Sheltering 10 billion people in a warming and resource-scarce world: challenges and opportunities

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Chapter 1: General introduction

1.1 Buildings demand worldwide

From more than one million years ago, when there were signs of civilized activities, to the modern age of the 21st century, human beings have developed their own living space from a simple natural cave sheltering from wind, rain, and wild animals to customized artificial buildings, a structure with a roof and walls in a variety of sizes, shapes, and functions. Today, buildings provide basic needs not only for shelter, but also for thermal comfort, communications, the delivery of energy, food, and water, fundamentally determining people's well-being and health[1-4]. The provision for adequate housing (goal 11), and resilient infrastructure (goal 9) for all are considered essential United Nations Sustainable Developments Goals (SDGs)[5].

There are currently 8 billion people on Earth living in building stocks radically out of balance across world regions[6]. Many high-income regions saw large housing stock accumulations over the 20th century[5]. More recently, emerging economies such as China have seen the fastest increase in building stocks in the historic record, boosting economic growth and increases in well-being indicators like the Human Development Index (HDI)[12]. Conversely, low-income countries severely lack housing and infrastructure, especially in some African, Latin American, and Asian regions, and are home to most of the world's over one billion slum dwellers[5,7]. The majority of populations worldwide are projected to get wealthier in real terms and will likely demand larger homes and offices, driving a rapid increase in demand for new buildings, especially in lower-income countries[8].

The global population is projected to grow to nearly 10 billion in the coming decades[9]. These additional one or two billion people, together with the rapid rural-to-urban migration of a similar magnitude, will raise demand for new dwellings even further. Also, note that buildings do not stand forever. At present, a building usually serves decades before being demolished and then replaced by a new building. This building turnover dynamic adds to construction demand on top of the growing needs of building stocks in service and related constructions.

Unchecked construction and maintenance of buildings are extremely resource-and energy-intensive and have substantial impacts on the environment, especially in terms of ecosystem damage and greenhouse gas (GHG) emissions (as detailed in sections 1.2 and 1.3 below). In a resource-scarce and warming world, a sustainable and efficient system transition in shelter supply is urgently needed to limit environmental damage and provide shelter in a dangerous world. Given drastically different current levels and future patterns of development across the world, an integrated regionalized global assessment that maps challenges and opportunities is essential.

1.2 Building materials

Building materials are witnesses to the history of human civilizations. Material choices are driven by not only a need to adapt to nature, but also to human desires for durability, flexibility, comfort, and fashion[10]. These factors may have played varying roles in different periods across different ancient civilizations, which is marked by several general trends.

Among the first example of a human shelter transition was the Stone Age shift over a million years ago from natural shelters like caves to simple artificial shelters made from easily forgeable natural materials such as leaves, branches, and animal hides[11,12]. There was then a rise in more permanent structures made from more durable natural materials like clay, stone, and timber[10]. Then came synthetic materials such as clay bricks, with the first examples dating back to 7000 BCE, making up for the shortage of natural stones in Ancient Mesopotamia, and enabling the construction of large-scale buildings[13]. Soon after, wooden constructions gained momentum with the development of techniques for cutting and shaping woods, with Neolithic longhouses built around 5000 BCE among the first examples[14], and the Chinese Nanchen Temple constructed in 782 AD the oldest surviving wooden building[15]. Given its abundance, wood is still a popular construction material in many parts of the world today mainly in lower-rise homes[16]. Since over 7000 years ago when ancient Egyptians stunningly poured at least one of the pyramids, concrete has played a huge role in shaping the path of human progress to this day[17]. However, the material only became very widely used in building construction since the 19th century with the invention of the modernized Portland cement and the development of the steel-reinforced concrete that improves workability and strength[18,19]. Today, building structures based on steel and concrete play a dominant role across most world regions.

The history of buildings is also a history of the struggle for light through windows[20]. Glass, invented for making vessels and jewelry in 3500 BC, wasn't used to make small window glass panes of uneven thickness until the 1st century in Rome to allow some light pass through but not see through[21]. In the 4th century, stained glass became popular in Europe, creating beautiful biblical images in early churches[22]. It was only until the 20th century that the maturity of the float glass technology promoted manufacturing of large sheets of glass of uniform thickness and perfectly flat surfaces[23]. Modern glass windows of today are clear and fortified, providing customized light, views, and aesthetics, on top of the original insulation function as part of the building enclosure system.

Climatic conditions have always been part of the development of the structural form and material types of buildings, often to resist rain and snow, extreme heat and cold. Vivid examples include how clay bricks were widely used in the ancient Mesopotamian for their resistance to prevalent climatic conditions and insulation from both cold and heat[13] and how traditional Chinese architectures adapted their roofs against extreme snow events[24]. Increasing the durability and thermal performance of buildings needs to consider changing climatic and environmental conditions (e.g. heat, rain, wind, humidity, erosive particles) in the specific locations[25,26].

The building sector today has become one of the major material consumers globally. Every year, the construction of buildings uses nearly half of global concrete, brick, and steel, and a large amount of other metals (such as copper and aluminium) and nonmetallic minerals (such as glass and ceramic tiles), cumulatively reaching gigatones (Gt) each year throughout the 21th century[27,28]. Most non-metallic materials (e.g., concrete, brick, glass) accounting for most building mass, are used only once under current building practices[29]. A huge amount of raw materials are extracted from the earth each year and are not reused or replaced. These extractions, accumulating over decades and centuries have driven a large ecological impact (e.g., ecosystem destruction, erosion, and biodiversity losses) and driven increasing scarcity in resources. For example, recent research efforts have pointed to a severe global crisis with sand - an essential component in concrete and glass - impacting regions as diverse as Cambodia, California, the Middle East and China[30-32]. These impacts may only get worse with continuous increases in demand[33].

1.3 The contribution of buildings to climate change

There are various processes during building construction that may generate GHG emissions that contribute to climate change[34]. These include extracting raw materials (e.g., gravel, sand, metal ores) from the natural environment, transporting raw materials to where they are going to be processed, manufacturing materials for the properties of construction use, which often involves GHG emission-intensive processes requiring high-temperature heat and process-related chemical reactions (e.g., when limestone is heated to form lime during cement production)[35].

In modern society, a building is more than a place to live in. After a building is built, various types of energy such as electricity, heat, natural gas and biofuels are consumed to achieve and maintain multiple building services from heating and cooling to lighting and cooking[36]. Thus, substantial GHG emissions are generated over the lifetime of a building, from the extraction and processing of construction materials (concrete, steel, glass, etc.) to maintaining multiple building services (lighting, heating, cooling, etc.).

At the same time the planet is getting hotter to become less habitable. Estimates show that the global average temperature over 2011 - 2020 was ~1.09 (0.95 - 1.20) °C hotter than it was in the pre-industrial era (1850 - 1900)[37] and the temperature is currently rising by 0.2°C (±0.1°C) per decade[38]. Numerous studies have shown that a warming world is a mounting threat that causes dangerous and widespread disruption to nature and impacts the lives of billions of people[39-41]. Examples of climate impacts include sea-level rise, weather extremes such as increased rainfall intensity and tropical cyclones, heat-related mortality and vector- borne diseases, and direct economic damages[39]. To avoid potentially irreversible climate catastrophe, 195 nations, or the vast majority of global countries, adopted the Paris Agreement in December 2015 to respond to the threat of climate change and aim to hold “the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels"[42]. Considering that temperatures have already increased well over 1 °C, we are left with a very narrow and rapidly shrinking solution space for achieving these ambitious climate goals. Strong actions are urgently needed to mitigate emissions across all sectors and world regions.

At present, the construction and maintenance of global buildings represent nearly 40% (nearly 10% and 30% of emissions, respectively) of total energy-and process-related GHG emissions annually[34]. In particular, the GHG emissions associated with steel and cement production are very hard to decarbonize due to technical challenges. This is because these materials require high-temperature heat (hard to electrify) and process-based carbon dioxide emissions from chemical reactions, respectivly[35]. These emissions are set to increase along with building stock expansions, which in the absence of radical decarbonization actions may put global climate targets in danger[3]. But there is hope. Recent technological developments in the building industry may allow us to use materials and energy more wisely and efficiently through 'material efficiency strategies' such as material recycling, reuse, and substitution[16,43-45]. Understanding the GHG emission reduction potential in these recognized material efficiency strategies is critical to delivering adequate living space and climate targets.

1.4 Impacts from climate change - buildings at risk of natural hazards

Buildings can fail to serve their designed lifetimes for various reasons. A particular problem going forward is the impact of natural hazards on destroying shelters. For example, the 2022 catastrophic flooding of Pakistan destroyed over 1.2 million houses along with thousands of kilometers of road and hundreds of bridges[46]. Not long before, the deadly 2017 Hurricane Maria on Dominica damaged 90% of buildings with 62% 'heavily damaged' and 15% destroyed[47]. Estimates have shown that over half of US building stock is exposed to potentially devastating natural hazards (i.e., earthquakes, floods, hurricanes, tornados, and wildfires) and 1.5 million buildings lie in hotspots for two or more hazards[48]. On a global scale, floods represent the most prevalent and costly natural hazards[49], accounting for nearly half of total disaster events reported over the past two decades[50] and over 70% of modelled hazard-related damages (among earthquakes, cyclones, and floods) to transport infrastructures[51].

To make matters worse, these natural disasters are likely to be exacerbated by changes in climate and land use (e.g., vegetation clearance and subsidence)[52]. Therefore, buildings and materials may be more frequently threatened by worse hazards, leading to an increasing amount of damage and loss. Both building stocks and natural hazards are not evenly distributed on the planet, which complicates adaptation efforts. To form a more concrete knowledge basis, it is essential to understand where and how severe the buildings are to be impacted or damaged across the globe.

1.5 Research questions

This thesis aims to contribute to a better understanding of what the major environmental challenges and opportunities are in delivering the very immediate demand for a decent living space for a growing population. This thesis focuses mainly on the provision of a building space through construction, but also on the general trends of energy use efficiency of building operation because of its key role - along with the material use efficiency - in mitigating building related GHG emissions. We aim to make the first steps in this long-run endeavor to form the knowledge base for housing in an uncertain world.

The main research question posed here is: What are the main challenges and opportunities in delivering decent shelters for nearly 10 billion people in a warming and resource-scarce world? We will start by exploring main challenges in securing the critical material basis of building construction – with one focus on sand, to reducing the impact of shelter provision on the environment – a second focus on increasing global warming, and finally to examining the in-use buildings at risk of devastating natural hazards – with a focus on flooding. Specifically, this endeavor incorporates several sub questions outlined below.

1) In the face of an unfolding sand crisis, how might demand for building sand develop in the future and how can we reduce this demand to secure the shelter needed and limit sand-related environmental impacts?

With a sand crisis unfolding across world countries, this question is of increasing significance to the sustainable development of the building stocks. We aim to develop the first global analysis of the development of building related sand use and mitigation potentials from implementing more efficient building practices.

2) How might greenhouse gas emissions related to building materials develop in the future with socioeconomic developments, how can we reduce these emissions by material efficiency strategies, and what does this mean for global climate targets?

GHG emissions from the construction of buildings are driven mainly by the production of materials such as steel, concrete, brick. We build a regionalized global analysis of the time-series change of GHG emissions of building material production.

Another major emission source is the energy used for building operations. We explore the developing trends in energy efficiency of building operations in different regions by asking:

3) What are the trends in the energy intensity of residential and commercial buildings, their relationship with economic development, and their future role in energy savings around the world?

Finally, this thesis presents the first attempt to understand how building stocks and materials may be at risk of and damaged by flooding hazards under current and future climatic conditions by addressing the following question:

4) Under current and future climatic conditions, what are the building stocks and materials at risk of riverine and coastal flooding hazards and embodied emissions of material losses?

1.6 Guide to this thesis

This thesis consists of 6 chapters as shown in Figure 1.1. The structure of the thesis broadly follows the flow in this first chapter, moving from resource scarcity to global warming to climate-driven natural hazards.

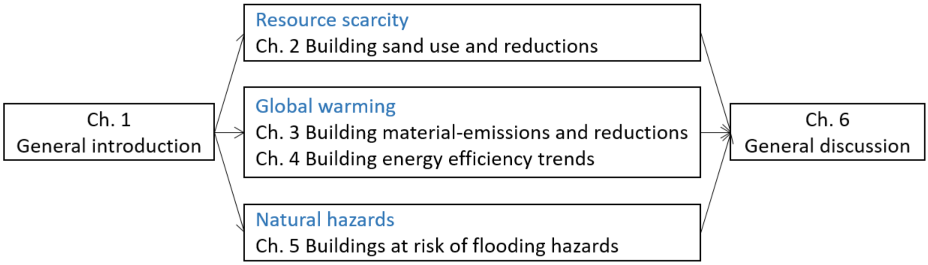

Figure 1.1 Outline of this thesis

This chapter, Chapter 1, discusses a world requiring more buildings to shelter a growing population, having less availability of raw materials, and seeing a warmer climate with more frequent and severe natural hazards. Chapter 2 analyses the development of the sand use to make concrete and glass in buildings construction and how the demand may be reduced by more efficient ways of using buildings and materials. In Chapter 3, we model GHG missions from the production of building materials globally, and how these emissions may be avoided by using buildings and materials more wisely. Chapter 4 discusses how the energy use intensity in buildings may change in the history and how they may develop in the future. In Chapter 5, we map the level of building stocks and materials impacted and damaged by current and future flooding hazards. In Chapter 6, we provide a synthesis of the answers to the research questions, followed by a general discussion about the scientific and policy implications of this thesis. We discuss limitations of the thesis and provide an outlook for future research.

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