, or find cleaner ways to produce that energy

Holistic List of Concerns

For ages, structures were built with one thing in mind: they should not fall down. Centuries ago, the strength of a structural design was estimated with experience, judgment, and perhaps testing of important components. Once the concept of stress came about the design was checked by comparing the calculated stress to some allowable stress. More recently, still for many decades, the stiffness of a structure, which determines the deflections, has also been checked to prevent discomfort by those using the structure. In modern codes the strength concern is formalized in ultimate limit-states, while the stiffness concern is checked with serviceability limit-states. Additional, but usually secondary limit-states exist in some codes, including fatigue, explosion-related limit-states, etc.

Allowable stress design has been used since the 1940s or 50s, and is still employed in some steel design codes. Limit-state design has been used since the 1970s and 80s, pioneered by reinforced concrete codes because it can be hard to calculate the stress in reinforced concrete components. Structural engineers designing against earthquake ground motion know that the 1990s and 00s brought yet another design paradigm, called performance-based engineering. In that approach, potential damage due to ground shaking is considered. Even if a structure does not fall down in an earthquake the damage may be unacceptably costly, as was observed for instance in the 1994 Northridge

earthquake near Los Angeles. Thus, monetary cost of repairs and downtime were added to the list concerns that should be considered by a structural engineer.

In addition to the concerns outlined above, humans are increasingly realizing that some of our activities are causing unacceptable pollution and causing the climate to warm. Construction and operation of buildings and civil infrastructure is one of the activities that cause substantial emission of greenhouse gases. The report from the UN commission chaired by former Prime Minister of Norway Gro Harlem Brundtland established "sustainable development" as an important goal for humanity (United Nations 1987). In that seminal work, environmental impacts were not the only concern; economic growth and social equality are the other legs of the "three-legged stool" that the Brundtland Commission constructed to foster sustainable development.

To address the concerns relevant for a structural engineer it is useful to identify the phases in the lifecycle of a building, bridge, or other infrastructure. The following list suggests the activities, or events, that are taking place within each phase:

0. Preparations
   a) Production of electricity
   b) Production of fossil fuels
   c) Extraction of materials
   d) Manufacturing of construction materials

1. Construction, repair, retrofit
   a) Construction of prefabricated components
   b) On-site construction

2. Ground shaking
   a) Damage

3. Operation
   a) Heating
   b) Cooling
   c) Deterioration

4. Demolition, deconstruction
   a) On-site demolition and deconstruction work
   b) Recycling of materials
   c) Processing at landfill

One activity that takes place in several lifecycle phases and many other aspects of life is transportation:

T. Transportation
   a) Materials
   b) Workers
   c) Water
   d) Fuel

With all those activities there are concerns. The lists below are suggested, with two comments attached. First, some concerns, such as greenhouse gas emissions, depend upon the prediction of another concern; namely, consumption of energy in the form of electricity or fossil fuels. Second, notice that the ultimate and serviceability limit-states

from current design codes, and also potential damage due to earthquakes, are baked into several of the concerns.

C. Consumption
a) Consumption of materials
b) Consumption of labour hours
c) Consumption of fossil fuels
d) Consumption of electricity
e) Consumption of water

The final concerns, ultimately translated into monetary values (see the next section) are:

I. Costs
a) Invoices
b) Loss of business

II. Emissions
a) Greenhouse gases
b) Air pollution
c) Toxic substances
d) Waste

III. Human well-being
a) Injuries, deaths
b) Loss of residence
c) Discomfort due to deflections and vibrations
d) Respiratory health problems
e) Poor aesthetics
f) Discomfort due to noise

Merger of Concerns into a Single Objective

The concerns listed above are numerous and dissimilar. How do you compare the invoice for a material purchase with the "cost" of poor respiratory health caused by emissions during production of that material? Some researchers suggest that the consideration of this multitude of concerns is a multi-objective decision problem, requiring so-called multi-objective decision techniques. A different approach is adopted on this website; all concerns are translated into monetary value. That is of course straightforward for direct costs paid through invoices, but less intuitive for, say, environmental impacts. Two points may help with the appreciation of this approach. First, think of the "carbon tax" suggested by William Nordhaus. At present, emission of a tonne of carbon is said to cost roughly $50. That idea, for which Nordhaus received the 2018 Nobel Prize in economy, is one example of expressing intangible concerns in monetary terms to promote good decision-making. Drew Shindell's monetary quantification of deteriorating human health due to pollution is another example (Shindell 2015). Second, note that even in multi-objective and multi-attribute decision-making it is ultimately necessary to place weights or preferences on each concern. Here it is argued that the translation into monetary value is a transparent way of doing that. That means that all **B** and **C** concerns require models to translate, say, greenhouse gas emissions into monetary cost values. Therefore, an example of a chain of models required in the suggested framework is:

- Model that predicts the consumption of fossil fuels [**U**.c] during transportation of materials [**T**.a] to the construction site [**1**.b]
- Model that predicts the emission of greenhouse gases [**II**.a] during the consumption of fossil fuels
- Model that predicts the cost of emitting greenhouse gases, i.e., [**II**.a]-cost

Perhaps the simplest example of modelling needs in this framework is:

- Model that predicts the invoice, i.e., direct cost [**I**.a] of the consumption of labour hours [**U**.b] during on-site construction [**1**.b]

Using the numbering introduced above it is possible to establish a big matrix of activities and concerns, with some cells requiring models, others not:

#	T	C	I.a	I.b	II.a	II.b	II.c	II.d	III.a	III.b	III.c	III.d	III.e	III.f
0.a	a-d	a-e												
0.b														
…														

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