2. Research overview

Research Focus

The research work within the group covers the interaction of buildings, structures and the built environment with the climate in form of the wind in the atmosphere and other parameters such as temperature, rain, snow and ice. The overall aim is to understand and describe atmospheric and environmental processes, their variation from different boundary conditions and their impact through physical loading on structural response and on human comfort in buildings and in the built environment. In this connection, the research work explores the development of new circular construction materials tailored for free-form manufacturing of optimised structures exposed to extreme climatic conditions. The work feeds into following main areas:

- Environmental Impact, Loads and Response of Structures
- Urban Environment
- Cold Climate Engineering
- Development of Material and Manufacturing Technologies for Optimised Structures

Amongst other, the research is conducted through field measurements in nature, experiments in a specialised climatic wind tunnel, numerical simulation, 3D printing and testing in the Structural Laboratory of the Department of Civil Engineering.

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Climate & Structures

Climate and Structures – A Concept of Interrelation

Throughout the history of humankind, structures were erected to create shelter from weather and environmental impacts, starting by using locally available materials. Structural geometry and concepts of the load carrying system were adapted and optimized through trial-and-error and systematic experimentation. Available resources were refined, material properties enhanced, and design methods improved, leading gradually to optimized structures within the associated ecosystem.
With the advent of globalization and industrialization, the supply chain for raw materials changed significantly and with that the advancement in architecture, design and structural performance. Construction materials, like concrete and steel, were produced from large-scale centralized industrial branches, affecting the environment by heavy resourcing of raw materials and changing its chemical state [1]. Such, not only standing in the direct interrelation with its local ecosystem, but rather affecting the biosphere and global climate, marking hence the era of the Anthropocene.

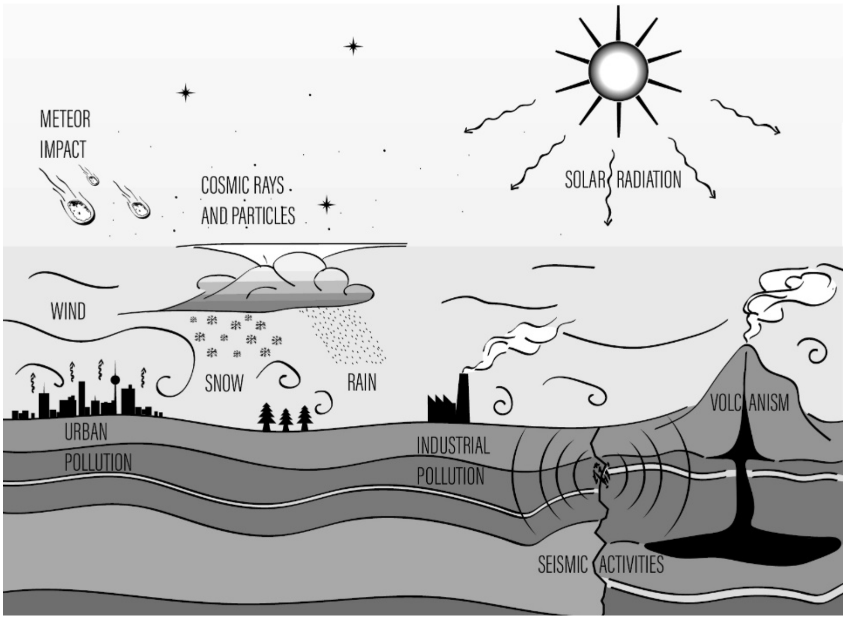


Figure 1: Aspects of climate-structures interrelation, including direct load impacts and long-term exposures of structures and humans within the built environment [1].

Figure 1 illustrates some of the main natural and anthropogenic elements in the ecology of natural environment, climate, structures and humans in the built environment. Structures are designed to withstand the impact from natural forces such as wind, snow, ice and earthquakes and are subjected to deterioration by climate impact like temperature, humidity and solar radiation. The climate in turn is affected by the manufacturing process of structures, e.g. through the herewith connected particle- and greenhouse gas emission, and through the expansion of urban land (e.g. surface albedo change). As described by the International Panel on Climate Change (IPCC), CO_2-

emissions are one of the key drivers in climate change [3], for which the construction sector plays a major role [2],[4],[5] - Cement production alone is responsible for around 4% of the world's fossil fuel emissions [6]. The material use in structural building components has therefore a direct influence on the climate and the change of its physical state. The drivers of climate change derive from anthropogenic sources of aerosols and greenhouse gases like other fossil fuel consuming industries and of natural origin like volcanism, solar radiation flux, impacts from cosmic rays and particles [7] or even extraterrestrial objects, etc. [3] some of which are still under discussion (Figure 1). Other natural- but not climate related boundary conditions include soil and seismic activities. These conditions influence the choice for material, manufacturing technology, design of structural components and transportation and consequently the extent of associated emissions. Figure 2 illustrates the circular dependency of climatic boundary conditions, choice of resources and building technology, associated impact on environment and climate.

Ecological Structures

Centralization of material resourcing and the establishment of ubiquitous architectural and engineering standards are increasing the construction industry's economical efficiency and safety. Construction materials are produced by large-scale industry branches and transported to construction sites, making it simple to apply proven and time-efficient structural designs. However, the same set of designs is used for all types of geographical highly diverse regions, giving less priority to the exploitation of local raw materials and customized designs. In this respect, current building practice has a significant impact on climate and environment caused by unnecessary greenhouse gas emission, resource consumption [4], and waste production.
As part of the UN-Sustainable Development goals [8], expressed by the EU-Commission [9] and the IPCC [2], sustainable solutions for mitigating climate change are needed. Therefore, awareness of an overuse of resources is also increasing in the construction sector, causing a call for more efficient technologies [10]. Recent advancements towards digitalization and automation could enable a high degree of structural customization for local climatic loading and resource availability. Technologies, such as advanced load simulation techniques, structural optimization methods, free form construction techniques, and novel material alternatives could increase the effectiveness of the industry [4] in terms of its ecological mutualism by rendering safe structures with minimal use of local materials.

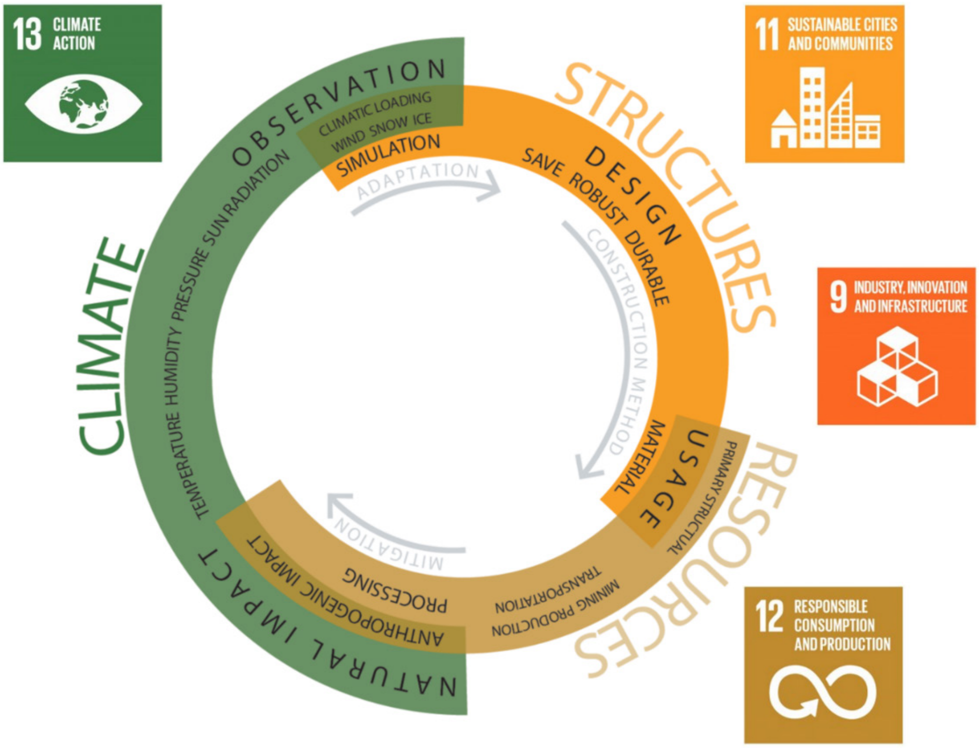


Figure 2: Illustration of circular dependency of climatic boundary conditions, resulting climatic loading, choice of resources and building technology, and the associated impact on environment and climate.

The central strategy of the research group 'Climate&Structures' is to contribute to sustainable advancements in the technological aspects of the circular interdependency between climate and structures. To this end, the research work focuses on three main areas: 1) observation and simulation of loading processes (physical states of the climate action), 2) response, deterioration and adaptation of structural designs to climate and environmental loads, and 3) advancement of material science and construction methods to render ecological structures with optimized performance.

Climatic Impacts and Loads

In structural engineering, climatic loads are extreme impacts resulting from the fluctuating state of the Earth's climate system in general or of processes in the Earth's atmospheric in particular. They are considered as single events such as extreme storms (e.g. hurricanes, extratropical cyclones) to ensure structural safety or as long-term processes to ensure durability. When planning development projects in urban areas not only the safe and durable design of the building or structure in question is of importance. With a trend to a high level of global urbanization, the effect of the local microclimate on human well-being has increasingly gained attention. A resourceful and climate conscious design of both, the built (structures and buildings) and urban (space between buildings) environment is indispensable to ensure sustainable urban planning [11].

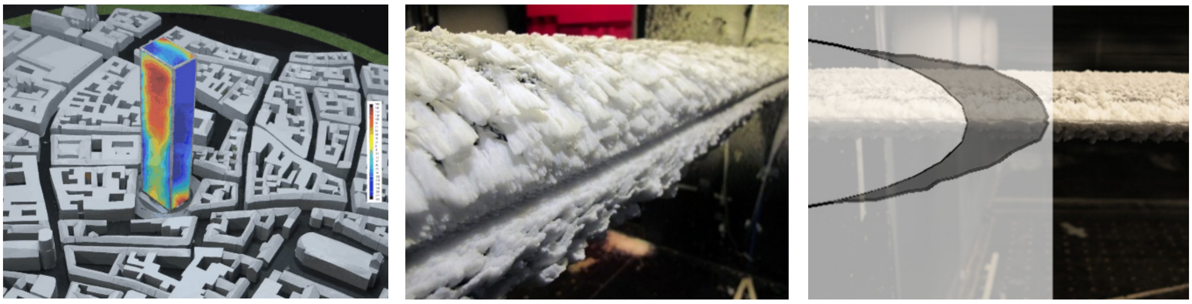
Wind

Few other forces have so universally shaped the diverse terrains and waters of the earth. Few other phenomena have exerted such profound influence on the history of humankind, on the way we live and how we build and where [12]. Being one of the principal forces in structural engineering, wind loads are determined by two main factors: the local climate and the shape of the object exposed to the wind. With the latter, the architectural form language plays a significant role for the loading the structure or building has to sustain throughout its lifetime. Hence, the load-carrying system on the inside and the outside shape of the building skin are key elements of any structural optimization process.

Wind loading is a fluctuating process governed by the aerodynamic behavior of the building, structure or structural element. To identify the extreme characteristic used for structural design, a large quantity of data is usually required and obtained through simulations with experimental or numerical models. Main challenge in these simulations is the accurate reflection of the turbulent atmospheric boundary-layer (ABL) in the lower part of the Earth's atmosphere. A mismatch in the turbulent structure and velocity distribution has a significant influence on the safety [13] or lifetime prediction of the structure designed with the data obtained through simulation. Wind tunnel testing (Figure 3a) is a proven and reliable method to investigate the complex wind loading process and allows amassing a large amount of data for reliable statistical analysis and probabilistic modelling of the structural response. On the other hand, a disadvantage of wind tunnel model is limit of shape variability. Depending on the type of model, a shape-load optimization has to done manually, i.e. through stepwise variation of the model shape (force balance models). Here, the numerical simulation provides the possibility of an automated process, linking aerodynamic optimization of the outer shape with a topology optimization of the load carrying structure. The present state-of-the-art of numerical simulation software and computational power puts some limits to a reliable and reasonably fast application. Current research effort within the group 'Climate&Structures' aims on numerical modelling strategies of sufficient accuracy and acceptable computation time [14],[15].

Icing

Icing of structures is part of phenomena occurring under cold climate conditions starting just under 0°C. The type of icing and magnitude of its effect on structural and aerodynamic loading is a function of temperature, wind speed and precipitation. All types have in common that the precipitating water is still liquid at the instant of impact on the object's surface and solidifies gradually in the subsequent thermodynamic process. Air temperature, wind speed, droplet size (median volume diameter), liquid water content (LWC) in air, object's surface and core temperature, thermal conductivity, geometric shape and surface roughness determine the ice accretion process and with that the quantity of additional mass on the object and the alteration of the object's geometry, i.e. its aerodynamic performance. The phenomenon of atmospheric icing on structural elements is the observable manifestation of a complex thermodynamic process which is best studied by recreating the governing climatic and structural boundary conditions as true-to-life as possible. For this reason, the 'Climate&Structures' group uses a climatic wind tunnel (CWT) jointly developed and operated with the Department of Hydro- and Aerodynamics of FORCE Technology [16]. Amongst other, in-cloud icing on structural bridge cables [17] and wind turbine wings are investigated. The wind tunnel allows using prototype samples of cables and wing section are studies at reduced scale compared as validation data to numerical icing simulations [18] (Figure 3b,c). Apart from additional mass and increase of aerodynamic resistance amplifying static loads or reducing energy production, ice accretion also bears a risk of aerodynamic instabilities such as galloping or flutter. Both can lead to large-amplitude vibrations reducing significantly structural lifespan and/or lead to structural failure. With respect to structural ecology, controlling and reducing the driving mechanisms behind aerodynamic instabilities for extreme and changing climate conditions allows minimizing maintenance and material consumption. The CWT is part of a wind tunnel network at DTU including test facilities at the Departments of Civil and Mechanical Engineering and of Wind Energy.



a) Wind tunnel study of surface pressure on a high-rise building in urban terrain for comparison with numerical simulation.

b) Study in climatic wind tunnel of ice accretion on structural bridge cable and its effect on overall aerodynamic performance and instability [19]

c) Icing study on an airfoil to specify the geometric characteristic of the ice layer at leading edge and the change of aerodynamic force coefficients during icing process.

Figure 3: Examples for investigations of wind actions on civil engineering structures under different climatic conditions.

Snow

With respect to structural loading snow is a considerable factor in cold climates, which in extreme cases exceeds the carrying capacity of roofs and, as in Arctic regions, can remain for months on the structure leading to densification and water penetration. Long-term penetration leads to mold growth deteriorating the integrity of the mostly wooden load carrying system and contaminating the indoor climate. The research group on 'Climate&Structures' looks at the relation of architectural design of Arctic residential buildings and snow accumulation on and around the buildings. The former address snow loading events whereas the latter focuses on the usability of buildings and their accessibility to formulate guidelines and recommendation for Arctic architecture and urban planning. Especially for Arctic regions, an increase of the annual mean temperature may lead to an increase of snow and wind event frequency and intensity. To investigate the mechanics of wind-driven snow accumulation the small closed-circuit boundary-layer wind tunnel at DTU Civil Engineering is fitted with a seeding mechanism of substitutional material. For validation of model-scale tests, a reference cube was installed in Nuuk (Greenland) with simultaneous monitoring of climatic conditions and snow accumulation throughout, up to now, two winter seasons.

Climatic Structural Design

Structures today are conceived from experience, mathematical description of mechanical behavior, experimental and numerical modelling, and are a result of a complex interaction of economical-, building performance- and infrastructural optimization. Automation and digitalization will possibly lower the dependency on large industrial manufacturing infrastructure and create structural customization for specific local climatic and loading condition (Section 2). It will thereby decrease resource consumption and increase the sustainability account of the construction sector. The interface between local loading conditions (climatic, natural forces, function, dead weight) and the construction material (primary material consumption, transport, manufacturing, waste) is the structural design (Figure 2). 'Climate&Structures' aims on the creation of climate-oriented structural designs, i.e. resource conscious structures that use a minimum of material to withstand extreme local climatic loading conditions using parametric and topology optimization tools.

Topology optimization

Structural optimization in terms of topology optimization can minimize the material use for a maximized structural performance within a given domain. A computational algorithm places material within a space of finite volumes at the location of high strain energy according to the given loading boundary conditions. To design structural components with this tool, a set of detailed loading conditions is required to prevent over- and under-dimensioning of the structure. 'Climate&Structures' uses topology optimization to create high performance structures for fluctuating loading impacts, obtained from wind tunnel simulations (Section 2.1). In Fernandoy-Bak, et al. [20], a vault-shaped structure was optimized (Figure 4-a) to withstand the stochastic loading process of wind-induced surface pressures. The turbulent structure of the simulated ABL-flow is visualized in Figure 4-b. First results indicate a common solution of the topology optimization for all loading instants [20]. This in turn could lead to a full stochastic topology optimization of the load carrying system for extreme climate impacts. Placing even inferior material strategically where it serves best structural safety and durability, will lead to a significant reduction of material consumption (Figure 2).

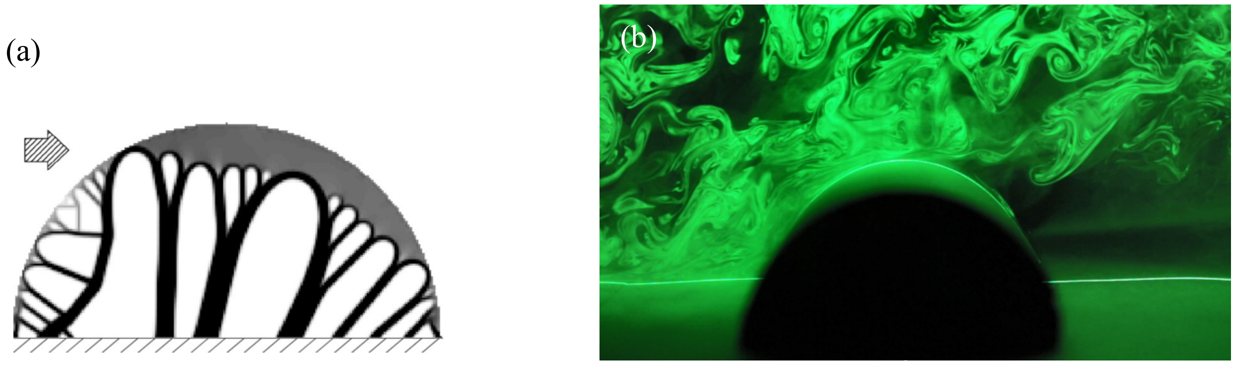


Figure 4: (a) Result from structural optimization (topology optimization) for wind loading scenarios [20], (b) visualization of turbulent flow over model in wind tunnel (flow from left to right).

Parametric multi-objective-optimization

'Climate&Structures' uses parametric design tools to optimize the performance of structural components. Through the inclusion of various performance objectives, the optimization process can consider not only material minimization of the structure as in Section 3.1, but include also e.g. manufacturing- and architectural boundary conditions. In Fernandoy-Bak, et al. [20], a frame-supported membrane structure has been parametrically designed for the use as an Antarctic research station. The structure was dimensioned to withstand extreme climatic loading conditions, to be transported to remote sites and assembled without mechanical help. The optimization scheme has therefore been adopted to the objectives of reaching a minimal number of structural components with limited dimensions and to create structures, being light in weight. Some of the outcomes are shown in Figure 5.

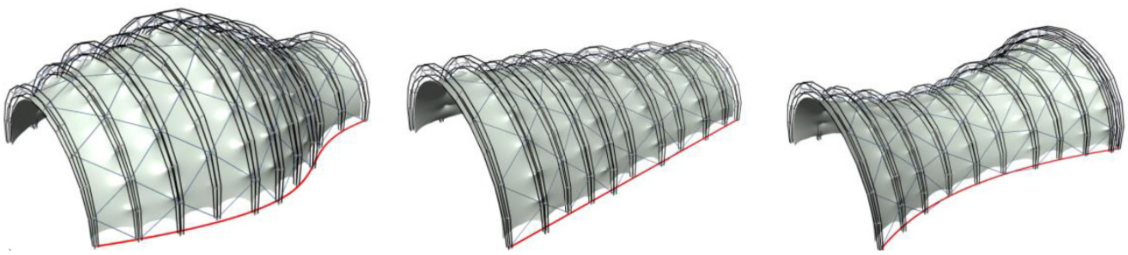


Figure 5: Frame-supported membrane structure, designed with multi-objective-optimization to withstand climatic loading impact and to fit several architectural boundary conditions. Image: [20].

Multi-objective optimizations with parametric tools give therefore the possibility, to design structural representations of climatic loading impacts, and at the same time respecting boundaries of manufacturing technologies, material resourcing, and architecture. Hence, representing the interface of all technological aspects (dark grey) in Figure 2.

Construction Methods and Resources

Computational optimized biomimetic structural design is a highly advanced field [21], pathing the way to create more sustainable and resource conscious constructions. However, the mostly biomorphic and freely shaped structural designs (Figure 4 - a) have a large draw-back in conventional manufacturing due to intensive use of non-standard molding and manufacturing shapes. Recent advancements in additive manufacturing (AM) [22] show possibilities in computer numerical controlled production without formwork and little waste material. The most advanced technology in constructional AM is 3D-printing of concrete using cementitious composites as a filament for construction. Judging the State-of-Art, designs manufactured by using this technology show a high potential for reaching construction-site-readiness in near future. Using cementitious filament allows relying on proven properties regarding performance as building material, but implies as well disadvantages such as lack of tensional strength, long setting times and environmental impact.
Novel construction methods and the associated material choices are the link between optimized structural designs, resource consumption feeding into the impact on the global climate (Figure 1). The aim of ‘Climate&Structures’ is to advance construction methods using materials, that enable the realization of the complex and optimized geometries presented in Section 3.

Additive manufacturing

The group explores possibilities of applying and advancing layered, extrusion-based constructional 3D-printing. The up to date, rather limited free form construction techniques, show difficulties in printing overhanging geometries needed for the realization of structures as shown in Figure 4. Climate&Structures focuses on the advancement of the filament’s performance in terms of hardening characteristics, early age material strength, printed induced dead load and increasing tensional strengths by attempting and introducing novel choices of extruded materials [23].

Use of secondary resources

Filaments for constructional 3D-printing can be taken from secondary resources of local industry branches as attempted before (e.g. in Guan [24]). These could deliver solutions to waste problems and increase reuse possibilities of secondary resources in constructions through modern construction technologies.

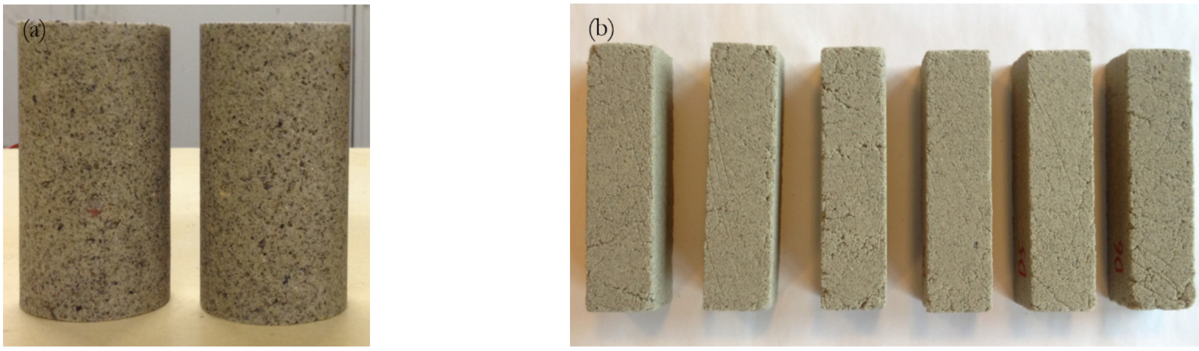


Figure 6: (a), (b) Concrete composite samples with biologically based binding materials, envisaged as filament for constructional 3D-printing. Image: [23].

Local resourcing from waste products reducing or even avoiding long transportation ways and production infrastructures is thereby one of the group's core ideas. The approach aims on the use of basic biological secondary materials connected with the food industry. The reuse of these materials could decrease emission and waste products due to lower production temperatures and recycle/reuse possibilities [23], falling in line with the EU's bioeconomic strategy [25]. Current research shows that use of secondary materials from food industry (biologically gels) as bio-based binding material for concrete (Figure 6) has a high potential for advanced applicability as filament in constructional 3D-printing [23].

Ecology: Structures, Part of a living System

Ecology, a science evolving from biology, describes the interrelation of organisms with their biotic and abiotic environment [26]. The investigated body within an ecological unit is thereby the ecosystem and includes the interaction of its biological, physical and chemical components [27]. This relation exists and is subjected to investigation at different scales: from Petri-dish bacteria cultures to our planetary biosphere [28]. On the example of the largest anthropogenic affected ecosystem, humans affect their environment by changing available resources in their physical, chemical and biological state [27]. In the same way, humans in turn are affected by other living components of the ecosystem and by the availability of non-living resources and physical states in nature. An ecosystem is often misunderstood as a community, limited to a field in ecology describing the interrelation of living biotic components (plants animals, microbes, etc.). By the definitions introduced above, a full view of an ecosystem includes as well numerous abiotic factors like climate, soil, and general energy and material consumption [26],[29].

In fields, such as ecological economics [30], ecological agriculture, or ecological building [26], the objective is to adopt the respective human systems (economics, industry, etc.) to be co-existent in symbiosis [31] (or mutualism [32]) with their environment. Consequently, these disciplines are a subsystem of the human organism within the ecosystem [30] of our own biosphere. The term 'ecological building' describes this role for the field of Civil Engineering and is explained in Daniels [26]. Focusing on a specific part of this field, the paper describes the interrelation of the load carrying structure (design and construction) as a subsystem of the human organism, with the climate as its abiotic environment. Conceptual relations are laid out by mapping interdependencies between climate and structures. Furthermore, strategies and methodologies are presented to understand, quantify and influence the ecological processes and are presented as part of the core disciplines of the research group 'Climate&Structures' at DTU Civil Engineering.

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