Societal metabolism of non-metallic minerals

非金属資源を対象とした社会の物質代謝に関する研究

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Abstract

Although environmental awareness is progressively carving its way into mass culture, and initiatives to preserve natural resources and favour the circularity of the economy are spurring throughout the globe, the endeavour towards a sustainable future is far from being over. Environmentalists have to deal with constantly increasing population, which translates into an increased requirement of natural resources, and an ongoing trend of higher per capita consumption. This all results into a constantly increasing environmental pressure, which makes sustainability goals progressively harder to achieve.

This trend results evident when looking at the composition of the recent yearly global material extraction. The share of non-metallic minerals extraction over the total materials which are extracted every year passed, in only 40 years, form a share of about 25% to the current 45%, and we can expect it to rise over 50% in just a few years. This material category, despite its prevalence, is also the one affected by the highest uncertainty, because of its commonness and low economic value.

In chapter 1 we describe that the scope of this dissertation is to shed light in one of the most underreported and overlooked categories of material flows and stocks by developing novel methodologies that assess the quantity and composition of non-metallic mineral consumption at a multi-scale level.

In chapter 2 we introduce a methodology based on engineering and best-practice knowledge to derive at the global scale the yearly consumption of non-metallic minerals used for construction using reported consumption of cement, bitumen and bricks as proxies. We find that our account is in line

環境に対する意識は、革新的に大衆文化に染まりつつあり、天然資源の保護及び循環利用の促進は、世界の経済社会においてますます活発となっている。それにも関わらず、持続可能な未来へ向けた様々な試みは未だ始まったばかりである。環境問題を専門とする研究家は、大量の天然資源を必要とし且つ一人あたりの資源消費量の増加傾向をもたらす、人口増加に対処する必要がある。諸問題の結果として、環境負荷は継続的に冗長し、持続可能な目標はより一層遠のいてしまう。

この傾向は、近年における世界の天然資源採掘の構成より明白である。非金属資源の採掘は、過去 40 年で 25%から 45%へとシェアを拡大し、数年後には 50%を越すと予測されている。非金属資源は、世界において広く活用されているにも関わらず、その幅広く使用される一般性及び低い価格のため、最も高い不確実性にさらされた資源のひとつである。

第 1 章では、新規手法を構築することで、過小に報告され、見落とされてきた物質フローおよびストックに着目し、マルチスケールレベルで非金属資源消費量の定量的な評価を行う。

第 2 章では、工学的且つ実践的な知識に基づき、各国における非金属資源の年間消費量を把握する手法を紹介する。具体的には、建設資材として投入されたセメント、アスファルト、レンガの消費量に関する統計報告書を活用する。近年においては、一人あたり消費量に基づく推計結果である既往研究とほぼ同程

with other per-capita-consumption based predictions for the most recent years, but that there was a consistent underestimation for the older periods of analysis.

度との結果が得られた。一方、過去の年代においては、一定して過小推計といった傾向がみられた。

In chapter 3 we investigate the potential waste flows of non-metallic minerals by assessing the precision of a macro-scale material stock and outflow model using real-world data and investigating how it reacts to different depreciation distributions. We discover that the stock prediction is only moderately affected by the distribution choice, but that waste forecast can change up to ±50%.

第 3 章では、実際の各国統計データを用いて、マクロスケールでの物質ストック・フローモデルの精緻さを評価し、廃棄率曲線に関する複数の分布関数形状に対して感度調整・比較をすることで、非金属資源の廃棄物量発生ポテンシャルを推計した。その結果、ストック推計は適度な範囲ではあるが、分布関数の選択のみに影響を受けており、廃棄物量は±50%程度に推計結果の幅があることが明らかとなった。

In chapter 4 we construct a model specific for road networks, which uses statistical reports on the extension of the road network, scheduled maintenance, and specific material intensities per road types, to infer material stock and flows of this sub-category of the construction sector. We find that roads are still heavily dependent on materials coming from quarrying or C&D waste, and that it could potentially saturate its absorption capacity of this down-cycle stream in only 20 years.

第 4 章では、道路網の整備拡張、計画された維持管理、及び道路種に応じた資材投入原単位に関する統計を活用することで、建設部門のサブカテゴリーにおける物質ストック・フローを推計するために、道路ネットワークモデルを構築した。道路は土石の採掘場もしくは着工・廃棄に関わる廃棄物に大きく依存しており、ダウンサイクルの利用に関してはこの 20 年程度で道路サイドの許容量が飽和すると予想される。

In chapter 5 we give a summary of our findings showing how they benefit both academics and policy makers. The former can apply the newly developed methodologies to any country or world region, modelling local characteristics, and obtaining realistic and specific results for their areas of interest. The latter have a tool that can be applied to forecast future trends of material consumption and plan for appropriate sinks for the huge flows of non-metallic minerals that are forecasted to come from building demolitions during the XXI century.

第 5 章では、本研究の成果が学術的価値に加え、政策立案者に大きな価値があることを示した。前者は、新たに構築された手法を全ての国や地域に適用することが可能であり、また局所的な特徴をモデル化することで、対象となるエリアの現実的かつ具体的な結果を得られる点である。後者は、物質消費の将来予測と、21 世紀における建築物から発生する膨大な量の非金属資源廃棄物を適切に活用できると期待される。

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1 Introduction

1.1 The issue of sustainability

While nowadays even elementary schoolers have heard about sustainability, when it comes to precisely define what sustainability is, and what actions undertake to lead towards a truly sustainable future, things get less clear.

First of all, it is important to start clarifying that the definition of sustainability is very often linked to what should more precisely be an "environmental sustainability" (Kahle and Gurel-Atay, 2013). Looking at the definition on the Cambridge dictionary it reports "the idea that goods and services should be produced in ways that do not use resources that cannot be replaced and that do not damage the environment". Yet, resources and the natural environment are only one of the components of sustainability. Since the 2005 World Summit on Social Development, three different aspects of sustainability have been identified: an economic, a social, and an environmental sphere (UN General Assembly, 2005).

The first type of sustainability, economic, focuses on securing jobs, wages, and distributing wealth in a way that everybody has means to satisfy its personal needs. The social sustainability focuses on communities, families, equity, and quality of life. Finally, environmental sustainability centres its efforts in preserving the natural environment and minimising the impact of human activities.

The preservation of the natural environment is an extremely broad and complex topic that can be tackled only by dividing the big picture into smaller pieces, to the point where a single issue can be studied, understood, and sustainability measures can be proposed. Amongst the criticalities that have been identified, such as global warming, ozone depletion, or biodiversity loss, one of the most critical points is the extraction and consumption of natural resources (Stocker, 2014). Every year millions of tonnes of materials are taken from the natural environment and brought into our economies to be used processed for nourishment, the production of commodities, or the construction of buildings and infrastructure (Heinz Schandl et al., 2017). This amount, intuitively, varies greatly among countries, and is dependent on a wide series of factors, such as personal lifestyle choices, income, application, lifespan, and obviously by the sheer amount of people (Heinz Schandl et al., 2017).

Industrial Ecology is a recent field of the environmental sciences, and its scope is to analyse industrial processes and environmental impacts, to link final demand and raw resources extraction, and to analyse waste streams to assess recyclability potential. In broad terms, the field aims to unpack the relations between human needs and the industrial processes that fulfil them (Allenby, 2006). In doing so, industrial ecologists map material inflows, stocks, and outflows, and its related energy consumption, carbon dioxide emissions, and potential threats for the natural environment. The most used methodologies are material flow analysis (MFA) (Augiseau and Barles, 2016; Fischer-Kowalski et al., 2011), life cycle assessment (LCA) (Lotteau et al., 2015), and input output (I/O) models (Wiedmann, 2009). While all of the approaches have some similarities and overlapping, they complement each other. MFA, sometimes called substance flow analysis, it is a method based on the principle of continuity of mass in a closed system, and uses simple equations to ensure that all the physical materials that enter or leave the system boundaries are tracked and recorded (Brunner and Rechberger, 2004). MFA tends to follow a single material or a small group of materials that are used in a variety of applications. LCA, on the other hand, tend to focus on a single product and tracks down all the materials inputs and outputs that are necessary for the production, use, and disposal of that specific product (Tukker, 2000). I/O models are often focussing on the economic aspect of the material rather thein their physical mass, and are characterised by having a great number of processes when compared to MFA, at the cost of overlooking by-products and waste with no economic value (Kitzes, 2013).

An emerging application of MFA is urban metabolism and the circular economy (Haas et al., 2015; Kennedy et al., 2007). Applying the principles of MFA to a city, urban metabolism creates a framework to assess the material and energy interaction between the city and the rest of the environment (Kennedy et al., 2007). In face of current concerns on global warming and resource depletion, this tool is of fundamental usefulness in aiming to understand our current lifestyle, the ways this impacts on the environment, and simulate paths and scenarios that could lead to future sustainable ways of living. This strongly correlates to the concept of circular economy, sometimes referred as closed-loop MFA, where industrial processes are seen in a holistic manner and waste becomes the resource for another productive process, all in order to minimise waste and energy dispersion (Schiller et al., 2016).

The monitoring of resources through MFA is a very relevant topic (Heinz Schandl et al., 2017). While it is obvious that the consumption of materials is necessary even for fulfilling the most basic human needs such as eating, dressing, and living sheltered from the natural environment, the current lifestyle of developed countries, and the rapid growth of developing countries who are aiming to reach the same quality of living of their richer counterparts, are posing serious questions to the sustainability of the current practice (Daly, 1977). Living in a planet which obviously has a vast, yet limited, amount of resources, and being in a situation where the annual per capita consumption becomes bigger and bigger, while the total number of people is constantly increasing, depicts a not very optimistic scenario. Higher strain on the environment, increasing mining of resources, consequential loss of natural habitat for endangered species, rising greenhouse gases (GHG) emissions for extraction, production, and disposal, and ever growing waste call for an urgent response (Dietz and O'Neill, 2013).

MFA has already left the theoretical field of the academia, and many countries in the world apply its principles in their national accounts to monitor material consumption. Nowadays the European Union and Japan are yearly producing their official MFA reports (Eurostat, 2013; Weisz et al., 2007), while the International Resource Panel (IRP), a team of highly skilled experts monitoring resource consumption that launched under the United Nations Environment Programme (UNEP), has tracked the use of natural resources in the world since 1970 until today (H Schandl et al., 2017). This has offered policy makers very useful insights to policy makers to aim for a sound material cycle society. Japan, for instance, has agreed since 2006 to promote the "3 Rs": reuse, reduce, and recycle (Takiguchi and Takemoto, 2008). This political initiative spurred a series of initiatives such as the "Law for the Promotion of Effective Utilization of Resources", the "Construction Material Recycling Law", or the "Eco Town Programs", which all aim to minimise resource and energy use and waste production. Unfortunately, despite the isolate case of Japan, the depletion of natural resources is a matter still overlooked by many of the big protagonists of the world economic scene (Wiedmann et al., 2015). This might be caused by several reasons, such as the perception of resources as unlimited, especially those widely available such as wood or rock; the unwillingness to rein material consumption because perceived as a restraint to economic growth; or, as for certain recent global leaders, the lack of belief in climate change and environmental protection programmes (Dannenberg et al., 2017).

To really make a difference in the real world, to revert the growing trend of material consumption and GHG emissions, and move the academic debate outside of university classrooms, scientists need to promote their findings to engage stakeholders and policy makers by offering reliable datasets, forecasts, and practical means to achieve economic growth and human wellbeing without exceeding the planetary boundaries.

1.2 Motivations of this research

When looking for a theme for my Ph.D. it took me some time to identify a research question that would be simultaneously novel for the research community, engaging enough to spend the next three years of my life, and that would make good use of my expertise, background, and previous studies. After some time spent reading scientific journal papers, reports from UNEP and the Intergovernmental Panel on Climate Change (IPCC), and discussing with my supervisors, I came to realise that I could actually use the notions about best construction practices gained during my studies and my (short) career as a professional engineer to fill a knowledge gap about construction minerals in the literature of Industrial Ecology (cf. Fischer-Kowalski et al., 2011).

The societal metabolism of non-metallic minerals was a topic that surely had been investigated before, but I realised that it was often a corollary of a bigger picture, and it rarely was the protagonist (Krausmann et al., 2009, 2008). In the end, rocks are practically everywhere, are benign materials with very little impact on the environment, and are surely not on the list of materials that risk depletion (Miatto et al., 2016). Nonetheless, non-metallic minerals are dominating the charts of MFA, and are the materials that have grown the most in the past 40 years (Heinz Schandl et al., 2017). Their quarrying causes great concerns for land-use change, the loss of the natural habitat for endangered species, and, if poorly executed, creates risk of landslides (Yoshida et al., 2016). I realised that all that time spent calculating concrete admixtures, chemical properties of construction materials, and pavement design have not been in vain. I thus started this 3-year journey to unpack the consumption of non-metallic minerals, their stock and flows, their sector of use, and their lifecycle.

Truthfully speaking, I would have never imagined the impact and reverberation that my research would have had both in the Industrial Ecology research community and to the wider general public. But I have to admit that, thanks to the wise guidance of my supervisors, thanks to the travel opportunities that I have been offered, and surely kudos to a tiny bit of luck, which is always welcome, I have been able to bring the results of my research to many international conferences around the world, to hone my research skills with some of the luminaries of the field, and to be listed as a contributor in one of UNEP's latest publications on resource consumption.

1.3 State of the art of MFA and urban metabolism

The first studies on urban metabolism started appearing in the '70s, for being soon forgotten in the following decade. They had a comeback during the 90's, and ever since they have been used by researchers as effective tools to assess energy requirements and flows of materials (Kennedy et al., 2007). Their application can support understanding the processes, cycles, and fluxes of energy and materials within cities, and, through carefully constructed numerical models, can provide quantitative data on material and energy consumption, and perform scenarios to inform policy makers about sustainable ways to develop (Kennedy et al., 2007).

Meanwhile, the concept of material flow analysis traces back its history to the famous chemist Antoine Lavoisier, known for his contribution in making chemistry a quantitative science rather than a qualitative one, by applying the principles of system boundaries and mass balance (Brunner and Rechberger, 2004). In more recent years, around the '70s, early studies on ecology, the limit of natural resources, and the idea that growth is a transient phase rather than a permanent one, marked the necessity for having an instrument capable of tracking material consumption (Baccini and Brunner, 2012; Brunner and Rechberger, 2004; Lichtensteiger and Baccini, 2008). Several seminal publications appeared, and since 2007 the UNEP instituted the IRP with the role to monitor the consumption of natural resources and inform policy makers and stakeholders on trends and risks related to the consumption (Eurostat, 2013; Weisz et al., 2007).

Many of the studies on urban metabolism and MFA have highlighted how, in more recent years, the majority of materials that enter our economies are non-metallic minerals used for construction and maintenance of buildings and infrastructure (Fischer-Kowalski et al., 2011; Gierlinger and Krausmann, 2012; Krausmann et al., 2011; Martinico-Perez et al., 2016). They also comprise the vast majority of materials that are stocked in our societies, and with their presence they provide fundamental services such a shelter secure from weather and animals, bridges that allow transits where it would otherwise be impossible or very time consuming, and roads to quickly travel long distances (Krausmann et al., 2017).

Despite their major role, non-metallic minerals used for constructions have often been accounted using simplistic approaches compared to other materials, such as biomass, fossil fuel, steel, and so on (Fischer-Kowalski et al., 2011; Krausmann et al., 2011). This depends on several reasons: the scope of the study, the fact that non-metallic minerals are widely available practically everywhere in the world, they extremely low monetary value per unit of weight, and the very low environmental impact. Yet it appears clear that, despite their seemingly innocuous and marginal role in the big picture of sustainable development, non-metallic minerals will play an even more dominant role in the near future (Fishman et al., 2016). Considering that the per capita amount of stocked non-metallic minerals is constantly growing (Krausmann et al., 2017), the total world population is growing exponentially (United Nations, Department of Economic and Social Affairs, Population Division, 2015), many developing countries are aiming to reach a level of welfare and services comparable to the more developed nations (Steinberger et al., 2010), and that in the near future the vast majorities of constructions built during the XX century will have to be replaced or refurbished (Müller, 2006), a clear understanding of the dynamics of consumption of non-metallic minerals is a priority for achieving a true circular economy, for minimising waste, and for reducing quarrying of natural resources (Haas et al., 2015; Schiller et al., 2016).

Until today scientific literature of Industrial Ecology has never dedicated non-metallic minerals specific studies, but rather has included their account into wider economy-wide studies (Fischer-Kowalski et al., 2011). This has, on the one hand, been very useful at the very start of this discipline to have a sense of the total physical dimension of the economy, and to get an indication of the magnitude of each economic sector. On the other hand, these approaches have often missed specificities and peculiarities of the technical requirements and turnover of constructions, at times resulting in somewhat arbitraries accountings.

1.4 Objective of the PhD

While many governments, cabinets, and local councils are actively promoting policies that favour circular economy and the reduction of waste (e.g. Takiguchi and Takemoto, 2008), the current level of understanding of flows, stock, and turnover of non-metallic minerals presents a serious liability to these programs. Non-metallic minerals have often been underreported or completely missing in official national statistics (Weisz et al., 2007), and have never been accounted for the in-use amount, the age of the stock, the expected quantity that will have to soon be demolishes, refurbished, or overhauled, and the sector of the economy that they occupy.

The objective of this dissertation is to shed light on these unresolved issues, with the intent to offer policy makers and stakeholders tools to understand the dynamics of this group of materials, and recommendations for not arriving unprepared to a near future where flows related to demolition and maintenance of buildings and infrastructure will reach an unprecedented level.

Specifically, our goals are:

To provide a tool for accounting the yearly material consumption of non-metallic minerals for every country in the world. This can be achieved through well-accounted materials that act as proxies, and best practice engineering knowledge to create consumption coefficients that can convert these well-accounted materials into non-metallic mineral equivalents.

To understand the lifespan of buildings in order to have realistic estimations of material inflows and related demolition outflows, to provide governments a tool that allows for best estimations of demolition flows that will have to be down-cycled into road beddings or landfilled.

To understand of the annual amount of non-metallic minerals consumption what is the share that goes into road construction and maintenance, to estimate what is their potential of absorption of construction and demolition (C&D) rubble, and what is the yearly amount of materials that are used to maintain functional this fundamental infrastructure.

1.5 Research structure

To answers the research questions listed in §1.4, we have divided the research into three steps, with the aim of tailoring the research method and models to better suit our purposes.

The first part of our research has focused on tracking the global apparent consumption[1] of non-metallic minerals for the years 1970-2010. The reason of this research is that national material flow accounts have often been poorly reported or completely missed non-metallic minerals (Fischer-Kowalski et al., 2011; Weisz et al., 2007). To overcome this information void, we have developed a novel methodology that applies coefficients derived from construction manuals, engineering handbooks, and best practice knowledge to convert well-tracked construction materials (cement, bitumen, and bricks) to the amount of non-metallic minerals required for their use in constructions.

While the first strand of research concentrated on material inflows, as we assume that, in the case of non-metallic minerals, inflows and apparent consumption are equivalent for the vast majority of countries, we then continued with an investigation of the best way to simulate construction demolition to estimate non-metallic minerals outflows. We first tested how a well-established stock accumulation model responds to different depreciation functions, getting a sense of how the stock and outflows vary. We then compare our results to existing waste accounts, to understand out of all the parameters of our simulations which are the ones that best reflect reality and have more influence to the model results.

We conclude our assessments of stocks and flows of non-metallic minerals by developing a new model specifically tailored to grasp long-term dynamics of road constructions. This model differentiates from some of predecessors because, for the first time, a stock accumulation model is specifically designed to consider the specificity of the road network, its material requirements and its turnover. We use coefficients calculated during our first strand of research, and lifespan analysis from the second, to come up with a dynamic material flows and stock model that uses the road extension as the main driver, and technological coefficients derived from best construction practice as parameters. This results in a detailed historical report of the material inflows, stocks, outflows, and recycle related to this sector of the economy.

1.6 Main findings

During our extensive study of the behaviour of non-metallic minerals, we discovered several novel findings that have significantly contributed to deepen the understanding of this important sector of the economy.

We found that in the past 40 years the consumption of non-metallic minerals has grew quicker than GDP, and has especially been pulled by the exponential growth in Asia and the Pacific. In 1970, the main consumer of non-metallic minerals was the North American region using about 8.5 tonnes of aggregate per capita. Their consumption decreased to 5.5 tonnes per capita in 2010. At the same time the Asia Pacific region passed from 1 to 6 tonnes per capita during the same period. At the same time, this is still the region that requires most material input per unit of GDP, clearly indicating that the way to decoupling and dematerialisation is still very long.

[1] The apparent consumption is calculated as the sum of the amount of materials that are imported and extracted, minus the quantity that is exported on a single year.

The choice of a lifetime distribution function over another only marginally affects stock accumulation, but greatly affects waste forecasts. Short-lived buildings follow a log-normally distributed demolition pattern, while patterns of long-lived building demolition depend on place, era, and building typology. When tuning model parameters of a top-down flows and stock model, researchers should pay the utmost attention in carefully choosing the most realistic average lifetime, while should not worry too much about the standard deviation of the depreciation curve, since this has a minimal impact on the stock and flows accounts.

The demolition activities are expected to grow quickly, and the XXI century will be characterised by the renovation of the vast majority of the buildings constructed during the previous century, and this will generate massive flows of C&D waste. A convenient and useful way to dispose these has been down-cycling them into road beddings. Applying our novel road stocks and flows model to the case study of the United States of America, the country that currently has by far the longest road network in the world, we have been able to estimate that, with the current projections, the risk of running out of this down-cycle sink can happen as soon as 2055. We also found how the share of non-metallic minerals used for road construction and maintenance has progressively decreased over time, arriving to occupy about 10% of the yearly consumption of non-metallic minerals in the United States. We also discovered how, during the past century, great effort has been put into improving the reliability and safety of the road network, rather than focusing on its sheer expansion. This technological leapfrog has been ignited by the new technological requirements posed by the advent of personal motor vehicles and the discovery of rubber vulcanisation.

1.7 Relevance of the research

During the course of this study we identified several novel findings that have been of interest to very diverse audiences: fellow academics, policy makers, and industry stakeholders.

Research scientists have benefitted of theoretical findings, such as the influence of parameters over top-down models, the reliability curves and their impact on stock and flow accounts, and the calculation of the material intensity relations for unit of cement and bitumen. These very practical discoveries offer immediate support to modellers and researchers in investigating the construction material stock and flows, a field that is rapidly gaining popularity in Industrial Ecology.

Policy makers can get very precious previsions on the role of roads, and their absorption potential of C&D waste. If, until today, it has been possible to use this sector as a sink of construction rubble, there might be in the near future a point where this will not be a viable alternative, and other solutions need to be identified and explored. Recycle into new concrete admixtures, inclusion in the asphalt concrete layer of roads, or identifying ways to extend the usability and lifetime of buildings are all options that are being currently evaluated, but still a clear path towards a truly circular economy has yet to be discovered.

Entrepreneurs can profit of this study for strategic planning of investments in the sector of C&D management, specialise their market target towards building refurbishment or demolitions since all points toward a surge of this activities in the next few decades. Furthermore, estimation of C&D waste down-cycling potential can timely inform companies to not arrive unprepared to the moment when this activity will shrink to the point where it will be unprofitable.

2 Global patterns and trends for non-metallic minerals used for construction

2.1 Introduction

Empirical studies of material flows and stocks indicate that there has been no sign of lasting reduction of material throughput and material accumulation in any country of the world or at any level of income (Fishman et al., 2014; Krausmann et al., 2009; Tanikawa et al., 2015; Wiedenhofer et al., 2015; Wiedmann et al., 2015). While developed nations, most notably European countries and Japan, have slowed their yearly material accumulation (Gierlinger and Krausmann, 2012; Krausmann et al., 2011; Schandl and West, 2012) developing countries such as China, Brazil, and India, among others, are experiencing an unprecedented period of rapid growth in materials use (Schandl and West, 2012; Singh et al., 2012; West et al., 2013; West and Schandl, 2013) caused by their transition to an industrial and urban metabolic profile. These booming economies are causing a large increase in the volume of global material extraction and globally traded materials (UNEP, 2015), as well as a fast increase in the material stock that underpins modern transport and communication infrastructure, modern buildings, and supports general improvement in well-being and people's material standard of living. To satisfy the very large infrastructure demand from the BRIC (i.e. Brazil, Russia, India and China) economies alone, the global production of steel and cement is now higher than ever (U.S. Geological Survey and U.S. Department of the Interior, 2013; World Steel Association, 2014).

A single category, non-metallic minerals – consisting of stones, clay and sand; minerals for fertilizer production; salt; quartz, gypsum, natural gem stones, asphalt and bitumen, peat and other non-metallic minerals other than coal and petroleum (OECD, 2001) – comprised over 50% of global material use in 2010 (UNEP, 2015). Some of these materials, specifically sand, gravel, clay, lime, and gypsum, are required for cement and brick production and are used in roads and bridges, for railway lines and in residential, commercial, and industrial buildings. A recent study comparing several global material flow accounts (Fischer-Kowalski et al. 2011) found that while non-metallic minerals are very important in volumetric terms they are also the material flow category with the highest data uncertainty. Total global extraction of non-metallic minerals estimates for the year 2000 range from 15.3 billion tonnes (WU, 2014) to 26.5 billion tonnes (Krausmann et al., 2008) and show the highest variability of all major material flow categories.

Reasons for this large difference between studies are a lack of data availability and data reliability. Non-metallic minerals are high-volume low-value flows and they tend to be underreported in economic statistics (Weisz et al., 2007). Either they have no price attached when a company extracts sand and gravel on its own premises, or they are not reported because it is a secondary activity (e.g. a construction company that also runs a quarry), or because the business size of extraction companies is small and hence the activity is not included in official statistics. In addition, there is a major difference between definitions of minerals in mining and quarrying statistics and economic statistics. The first referring to geological characteristics of minerals, the latter often focussing on use (Weisz et al., 2007).

The lack of original data has prompted previous studies to attempt to estimate the amount of non-metallic minerals that would be required for concrete, bitumen, and brick production, for which physical numbers are available. Previous studies (Gierlinger and Krausmann, 2012; Krausmann et al., 2014, 2011; Singh et al., 2012; West et al., 2014; West and Schandl, 2013), however, have employed overly simplistic accounting strategies and have not taken into account the technological complexity and relevant engineering knowledge that is available for the material requirements of concrete, road, and brick production.

Nevertheless, these materials are associated with serious environmental issues including topographical and land use change during extraction and disposal, and high energy requirements for extraction, transportation, production, construction, and disposal. Moreover, quarrying activities have been associated with land transformation, biodiversity loss and groundwater pollution (Chang and Koetter, 2004; Ekmekci, 1990; Hashimoto et al., 2006). A more accurate account of non-metallic minerals is important to strengthen the overall reliability and credibility of global, regional, and national material flow accounts at a time when they have become more politically and economically relevant (Schandl et al., 2015).

The objective of this research is to address the research gap that exists for global and country-by-country estimates of non-metallic minerals extraction, by establishing a new account based on data for concrete, roads, rail, and brick production. The new estimate utilises state of the art engineering and production process knowledge to improve the precision of construction material flow accounting at several scales. The analysis provides a detailed account for each type of aggregate, each global region and country, and each main purpose of use. We also describe and analyse the technical and data-related issues that can lead to uncertainties in such accounting. Based on the new global multi-country dataset we are able to answer why per-capita use of non-metallic minerals differs between regions, and how growth in non-metallic minerals is related to population growth and economic growth.

We analyse the relationship between the extraction of non-metallic minerals, economic activity, and population for seven world regions (North America; Latin America and the Caribbean; Africa; Europe; West Asia; Eastern Europe, Caucasus and Central Asia; and Asia and the Pacific) to assess regional differences and progress in decoupling economic activity from the use of construction materials and thus determine whether demand for new infrastructure is high or low. This may be interpreted as a proxy for the sufficiency of existing infrastructure as well as the need for new infrastructure in the absence of in-use stock accounts.

2.2 Data and Methods

The new database created for this research reports five main use categories of non-metallic minerals: concrete, roads, bricks, foundation sub-layering, and railways. Any other usage of aggregate for construction is insignificant in its scale and has thus been excluded from the analysis.

2.2.1 Concrete

2.2.1.1 Data

The estimate of the yearly extraction of non-metallic minerals related to the production of concrete is based on the apparent consumption of cement.

$$Apparent\ consumption = Import - Export + Domestic\ Extraction$$

Data for cement production was sourced from the United Nations Statistics Division commodities production database (UN Statistics Division, 2011a), which presents the production of cement between 1950 and 2008 for most countries – however data before 1970 is sparse. Data for imports and exports came from UN Comtrade (UN Statistics Division, 2011b), which reports trade of cement for most countries for the period 1962 to 2009. Combing the two datasets, an account for the apparent consumption of cement from 1970 to 2008 was established. To validate the quality of UN data for the years 2000 to 2008, and to include the years 2009 and 2010, data from Cembureau was used (Cembureau, 2014), which provides information about cement production and trade for most countries globally for the years 2000 to 2011.

2.2.1.2 Accounting methodology

Concrete is produced by mixing cement with aggregate and water in specific ratios in order to obtain a mix that satisfies the technical requirements of a construction project. Technical specifications may require concrete to be very resistant, to minimise costs, to achieve high workability, to be particularly resistant to marine agents, and so on. The specification of concrete has become so complex that the profession of concrete designer now exists in the construction market.

The main parameters to consider when designing a concrete mix are: concrete final resistance; cement type; aggregate type (i.e. natural, crushed, mixed); maximum size of aggregate; average standard deviation of the concrete samples; and water to cement ratio.

We calculated an array of possible concrete mixes for each type of standard concrete (BSI, 2013), obtaining 1,620 possible combinations of cement content per cubic metre of concrete.

$$C_i = f(b; d; e; g; h)$$

where C_i is a matrix containing 1,620 possible combinations of cement content per cubic metre of concrete mix and is calculated as $\left[{}^{m^3}/_{m^3}\right]$ and is a function of the parameters b, d, e, g, and h; the subscript $i = (C_{16-20}, C_{20-25}, \dots, C_{45-55})$ indicates the type of concrete; $b = (32.5R; 42.5R; 52.5R)$ is the possible type of cement as per norm EN197-1 (European Norm, 2011); $d = (2, 3, \dots, 10)$ is the standard deviation of the produced concrete from the design requirements calculated in $[MPa]$; $e = (natural, crushed, mixed)$ is the type of aggregate used in concrete mix; $g = (8, 16, 32, 50)$ is the maximum diameter of the aggregate that is included in the concrete mix and is calculated in $[mm]$; $h = (S1, S2, \dots, S5)$ is the required fluidity (slump) of the concrete mix.

The content of cement in each possible concrete mix allows calculation of the aggregate content with the following equation:

$$A_i = 1 - C_i - W_i - H_i$$

where A_i, measured in $\left[{m^3}/{m^3}\right]$, is an array containing n number possible aggregate content per cubic metre, C_i is the cement content, W_i is the water content, and H_i is the air content.

The average content of aggregate and concrete for each type of concrete is:

$$\bar{A_J} = \frac{\sum_{i=1}^{n} A_i}{n} \cdot \rho_A$$

$$\bar{C_J} = \frac{\sum_{i=1}^{n} C_i}{n} \cdot \rho_C$$

Where $\bar{A_j}$ and $\bar{C_j}$ are respectively the average content of aggregate and cement per each type of concrete resistance j and they are measured in $\left[{kg}/{m^3}\right]$, n is the number of possible combinations, and ρ_A and ρ_C are respectively the density of aggregate and cement.

It is possible to obtain the average content of aggregate and cement in concrete by interpolating the previous results with a distribution function:

$$A_{concr} = \bar{A_j} \cdot f(distribution)$$

$$C_{concr} = \bar{C_j} \cdot f(distribution)$$

Where A_{concr} and C_{concr} are respectively the final global average content of aggregate and cement in concrete and are measured in $\left[{kg}/{m^3}\right]$, and $f(distribution)$ is a distribution function that takes into account the real-world consumption for each type of concrete resistance. It is based on consultations with experts from the construction sector who provided advice about typical concrete resistance requirements for buildings and infrastructure (Piccin S., 2015).

Using the average content of aggregate per cubic metre of concrete, as well as the average content of cement, we established the relation between these two materials, and used the cement consumption database to estimate the amount of non-metallic minerals used for concrete production.

$$\lambda_{concr} = \frac{A_{concr}}{C_{concr}}$$

Where λ_{concr} indicates the intensity of the aggregate that goes into the concrete mix, and it is measured as $\left[{kg}/{kg}\right]$.

2.2.2 Roads

2.2.2.1 Data

To compile the database of apparent consumption of bitumen we used data provided by the International Energy Agency (International Energy Agency, 2014) on the imports, exports, and production of bitumen for the years 1960 to 2011. We cross-checked the data against bitumen data from the UN commodity production database (UN Statistics Division, 2011a) and also filled data gaps. Our final database shows the apparent consumption of bitumen for the years 1970 to 2010.

2.2.2.2 *Accounting methodology*

To estimate the average requirement of aggregate to construct 1 km of road we employed a similar approach to the estimate of aggregate intensity in concrete, i.e. analysing how a road is designed, in order to extrapolate the average aggregate and bitumen requirement per linear kilometre. We then used bitumen production as a proxy to estimate kilometres of constructed roads, and to establish the related aggregate requirement. We included a set of variables that play a role in determining road depth, which is the factor that affects the amount of material required per km of road:

$$E_k = f(p, q, r, s)$$

Where E_k is an array containing n different combinations of the four parameters of the function and express the number of Equivalent Single Axis Loads (ESALs) that a single lane of any road is supposed to undergo before being overhauled, p takes into account the design life of the road until maintenance, q is the number of ESALs per day and direction, r is a parameter that takes into account the line distribution of traffic, and s is the expected yearly traffic growth.

The calculated E_k is then weighted through a weighting matrix based on technical knowledge from construction (Pianon M., 2015) about typical road composition in order to have a plausible and realistic outcome.

$$\bar{E} = \frac{\sum_{k=1}^{n} E_k \cdot W_k}{n}$$

where $\bar{E}$ is the weighted result of E_k, and W_k is the weighting coefficient array.

Using $\bar{E}$ the structural number SN is calculated through the following relation:

$$SN_l = \frac{\sum\left(\alpha_l \cdot \bar{E}^{\beta_l}\right)}{n}$$

Where SN_l is the structural number in which l refers to the l-th soil resistance, α_l and β_l are factors that convert the ESALs to SN, and n is the number of possible combinations analysed.

The structural number provides information on how to build a road based on economic and environmental considerations. We assumed that 50% of roads are made of an asphalt concrete pavement (ACP) and a granular base course (GBC), and the other 50% of an asphalt concrete pavement (ACP), granular base course (GBC), and granular sub-base course (GSBC). Using the preferred road design the structural number SN is converted to an actual layer depth through the following relation:

$$GBC_{1,l} = \frac{SN_l - ACP_l \cdot \gamma_{ACP}}{\gamma_{GBC} \cdot \gamma_D}$$

where $GBC_{1,l}$ is the depth of the granular base course expressed in $[mm]$, ACP_l is the designed asphalt concrete pavement depth expressed in $[mm]$, γ_{ACP} is the structural coefficient of the ACP, γ_{GBC} is the structural coefficient of GBC, and γ_D is the road draining coefficient.

In case of a road having also a GSBC, the equation is as follows:

$$GSBC_l = \frac{SN_l - ACP_l \cdot \gamma_{ACP} - GBC_{2,l} \cdot \gamma_{GBC}}{\gamma_{GSBC} \cdot \gamma_{Drain}}$$

where $GSBC_l$ is the depth of the granular sub-base course expressed in $[mm]$, $GBC_{2,l}$ is the depth of the GBC in case of the presence of GSBC, and γ_{GSBC} is the structural coefficient of GSBC.

Once we had accounted for the several depths of layers for different soil resistance we combined them through a weighted average:

$$A_{road} = \left[0.5 \cdot\ GBC_{1,l} + 0.5 \cdot \left(GBC_{2,l} + GSBC_l\right) + 0.95 \cdot ACP_l\right]\ \cdot \rho_A \cdot f(distribution)$$

$$N_{road} = 0.05 \cdot ACP_l\ \cdot \rho_B \cdot f(distribution) \cdot \delta$$

where A_{road} and N_{road} are respectively the average quantity of aggregate and bitumen that go into a square metre of road, and are measured in $\left[{}^{kg}/_{m^2}\right]$, ρ_A and ρ_B are respectively the density of aggregate and bitumen, the number 0.5 refers to the fact that we assume that 50% of roads are composed of ACP and GBC, while the other 50% are ACP, GBC, and GSBC; the numbers 0.95 and 0.05 are because of the composition of the ACP layer: 95% aggregate and 5% asphalt – which is the typical bitumen and aggregate ratio of asphalt concrete pavement –, the $f(distribution)$ function was made thanks to consultation with experts from the transportation sector, and δ represents the ratio of new roads and refurbished roads, here assumed as 18% after consultation with the experts.

It is now possible to calculate the intensity of aggregate in roads as:

$$\lambda_{road} = \frac{A_{road}}{N_{road}}$$

2.2.3 Bricks

2.2.3.1 Data

To build a database for the apparent consumption of bricks we used the United Nations commodity production data for bricks (UN Statistics Division, 2011a). Time series cover the years 1950 to 2008 but before 1970 data is very sparse. Since there are many gaps in the dataset and several important countries such as Japan, India, China and Italy were missing, we supplemented the UN database with data provided by Comtrade (UN Comtrade, 2014). Merging the two datasets, and checking that the overlapping data were consistent, we built a database covering most of the countries in the world.

Data for China and Japan, however, appeared to be implausible. Data for brick sales in China, for instance, dropped dramatically after 1995 suggesting that consumption of bricks had reduced by 90%, which we dismissed as unrealistic. Since the unrealistic numbers coincided with the official Chinese Construction Material Statistical Yearbook (China Building and Industrial Materials Yearbook, 1982) we used figures for 'constructed floor space' and building type as a proxy for the evolution of brick consumption and were able to correct data and fill gaps.

For Japan the international figures showed a high discrepancy with the data from the Japanese Construction Materials Statistics (Ministry of Economy, Trade and Industry, Japan, 1986), which showed much lower figures.

The UN database was completely missing the apparent consumption of bricks in India, which is perhaps the largest consumer of bricks. Despite the importance of the brick industry in India the Indian Ministry of Environment confirmed that there are no official figures for brick production and consumption available in India. Unofficial estimates were provided by the Indian government, allowing this serious data gap to be filled.

2.2.3.2 Accounting methodology

To calculate the usage of non-metallic minerals (i.e. clay) in the production of bricks we used the chemical reaction in the kiln as a starting point.

$$\mathrm{Al_2Si_2O_5(OH)_4 = Al_2O_3 * 2SiO_2 + 2H_2O}$$

Where $\mathrm{Al_2Si_2O_5(OH)_4}$ is the typical composition of kaolin, one of the most used minerals for the production of bricks, $\mathrm{Al_2O_3 * 2SiO_2}$ is the chemical composition of a cooked brick, and $\mathrm{2H_2O}$ is the evaporated water that is lost during the cooking process.

Calculating the molar masses of the two compounds, we calculated the intensity of aggregate in bricks:

$$\lambda_{brick} = \frac{B_r}{B_c}$$

where λ_{brick} is the intensity of aggregate in bricks, B_r is the molar mass of the kaolin, and B_c is the molar mass of cooked bricks.

2.2.4 Building sub-layers

2.2.4.1 Data

Whenever the lowest floor of a building does not go below groundwater level it is good practice to separate the structure from the ground soil by a layer of aggregate, to protect health and allow the runoff of rain water. This layer greatly depends on the type of soil, the depth of the groundwater level, building typology, building height, designation, and many other factors specified by local building codes. Unfortunately, there is not any data that covers this very specific usage of aggregate.

To solve this issue, we used the detailed account of Japanese construction material use (Tanikawa et al., 2015) and calculated the amount of aggregate used in the sub-layer of buildings and infrastructure.

2.2.4.2 *Accounting methodology*

Our previous calculation of the intensity of aggregate in concrete provided data on how many tonnes of aggregate to expect per tonne of cement. Applying this ratio to the cement consumption calculated for Japan, we can estimate how much aggregate has been used to produce concrete.

$$A_{concr,JP} = C_{concr,JP} \cdot \lambda_{concr}$$

Where $A_{concr,JP}$ is the calculated consumption of aggregate in Japan, $C_{concr,JP}$ is the value taken from statistics on the cement consumption of Japan, and λ_{concr} is the intensity of the aggregate in the concrete that we previously calculated.

We then proceed to compare this finding to the aggregate figures in the official statistics.

$$\Delta A_{sub} = A_{concr,stat,JP} - A_{concr,JP}$$

Where ΔA_{sub} is the difference between the calculated and the actual consumption of aggregate in Japan, and $A_{concr,stat,JP}$ is the value of aggregate consumption taken from the statistic.

Since the actual usage of aggregate in construction exceeds the amount required for concrete production, we calculated the sub-layer intensity as follows:

$$\lambda_{sub} = \frac{A_{concr,stat,JP}}{C_{concr,JP}} - \lambda_{concr}$$

Where λ_{sub} is the intensity of aggregate used in the sub-layer per unit of cement, and λ_{concr} is the previously calculated intensity of aggregate per unit of cement in the production of concrete.

2.2.5 Railways

2.2.5.1 *Data*

We used the World Bank Transport Division database (World Bank, 2015) that provides a very detailed account of railway networks and added rail kilometres per year for a great number of countries. We might be underestimating the total amount of non-metallic minerals being used in railways due to the fact that this database only reports the total length of the rail network, but does not report improvements to rail lines such as gauge increments, doubling of lines to allow for high speed trains, and other improvements. Nonetheless, this underestimation is likely to affect only the most developed countries of the world, which are now aiming to improve rather than expand their existing networks. The underestimation can be considered negligible at the global scale. For technical details regarding the depth of the gravel base on which tracks are installed we used information from the Japanese Infrastructure Construction Manual (Hayakawa T., 2013; Tanaka K., 2014; Tanikawa et al., 2015), and we supplemented this database with information on rail gauges (Zinoviev D., 2012).

2.2.5.2 *Accounting methodology*

From the Japanese Infrastructure Construction Manual, we obtained the amount of gravel required for constructing one metre of track for both Japanese normal trains (narrow gauge) and high speed trains (standard gauge). Using these two data points we linearised the relation using the following formula:

$$m = \frac{i_s - i_n}{w_s - w_n}$$

Where m is the slope of the linear relation, i_s the gravel intensity for the standard gauge, i_n the gravel intensity for the narrow gauge, w_s the width of the standard gauge tracks, and w_n is the width of the narrow-gauge tracks.

We then calculated the point of interception of the vertical axes:

$$b = i_n - m \cdot w_n$$

where b is the y-intercept constant.

Knowing b and m we could calculate the intensity for any given gauge, and then multiply it by the yearly increase to the length of the railway to see the usage of gravel in railways.

$$\lambda_{rail,y,i} = (l_{i,y} - l_{i,y-1}) \cdot m \cdot g_i + b$$

Where $\lambda_{rail,y,i}$ is the yearly usage of gravel for railways in the i-th country, $l_{i,y}$ is the length of the railway of the i-th country in the y year, $l_{i,y-1}$ is the length of the railway in the i-th country in the previous year, and g_i is the width of the railway in the i-th country.

2.2.6 Cement

2.2.6.1 *Data*

We used the same dataset that we used to calculate aggregate consumption related to concrete production to calculate the amount of primary material that was required to produce cement, i.e. limestone, clay, and gypsum. Other materials that can be incorporated, such as fly ash, silica fume, and other additives, have not been taken into account because their usage is limited, greatly depending on each country's legislation and traditional local construction practices.

2.2.6.2 *Accounting methodology*

Using a study from the Portland Cement Association providing technical detail for cement production (Nisbet, 1996), we calculated the ratio of materials between cooked cement ready to be sold, and the raw materials that enter the kiln.

$$\lambda_{cem} = \frac{C_r}{C_c}$$

Where λ_{cem} is the intensity of the cement production materials, C_r is the mass of the raw materials that go into the kiln, and C_c is the mass of the finished product. C_r is the sum of its basic ingredients: $C_{lime}, C_{clay}, C_{gypsum}$. The typical cement mix consists of 0.77 parts of lime, 0.20 parts of clay, and 0.03 parts of gypsum respectively (Nisbet, 1996).

2.2.7 Recycling of construction material

Many countries recycle or down-cycle construction demolition waste and use it as road base or for other applications that do not require virgin materials. Recycling amounts vary greatly among countries and data about the volumes recycled is often not available. To be consistent with our accounting methodology we would need to establish and estimate for recycled materials and subtract it from the extraction account since recycling will replace some virgin material and hence extraction. Not to include recycling results in an overestimation of extracted virgin materials. Because recycling data is not available we have ignored this issue for our account. We believe that the share of recycled non-metallic minerals is generally very small and the overestimation of extraction therefore negligible. This is especially the case in such regions where the demand for non-metallic minerals grows very fast and recycling will not be available to any relevant extend.

2.2.8 Intensity summary

Table 1 shows the ratios we calculated and applied to our calculations:

Table 1 Summary of the intensities applied to six construction categories

Concrete	Roads	Bricks	Sub-layers	Railways	Cement
$\boldsymbol{\lambda_{concr} = 5.26}$	$\lambda_{road} = 51.12$	$\lambda_{brick} = 1.16$	$\lambda_{sub} = 0.42$	$\lambda_{rail,y,i} = \Delta l \cdot 2119.3 \cdot g_i - 581.2$	$\lambda_{cem} = 1.57$

2.2.9 Uncertainty range of the new account

Changing the frequency functions for concrete and road design allows us to assess uncertainty ranges for our account of non-metallic minerals extraction. For concrete, the coefficient varies between a minimum of $\lambda_{concr} = 4.73$ (assuming an even use of all possible types of concrete) and a maximum of $\lambda_{concr} = 5.90$ (a case where over half of all concrete would be the weakest type, i.e. C16/20).

For roads, the minimum coefficient is $\lambda_{road} = 50.78$ (assuming the lowest soil resistance, i.e. 20 MPa, for more than half of all cases) and the maximum is $\lambda_{road} = 52.74$, (which is the case when all roads are built on hard soil, i.e. high soil resistance of 70MPa).

For gravel in building sub-layers the literature (Tanikawa et al., 2015) suggests that the amount of gravel for foundations varies between 5 to 10% of the building concrete weight, depending on the location, function, and size of the construction, which provides a quite narrow uncertainty range. In this study we did not establish uncertainty ranges for bricks and cement production which are, however, of less importance with regard to magnitude.

Establishing uncertainty for our overall account based on the range of fluctuation for concrete and roads, which comprise 80% of non-metallic minerals used, we estimate an uncertainty range of 1 billion tonnes equal to ±6% of the calculated 8.8 billion tonnes in 1970 and a range of 5.5 billion tonnes equal to ±8.5% of the calculated 32.9 billion tonnes in 2010.

2.3 Results

2.3.1 The Global Scale

This study quantified the extraction of non-metallic minerals – gravel, sand, clay, limestone and gypsum – used for construction for the years 1970 to 2010 for every country, seven world regions and the globe.

Figure 1 shows the global extraction of non-metallic minerals, starting at around 10 billion tonnes in 1970 and reaching about 35 billion tonnes in 2010, a 3.5-fold growth and a yearly average growth rate of 3.4%.

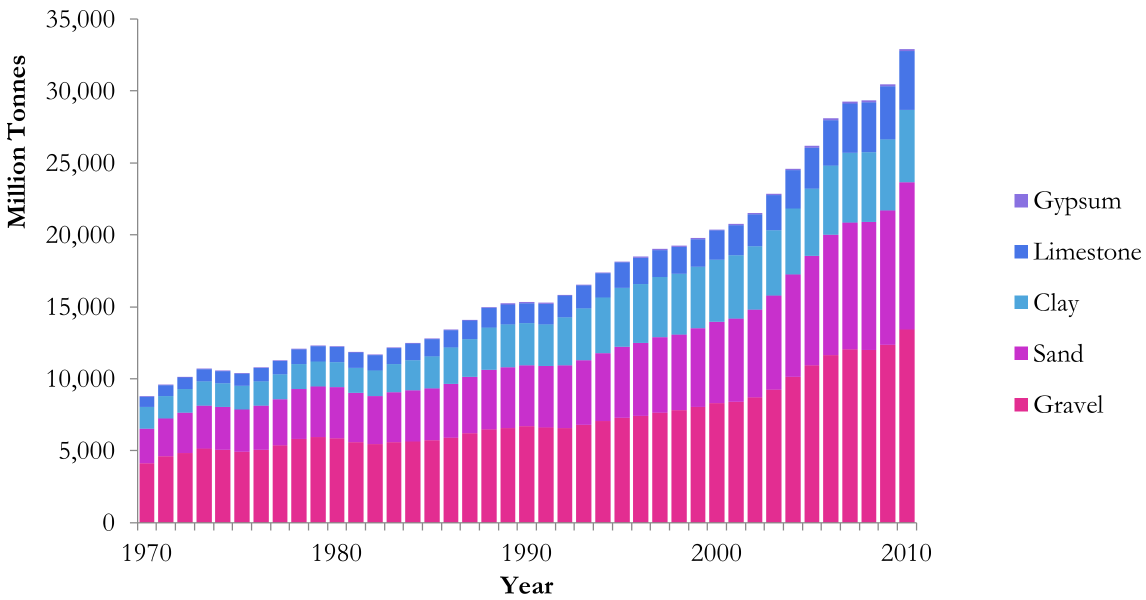

Figure 1 Global extraction of non-metallic minerals by type, 1970–2010, million tonnes

Sand and gravel constituted the main share of global extraction of non-metallic minerals in 2010 (40.8% gravel and 31.1% sand). Limestone, used for cement production, had the fastest average annual growth rate of 4.5%, gravel extraction grew by 3.7% per year, and clay grew by 3% per year.

Figure 2 shows the relative importance of use of non-metallic minerals by sector. Concrete in buildings and infrastructure[2] is the largest contributor to the usage of sand and gravel – about three quarters of total non-metallic minerals use – and has the highest growth rate of 4.5% yearly average growth, which is related to the fast build-up of new residential, commercial and industrial buildings, most notably in Asian developing countries. Non-metallic minerals for roads and bricks are of a similar magnitude and show a slower average growth rate compared to non-metallic minerals for buildings. The average annual growth rate for roads was

[2] With buildings and infrastructure we include the actual buildings, and other infrastructure such as dams, water tanks, bridge pillars, and so on.

0.8%, compared to 2.8% for bricks. The amount of non-metallic minerals required for rail tracks is very small and negligible.

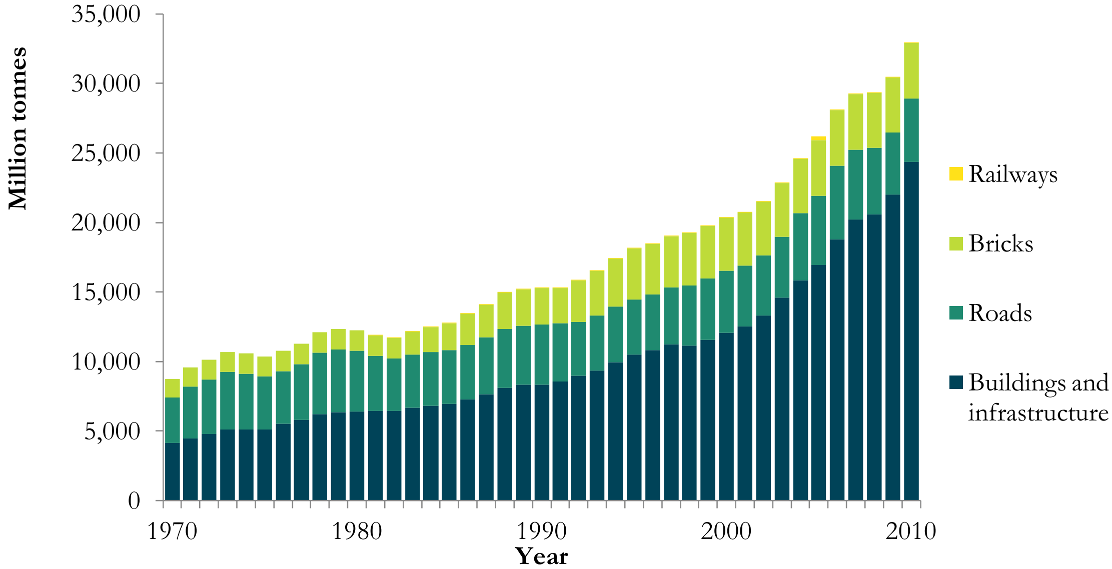

Figure 2 Global extraction of non-metallic minerals by sector of use, 1970–2010, million tonnes

Figure 3 shows the new account for global non-metallic minerals extraction in comparison with previous studies (Krausmann et al. 2009; Schaffartzik et al. 2014; UNEP 2015) as consistently higher but more or less following a similar trend. The coloured area shows the interval of uncertainty of this study; notice that it is not a function of time, but depends on the amount of cement and bitumen produced each year. Previous accounts seem to have underestimated the extraction of non-metallic minerals, especially in early years of our time series. The difference between our new account and previous studies was larger in 1970 (between 25% and 56% above the previous estimates) and closer for 2010 (between 7% and 21% above previous estimates).

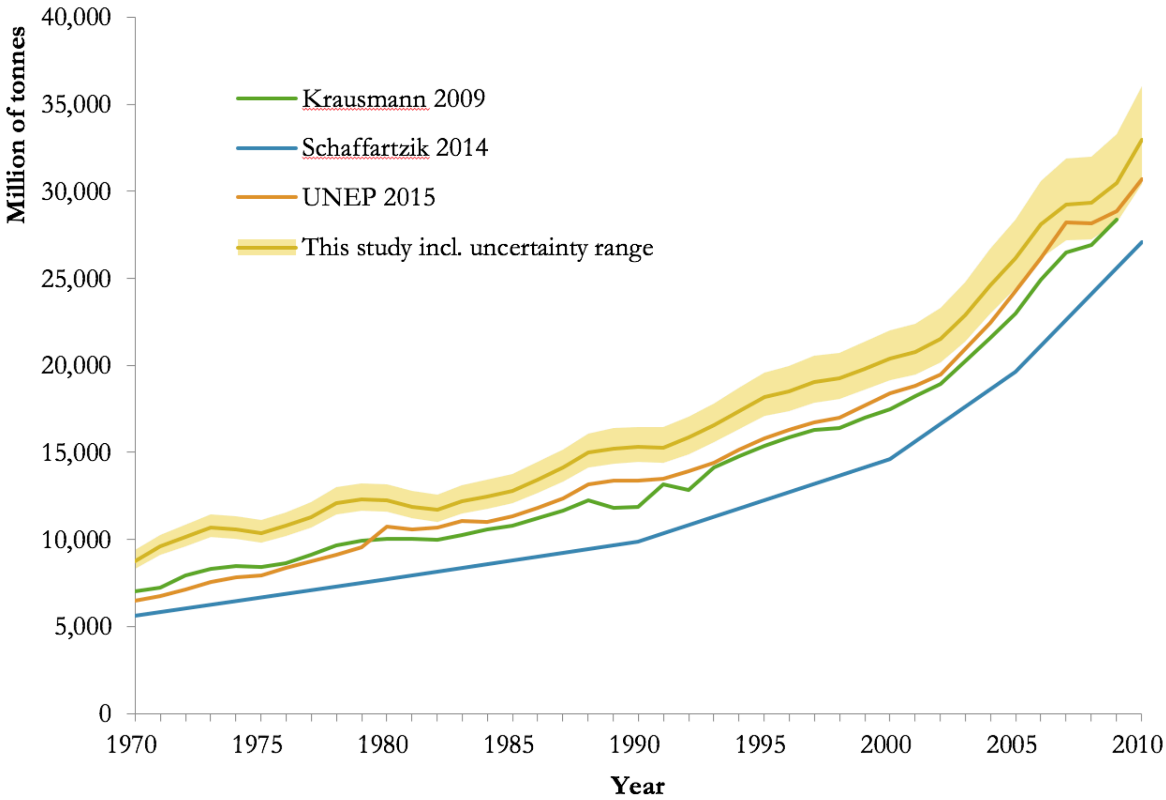

Figure 3 Comparison of the new account of global non-metallic minerals extraction with previous studies, showing the range of uncertainty, million tonnes

Figure 4 shows that global growth in extraction of non-metallic minerals has recently overtaken GDP growth.

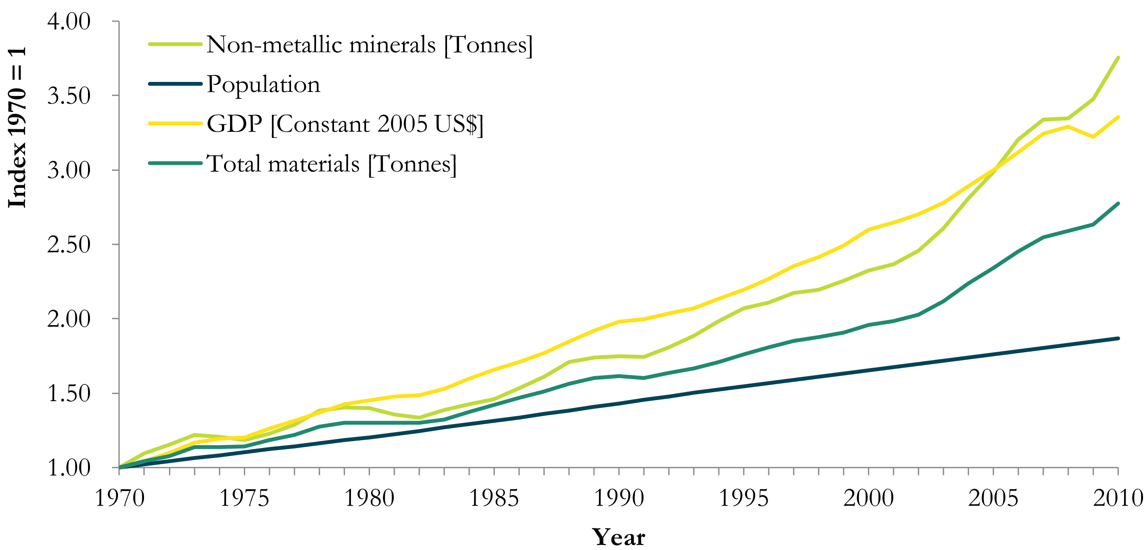

Figure 4 Global population, GDP, global extraction of materials (DE) and non-metallic minerals extraction, 1970–2010, indexed 1970=1

During the past four decades non-metallic minerals grew by a factor of 3.8. Population growth followed a linear trend and global population almost doubled over the four decades from 1970 to 2010. Global extraction (DE) of materials grew 3-fold. For most of the four decades GDP grew faster than the extraction of non-metallic minerals, but this changed in 2005 when GDP grew less than non-metallic minerals extraction. From 1970 to 1978 GDP and non-metallic minerals grew in parallel, at a yearly average of 4.1%. There was then a relative decoupling, and for the period 1981 to 2002 these two categories moved in parallel, with yearly average growth of 2.9%. From 2002 non-metallic minerals extraction grew much faster than GDP (5.4% average annual growth for non-metallic minerals extraction compared to 2.7% for GDP). The share of non-metallic minerals in total domestic extraction (DE) increased from 33% in 1970 to 45% in 2010.

2.3.2 World Regions

There have been large differences in non-metallic minerals extraction and use in seven world regions – Africa; Asia and the Pacific; Eastern Europe, Caucasus, and Central Asia (EECCA, the predecessor states of the former Soviet Union); Europe; Latin America and the Caribbean; North America; and West Asia – over the past 40 years, caused by different levels of investment into buildings and transport infrastructure and reflecting the amount of physical infrastructure needed to support economic growth and population growth in different parts of the world.

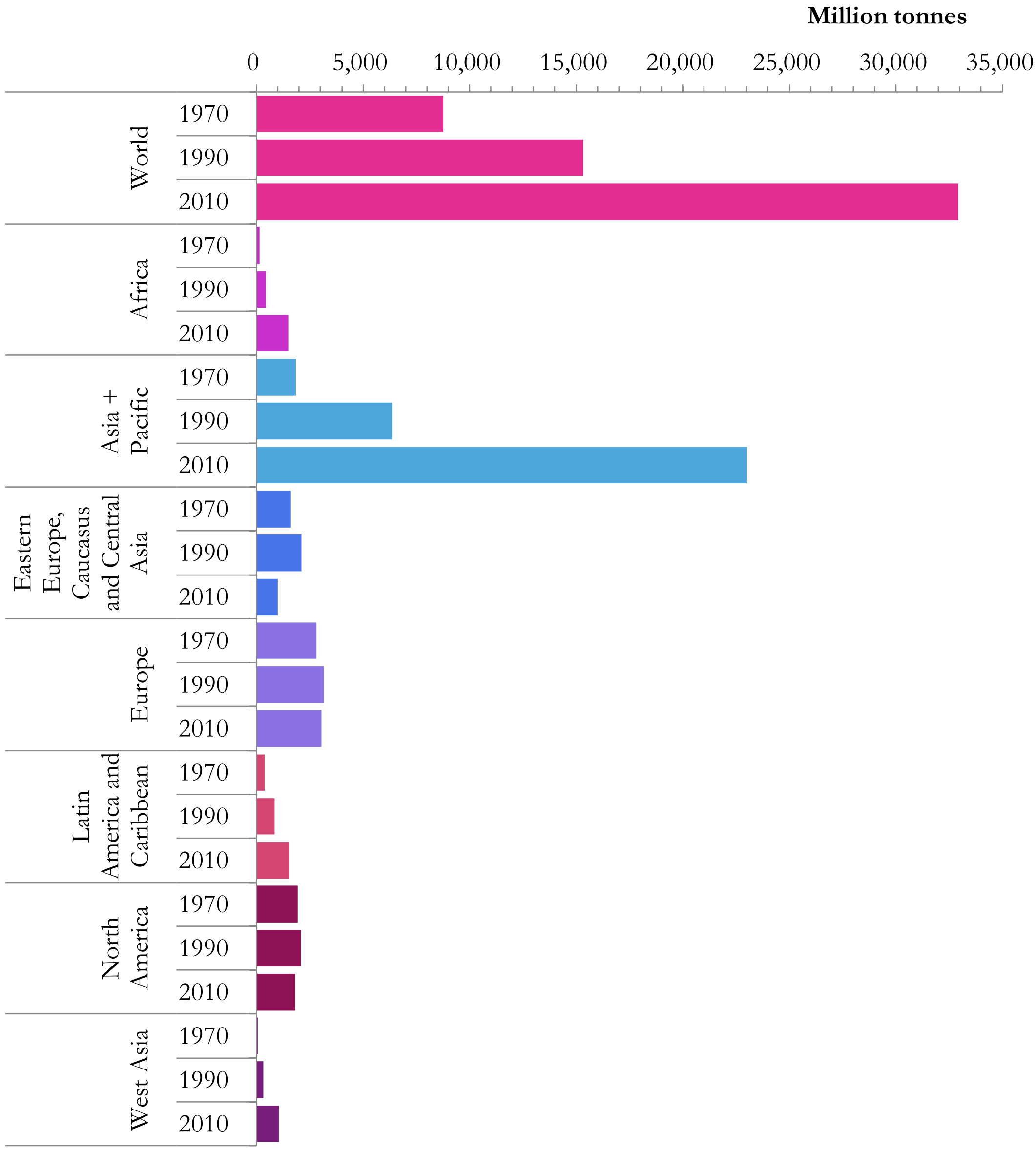

Figure 5 Non-metallic minerals extraction in seven world regions, 1970, 1990 and 2010, million tonnes

Figure 5 shows that global non-metallic minerals extraction accelerated during the four decades from 1970 to 2010. Extraction grew by an average of 328 million tonnes per year between 1970 and 1990 and by an average of 880 million tonnes per year between 1990 and 2010. Africa, Asia and the Pacific, Latin America and the Caribbean, and West Asia all show a similar pattern, where yearly extraction and consumption of non-metallic minerals increased over time, but the Asia-Pacific region had the highest growth rate at a yearly average of 6.5% to build the urban and manufacturing infrastructure which now underpins the economic dynamism in the region. Non-metallic mineral extraction in the EECCA region increased between 1970 and 1990 but then dropped markedly as a result of the economic transformation and divestment in infrastructure that occurred in the early 1990s. Europe and North America present a stable trend in non-metallic minerals extraction and use over the four decades until 2010, suggesting that the level of physical infrastructure that was reached by 1970 was already – at least for the period analysed in our study – adequate and a major part of the stock was already present at that time.

Figure 6 shows per-capita levels of non-metallic minerals extraction, which doubled globally between 1970 and 2010 and reached about 5 tonnes per capita. Europe and North America show a similar level of extraction in 2010 but have reduced their per-capita extraction compared to 1970.

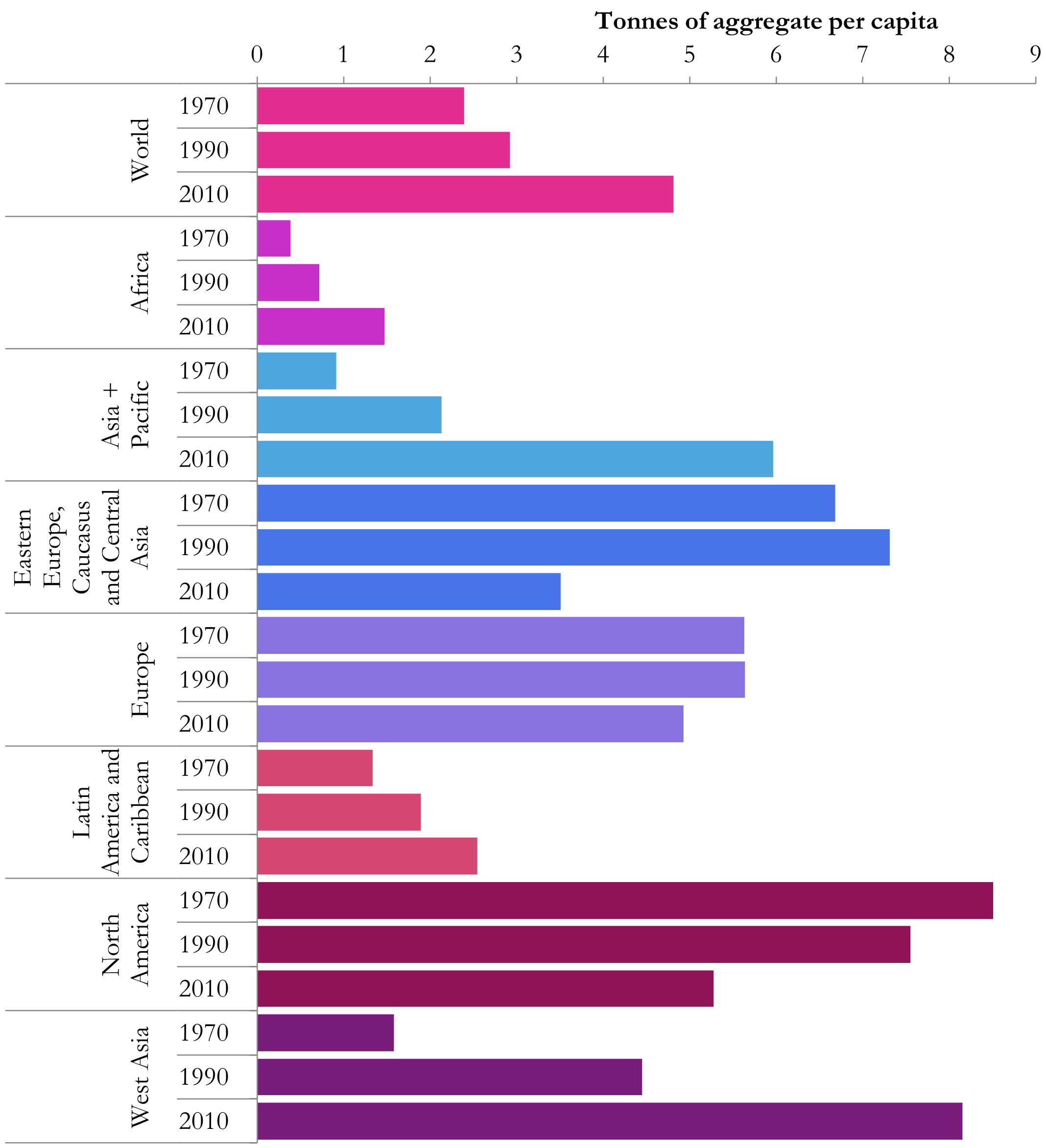

Figure 6 Per-capita extraction of non-metallic minerals in seven world regions, 1970, 1990 and 2010, tonnes

The Asia-Pacific region has increased its extraction most of all seven regions and now consumes six times the amounts of 1970 at 6 tonnes per capita in 2010. Per-capita extraction in Latin America and Africa is much lower than the global average; this relates to gaps in the physical infrastructure that will need to be addressed in the future to underpin productivity and economic prosperity in these two world regions.

Figure 7 relates the extraction of non-metallic minerals to national GDP and shows the extraction intensity of building materials (and the demand for built infrastructure) of GDP. As expected, the extraction intensity of non-metallic minerals has increased in Asia and the Pacific, Africa and West Asia but has been stable in Latin America. Europe, EECCA and North America have had declines in the extraction intensity of their economic growth but for different reasons.

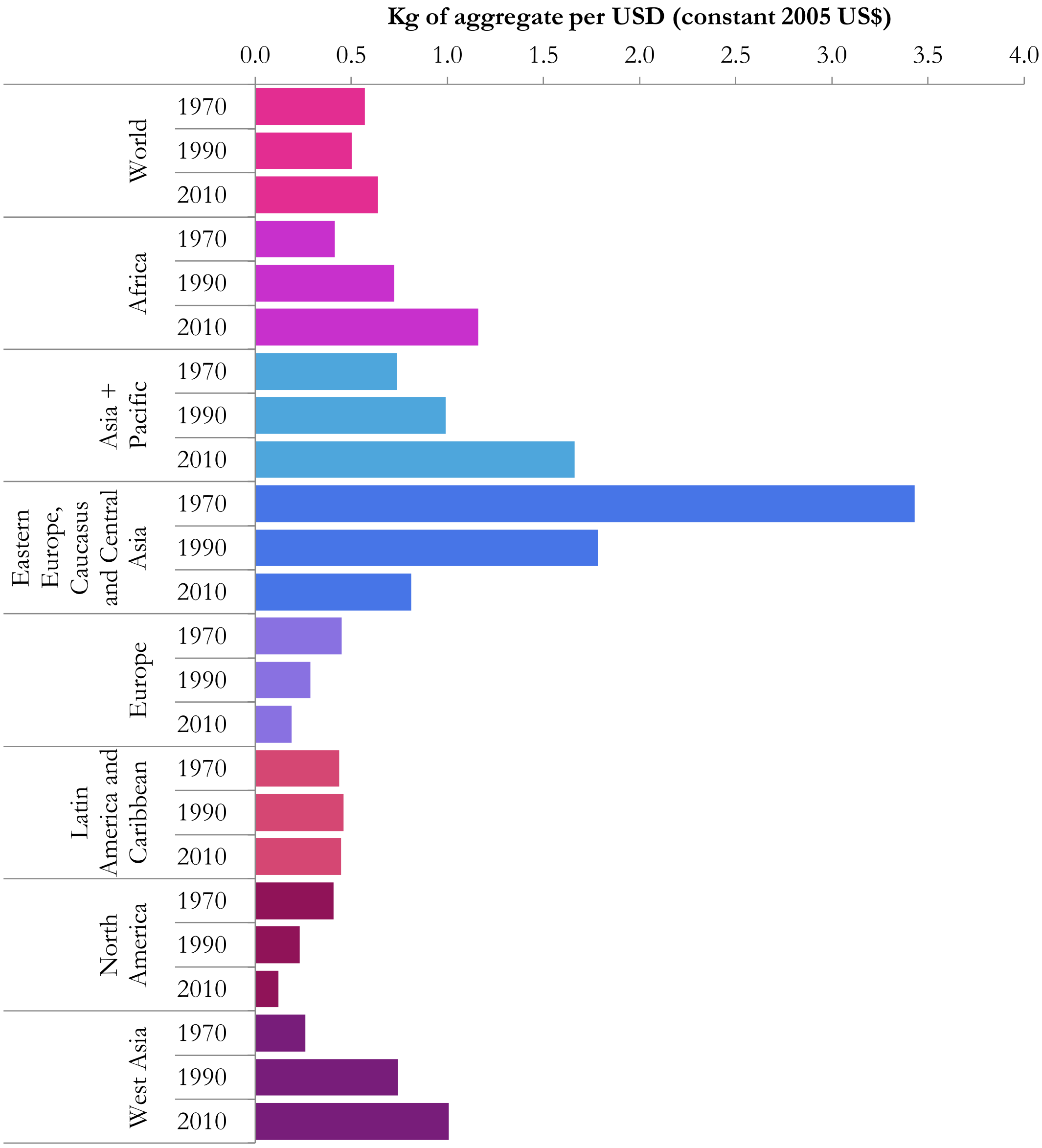

Figure 7 Non-metallic minerals extraction per unit of GDP for seven world regions, 1970, 1990 and 2010, kg/US$

Globally, non-metallic minerals extraction per unit of GDP has not changed much during the past 40 years, starting at 0.57 kg/US$ and ending at 0.64 kg/US$, which is the combined effect of increased intensity in some regions being balanced by decreased intensity in other regions.

2.4 Discussion

The results of this study confirm the order of magnitude of the previous studies measuring global extraction of non-metallic minerals, but there is a larger difference for earlier years between the new account and previous accounts. This might be due to underestimation of bricks and/or the road sector, but we cannot tell for sure due to the aggregated way in which the data are presented (Krausmann et al., 2009; Schaffartzik et al., 2014; UNEP, 2015).

In contrast to previous studies (Krausmann et al., 2009, 2008) which relied on coefficients based on educated guesses, the coefficients we used in our calculations are based on actual engineering knowledge. A wealth of technical detail has gone into the final coefficients used to estimate the extraction of different types of non-metallic minerals. We have developed a sophisticated analytical framework that can be applied to the specific characteristics of a national economy; this goes beyond the analysis in this study where we are still using world averages. The new method is, however, much better justified and grounded in the technical literature than what has been available to date. To further increase the precision of the account a bottom-up approach – which is a detailed accounting that uses spatial maps as sources of information rather than statistical accounts – for specific countries would be needed. Some of the greatest uncertainties in calculating the factors are typical concrete requirements (this might change significantly according to the level of seismic activity in different areas, and may depend on local climate and humidity, the dominant building design, and the financial capacity of customers) and typical soil composition. Such information would require spatial analysis combined with statistical data for the approach developed in this study to be applied and tested.

Rates of recycling and down-cycling of construction materials are mostly unknown for the majority of the world. Japan currently recycles 95% of its concrete and asphalt concrete waste (Hashimoto et al., 2007; Ministry of Land, Infrastructure, and Transport of Japan, 2002), yet this is probably the most virtuous example, and demolition estimates for Europe show very low yearly demolition rates (Bradley and Kohler, 2007) with large quantities of construction waste ending up in landfills. Bitumen is also recycled, and can be mixed in small amounts with virgin bitumen; yet we do not have sufficient data for recycling rates. Most of the extraction of aggregate is driven by developing world regions, which still do not have much material stock that can be recycled and/or down-cycled. For these reasons, we decided not to account for recycling in our model, which may have caused an overestimation of non-metallic minerals extraction. We consider the overestimation to be very small and negligible for the globe and for most countries.

Not being able to include recycling rates in our model is, however, an important limitation and could be addressed in future research especially in national case studies.

The extraction patterns of non-metallic minerals for the seven world regions confirm previous findings about different global metabolic regimes (Krausmann et al., 2008) and the position and trajectory of different world regions with regard to material extraction and consumption. We distinguish three main groups: developing countries of the global South; affluent countries; and the predecessor countries of the former Soviet Union.

Developing economies in Africa, Asia and the Pacific, Latin America and West Asia have a large need for further infrastructure investment and as a consequence the extraction of non-metallic minerals per capita and per dollar constantly grew during the period from 1970 to 2010 (Dittrich et al., 2011; Russi et al., 2008; Schandl and West, 2010; West et al., 2013; West and Schandl, 2013). There is no sign yet of deceleration and stabilisation of the extraction and demand for construction materials; new buildings and roads are still being established in large numbers and in short time periods. This ongoing process of industrialisation and urbanisation requires ever-growing amounts of primary materials in the construction industry and in many cases results in rising in material intensity, especially when traditional building materials (such as timber and rice straw) are replaced by modern materials (concrete, steel) and when new manufacturing capital is introduced which replaces manual labour with machinery and tools. The lack of infrastructure in many parts of the world, especially Africa and Asia, indicates further growth to come. This also creates a window of opportunity, however, for sustainability, because if investment is directed towards green buildings, public transport infrastructure, opportune urban morphology that minimises sprawl and commuting distance, and renewable energy systems, this will have a lasting positive effect by reducing carbon and material intensity of economic development and improving living standards and the lifespan of stock. Moreover, it is not only the quantity of stock that matters, but especially its quality, since better buildings and infrastructure will last longer, require less maintenance, and satisfy users' needs for longer, therefore resulting in an overall reduced burden for the environment.

The affluent countries in Europe, North America and Asia show signs of stabilisation of their primary material demand, especially in the domain of non-metallic minerals. Consequently, non-metallic mineral consumption per capita and per dollar has decreased. Many countries have achieved relative decoupling of construction material demand from economic growth and some have reduced their absolute yearly requirement of non-metallic mineral extraction, such as Japan, the United States (Fishman et al., 2014), Spain, and Italy – though the two last countries might have experienced an absolute reduction of non-metallic mineral extraction due to the economic downturn during the global financial crisis of the late 2000s. To establish whether this stabilisation of demand for construction materials in the affluent parts of the world is happening because of a saturation of material stock would benefit from accounts of in-use stock and precise recycle rates, both of which are not available for most countries. We can, however, infer from the slowdown of extraction that the demand for stock has also slowed. It would also not be a surprise that the global financial crisis has curbed investment into new infrastructure.

Eastern Europe, Caucasus and Central Asia has a story of its own due to the political vicissitudes that caused the collapse of the economy after 1991 (West et al., 2014). Before this point the former Soviet Union used to have the highest amount of aggregate consumption per unit of GDP, and it is only after 1991 that this reached values similar to those of other regions. After the dissolution of the Soviet Union both GDP and non-metallic mineral extraction and consumption started to decrease conspicuously. Recent years, however, show a rapid growth of the economy, followed by an equally rapid reprise in the consumption of non-metallic minerals. It is hard to establish at which point the Russian Federation and other economies that emerged after the break-up of the Soviet Union will start to stabilise their non-metallic minerals requirement.

From this analysis, we can say that globally there is no sign of a reduction in the extraction of non-metallic minerals despite a slowdown in Europe and North America, and Japan. Currently the greatest demand for construction minerals comes from the Asia and the Pacific region, which is developing fast, and has yet to accumulate sufficient material stock to enter the phase of demolition and refurbishment – compare this to the case of housing in the Netherlands (Müller, 2006). This difference might become significant in a few decades, therefore a detailed account of the material stock and recycling rate is desirable. Notwithstanding the global growth trend, the figures for Europe and North America indicate that in future there may be a saturation point at which new infrastructure will barely be needed and all new inputs to the system will only be to maintain the physical infrastructure already in use; this is not yet the case (Wiedenhofer et al., 2015).

2.5 Conclusions

In this research we established a new global and country-by-country account for the yearly extraction of non-metallic minerals for most countries in the world for the years 1970 to 2010. We provided information regarding types of aggregate – e.g. gravel, sand, limestone, etc. – and their use in the construction of buildings, transport infrastructure, etc. We established a detailed accounting framework and methodology based on technological and engineering information and building standards, and derived global multipliers to estimate the extraction of non-metallic minerals based on the apparent consumption of cement, bitumen, bricks and railway tracks. This method is similar to how previous studies estimated non-metallic minerals extraction but is superior in four ways: it is based – for the first time – on engineering and technical knowledge and is well-referenced, it delivers a greater level of detail for specific materials, it provides guidelines to establish bottom-up accounts for individual countries, and it accounts for a range of uncertainty in accounted non-metallic minerals. We investigated engineering manuals and construction codes, and consulted practitioners, in order to receive real-world information about current trends and standards in the construction of buildings, roads and rail tracks. This improved methodology provides detailed information about the quantity, type, and main sectors in which aggregate has been put in place.

The new global account of non-metallic minerals extraction confirms the order of magnitude of this material group suggested by previous studies, but suggests that earlier years were severely underestimated, while more recent years concord more with the previous literature. We find, as many previous studies on global material flows and stocks have done, that there is no sign of deceleration of primary materials demand for ‘construction materials’ at the global scale, but a slowdown in extraction and use has occurred in the most wealthy parts of the world including Europe, North America, Japan and South Korea. This hints that, once a country has reached its fully developed stage, there might be a point of material saturation of physical stock and a stabilisation of yearly required inflows of non-metallic minerals. Nevertheless, to fully understand whether this saturation point exists, it is necessary to consider not only yearly inflows, but also recycling, waste production, and analysis of current amounts of existing stock.

To achieve a global accounting, this methodology relied on consultation with experts to answer questions, such as which is the average type of concrete required in a specific market. While this is not a problem for a global account because local idiosyncrasies tend to balance out, focusing on a single region or a single country would allow researchers to unpack local characteristics and reach a greater degree of precision, informing the international research community about the specifics of that nation. Sustainable materials management has become an important issue for many national policy communities and globally. Improving the accounts for the important primary material group of non-metallic minerals aims to improve the knowledge base for policy making. If this study were to encourage follow-up research for specific countries its aim would be fully achieved.

3 How important are realistic building lifespan assumptions for material stock and demolition waste accounts?

3.1 Introduction

Studies of material throughput have become a common feature of the Industrial Ecology literature over the past two decades (Adriaanse et al., 1997; Matthews et al., 2000; Fischer-Kowalski, 2011). Some materials, such as biomass or fossil fuels, are usually quickly consumed, and rapidly leave the economic sphere in the form of waste and emissions, while others stay within the economy for much longer periods. Of those, construction minerals are probably the materials which have the longest use phase and lifespan. A recent study by Haas and colleagues showed that over 99% of the 24 Gt of construction materials that entered the economy in 2005 ended as material stock (Haas et al., 2015). In recent years an increasing number of studies have attempted to calculate stocks of several key materials at different levels adopting different methodologies (for an extensive review see Müller et al., 2014 and Tanikawa et al., 2015). Accounting for accumulated material stock through this approach is apparently trivial: inflows + domestic extraction – outflows + a number of correction factors[3] = net addition to stock. It is then sufficient to repeat this "simple" equation for a sufficiently long time series to calculate total (in-use) material stock. Nevertheless, despite its apparent simplicity, solving this formula is far from trivial. Robust and reliable data for outflows from the construction sector, i.e. construction demolition waste data, is hard to come by (Thomsen and van der Flier, 2009). In rare cases, demolition data is collected at the national level, allowing for analysis of trends and the spatial distribution of demolitions for the whole country (Huuhka and Lahdensivu, 2016). In other cases, researchers have managed to extrapolate detailed data of construction and demolition activities at the city level (Aksözen et al., 2016b). A possible strategy to overcome data limitation is creating models which simulate waste outflows, but this obviously poses new challenges in terms of data requirements, and modelling assumptions and limitations. It is generally agreed that a better understanding of the dynamics that characterise the construction and demolition of buildings is a necessary step towards a more sustainable built environment (e.g. Aksözen et al., 2016a; Allen and Hinks, 1996; Thomsen and van der Flier, 2009; Thuvander et al., 2015)

Tanikawa and colleagues identified four different approaches to material stock accounting, including bottom-up accounts, top-down accounts, demand-driven accounts, and accounts based on remote sensing technologies (Tanikawa et al., 2015). Each of these methodologies has its own strengths and weaknesses. Bottom-up accounting relies on item inventories and materials intensities (e.g. Wiedenhofer et al., 2015). At times this information is supported by spatial maps, making the stock geographically explicit, but involves a very time-consuming compilation process (e.g. Lichtensteiger and Baccini, 2008; Tanikawa et al., 2015; Tanikawa and Hashimoto, 2009). The top-down method looks at the stocks using inflow statistical data and imposing a lifetime distribution on the depreciation of stock. While this method is relatively quick to compile it loses information on the spatial distribution of the stock and relies on the goodness of the chosen lifetime distribution and parameters (e.g. Fishman et

[3] With "a number of correction factors" we intend all those operations needed to ensure a material mass balance, since often statistical yearbooks are affected by inconsistencies and imprecisions.

al., 2014; Hashimoto et al., 2007; Hatayama et al., 2010). Demand-driven accounts use a series of parameters such as population, average household size and material intensity to derive inflows, stock, and outflows of materials (e.g. Müller, 2006; Pauliuk et al., 2013; Vásquez et al., 2016). Remote sensing accounting uses satellite images to investigate stock levels and, despite not reaching the popularity of other methods – mainly due to the lack of validation of the accounts against independent data, could be the only viable option for countries where material flow statistics and detailed maps are not available (e.g. Liang et al., 2014; Rauch, 2009; Yoshida et al., 2016). Among these four methodologies, two depend on lifespan assumptions: the top-down approach, and the demand-driven approach.

Most stock accounts available in the scholarly literature have used top-down and demand driven approaches, and relied on assumptions regarding lifespan distribution to model demolition outflows in some way. Müller and colleagues identified that dynamic material flow analysis used to account for metal flows and stocks mainly relied on the Dirac delta distribution and the Weibull distribution (Müller et al., 2014). Accounts of construction material stocks relied mainly on the normal distribution (e.g. Fishman et al., 2014; Müller, 2006) and Weibull distribution (e.g. Cai et al., 2015; Sandberg et al., 2014).

The main issue, common to all the approaches which rely on lifespan data, is that, up to today, a proper cohort-based dataset is yet to be available, especially for non-residential buildings and infrastructure. A comprehensive comparison of the effect of different distribution functions on stock accounts is yet to be done and is the main aim of this research. We ask:

- How does the choice of a specific lifespan distribution affect the stock account?
- How does this choice influence the forecast of demolition waste?
- Can we identify a demolition probability distribution function that better fits the lifetime of buildings in the real world?

To answer these questions, we first present a theoretical discussion on modelling lifespan distribution, starting from the concept of hazard rate and how this applies to buildings. We then discuss the limitations of some popular probability distribution functions that have commonly been used in lifespan modelling. We demonstrate how the choice of different lifespan distributions and parameters affects the material stock account and waste flow account in a case study of building stock in Japan and the United States. Finally, we test the sensitivity of our results by changing the lifespan distribution parameters to identify those parameters that most affect the results.

3.2 Calculating building lifespan of real world data

A widespread interest in lifespan analysis arose during the 1970s, when several fields, including engineering, electronic component manufacturing, medicine, and insurance, gained interest in the systematic and scientific analysis of the mortality of particular artefacts, products and people. From the 1980s specific software, such as SAS (SAS Institute) and S-Plus (Statistical Sciences Inc., now TIBCO Software Inc.), became available to study lifetime data. The research field of survival analysis emerged quickly after that.

With lifespan, or lifetime, in its broadest sense, we indicate the period that elapses between two events: from birth to death of a living being, from the production of an engine till its failure, from the construction of a building till its demolition, or even from university graduation till first employment. While common sense suggests that lifespan is something that measures cradle-to-grave intervals, its meaning in the context of survival analysis is much broader.

The lifespan of a single building can be calculated as the difference between the year of its construction and the year of its demolition, whether deliberate or caused by a natural disaster. For objects such as buildings and infrastructure the number of years has been chosen as a convenient unit of time, on the one hand because it is often impossible to retrieve more detailed information (month and day of completion and demolition are usually non-reported, or not disclosed), and on the other because these types of objects have lifespans in the order of decades – sometime centuries – and accounts in months or days would be redundant.

This section will not explain in detail all the methods available to model lifespan. Readers interested in survival analysis will find plenty of literature available (e.g. Lawless, 2011), but we will limit it to the explanation of the concept of hazard rate. This will be followed by the analysis of lifespan distribution models and relative hazard rate, as widely used and suggested in the literature.

3.2.1 Hazard rate

The hazard rate, or hazard function, is a mathematical expression that indicates the instantaneous rate of death of a unit of interest at a given time *t*; formally it is defined as:

$$h(t) = \lambda = \lim_{\Delta t \to 0} \frac{Pr(t \leq T \leq t + \Delta t | T \geq t)}{\Delta t} \tag{1}$$

Reminding that $\Pr(A|B)$ is the probability of A under the condition B, the previous equation indicates the probability of the event *T* happening in the interval between *t* and $t+\Delta t$, given that *T* did not happen before *t*, divided by Δt. The normalisation by Δt is important since it makes two hazard rates comparable even if they have been calculated using two different time intervals. It is important to point out that the hazard rate function is not a probability distribution, and that its unit of measure is $time^{-1}$.

An alternative way of expressing the hazard rate is:

$$h(t) = \lambda = \frac{f(t)}{S(t)} = \frac{f(t)}{1 - F(t)} \tag{2}$$

Where f(t) is the probability density function (PDF), S(t) is the reliability function (RF), and F(t) is the cumulative density function (CDF).

In simple terms, the hazard rate is a function that expresses the likelihood of failure occurring at a certain time, expressed as *failures per unit of time*. The proper unit of time, seconds, days, years, etc., depends on the specific application for which the function is applied.

3.2.2 Commonly used probability distributions in material stock analysis

In the past few years several studies have attempted to calculate material stocks by employing a top-down accounting approach[4] and using different distributions. Some researchers opted for a normal distribution (Fishman et al., 2014; Vásquez et al., 2016); others chose a right-skewed distribution: Weibull (e.g. Bradley and Kohler, 2007; Cai et al., 2015), Log-normal (e.g. Hashimoto et al., 2007; Tanikawa et al., 2015), or Gamma (e.g. Kapur et al., 2008); while others applied a left-skewed Gompertz distribution (e.g. Sarkar et al., 2011). For a brief description of distribution skewness refer to the Supporting Information (SI 1.4). Among these commonly used distributions, the one which best fits stock accumulation modelling is still unclear. Opting for one over another might seem a small decision at a superficial glance, but our results display wide variability, with considerable effects for the speed of stock accumulation, and the forecast of waste production.

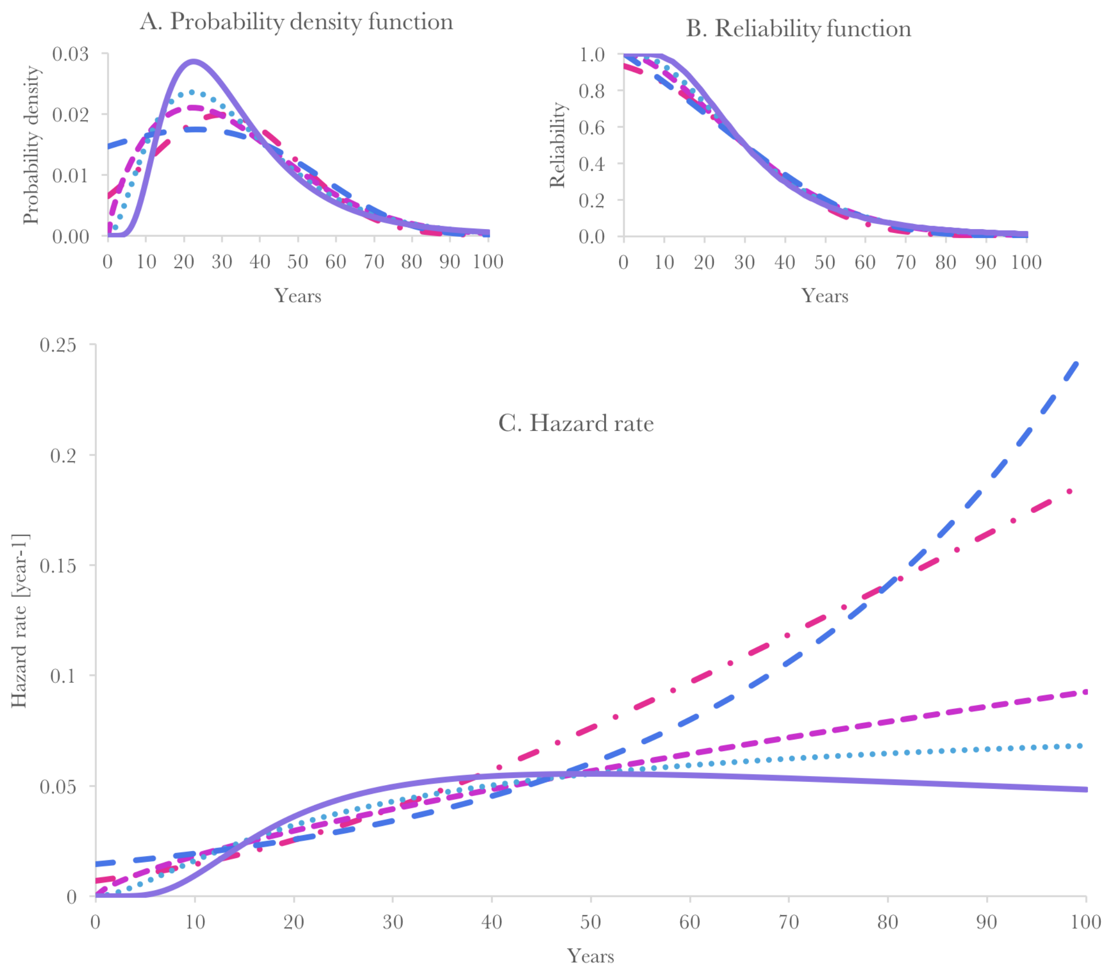

Figure 8 – a) Probability density function for five different distributions. b) Reliability function for five different distributions. c) Hazard rate for five different distributions. All the functions have been modelled to have median = 30 years, and standard deviation = 20 years.

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[4] For a detailed explanation of this and other stock accounting methodologies refer to Tanikawa et al., 2015.

Figure 8a demonstrates how the five distributions discussed above are shaped when modelling them with the same median (30 years) and standard deviation (20 years). While the Weibull, Gamma, and Log-normal distributions show a PDF of 0 at the year 0, the Normal and Gompertz distributions shows a positive value from the very beginning. This means that, with these particular parameters, the total area below the PDF of these two equations is below 1, assuming therefore that a part of the stock is removed right after construction. This is a modelling issue particularly relevant in the case of short-lived buildings, when modellers have to decide whether to compress the distribution towards the mean in order to avoid cutting part of the left tail, or vice versa to simulate a more spread demolition over time at the cost of assuming that part of the stock is removed straight after its construction.

Figure 8b illustrates the reliability function for the previously shown five distributions applying the same parameters. Modelled with a median of 30 years, they all intersect at the point (30, 0.5). All the curves start at the point (0, 1), except for the normal distribution, which starts at (0, 0.93). In this latter case, based on these assumptions, the normal distribution assumes that roughly 7% of buildings would get demolished within a year of their construction.

Figure 8c shows the hazard rate for the five distributions, which indicate the instantaneous likelihood of demolition. At year 0, the only functions which do not have a hazard rate of 0 are the normal [h(t)=6.9E-03] and Gompertz [h(t)=1.5E-02] distribution functions. After an initial moment of stabilisation, the normal, Weibull, and gamma hazard rates grow linearly, while the Gompertz hazard rate grows exponentially. This is because the Gompertz distribution is mainly used in modelling the lifespan of living beings, which present an exponentially increasing risk of death. The log-normal distribution is the only function, among these five, that remains flat in the early years, presenting a peak at about 50 years, after which it slowly decreases.

The Supporting Information (SI) contains a detailed description of the parameters of these distributions (SI 1.1), their reliability functions (SI 1.2), and formulas to calculate their mean and standard deviation (SI 1.3).

3.2.3 Some theoretical considerations on building demolitions

When thinking about the likelihood[5] of demolition, common experience suggests that, apart from in cases of catastrophic events or exceptional structural deficiencies, very recently built infrastructure and buildings are very unlikely to get demolished. The peak of demolition likelihood will happen after some time has passed, based on the location, period, typology of the construction, et cetera. Those buildings which survive their demolition peak are most likely to represent the best of their cohort, in terms of both architectural design and structural qualities. These individual items are probably worth preserving, and might even gain a historical bond, crystallising even more their presence in the urban fabric. The reader interested in more theoretical considerations about the building stock is invited to refer to the paper

[5] We talk about likelihood, and not probability, because, formally speaking, the hazard rate is not what is mathematically defined as a probability.

"Understanding obsolescence: a conceptual model for buildings" (Thomsen and van der Flier, 2011)

Given these considerations, the only curve that matches the above description is the log-normal distribution. To verify whether this theoretical assumption holds in the real world, we test the best fitting for these curves using three empirical case studies: Nagoya (Japan), Wakayama (Japan), and Salford (UK).

3.2.4 Case studies

For brevity, this chapter reports only the results for the totality of buildings of the study areas. Details on the R^2s, average lifespans, standard deviations, and parameters used to calculate the reliability functions for different building groups (residential, commercial, etc.) and for each single cohort can be found in the Supporting Information (SI 2).

3.2.4.1 Nagoya (Japan)

Through the 4D-GIS methodology introduced in 2009 (Tanikawa and Hashimoto, 2009), Tanikawa and colleagues were able to establish a database of buildings spanning over a significant number of years. This methodology has been applied to the case study of the Naka-ward of Nagoya, the main commercial and service sector district of the city, which today features more than 70,000 buildings. The time steps for which building data had been available include 1960, 1970, 1980, 1990, 1997, 2003, and 2009.

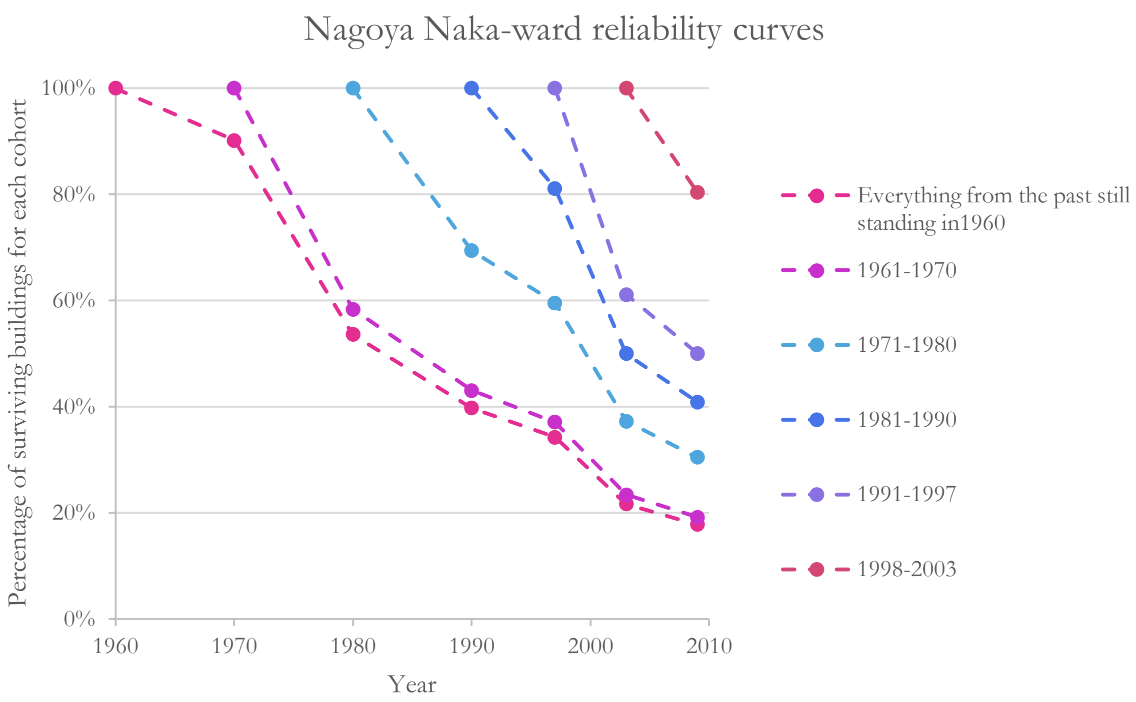

Figure 9 - Survival curves for Naka-ward, Nagoya. Each curve represents a single cohort. The last year of analysis was 2009.

The reliability curve for each cohort is shown in Figure 9, and normalised so that all start from 100%. It is important to point out that each cohort is independent of the others and, for example, the 1970 cohort comprises buildings newly constructed from 1961 to 1970. Using the empirical data, we performed a best fit calculation for the five most commonly used probability distributions, and the results are shown in Table 2.

Table 2 – Nagoya R^2 values expressed as percentage for curve fitting. The left column represent the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Nagoya R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=28664)	94.5%	98.0%	98.3%	97.1%	98.8%
1970 (n=29104)	89.3%	98.9%	99.0%	98.3%	98.5%
1980 (n=26498)	94.8%	98.2%	98.1%	98.4%	97.6%
1990 (n=23745)	92.2%	97.5%	97.7%	96.6%	98.4%
Average R^2	92.7%	98.1%	98.3%	97.6%	98.4%
R^2 std dev	2.5%	0.6%	0.5%	0.9%	0.5%

The log-normal distribution performed the best for the 1960 and 1990 cohorts, while the gamma distribution performed best for the 1970 cohort and the Weibull for the 1980 cohort. All these distributions are right skewed, and match with the theoretical assumption that buildings have an initial demolition-free period, followed by a spike and a long tail. On average the log-normal distribution performed best, both in terms of average R^2 and its relative R^2 standard deviation, while the normal distribution performed the worst for every cohort, even worse than the left-skewed Gompertz distribution. This is probably because the normal distribution, when applied to short-lived buildings, is the only one whose reliability function starts at a value different than 1, id est it assumes that a fairly consistent number of buildings are demolished within their first year after construction, which of course is an unrealistic proposition.

The calculated average lifespans and standard deviations are shown in Table 3.

Table 3 - Nagoya average lifespan and, between parenthesis, standard deviation for four different cohorts and five different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number.

Nagoya lifespan and std dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=28664)	27.3 (19)	25.2 (21.1)	24.9 (22.3)	25.6 (19.3)	24 (31.2)
1970 (n=29104)	19.3 (18.5)	14.8 (31.5)	14.5 (29.5)	16.3 (n/a)	14.4 (76.7)
1980 (n=26498)	14.3 (14.3)	18.6 (19.3)	18.5 (20.7)	18.9 (15.7)	18.1 (37.5)
1990 (n=23745)	15.2 (9.9)	14.7 (13.3)	14.6 (14.3)	15 (11.4)	14.4 (24.3)

The log-normal distribution tends to account for shorter lifespan, while the normal distribution assumes – on average – the longest life expectancy. As this case study mainly focused on a commercial area, it shows very quick replacement rates, with much shorter times than the circa 30 years that have been found in other studies focused on Asian countries (Cai et al., 2015; Hu et al., 2010; Tanikawa and Hashimoto, 2009).

There seems to have been an abrupt change in lifespan from 1960 to 1970. While this might have been triggered by a shift in the economic conditions of Japan in its path of industrialisation, it might also be due to the composition of the 1960 cohort. In fact, this cohort includes all buildings standing in 1960, for which the year of construction is from any year until

1960. The 1970 cohort includes all standing buildings that were constructed between 1961 and 1970, de facto greatly limiting the heterogeneity of the sample group.

3.2.4.2 Wakayama (Japan)

Wakayama is a mid-sized city located in the Kansai region. While the whole municipality has about 370,000 inhabitants, the case study conducted by Tanikawa and Hashimoto focused on the city centre of about 27,000 buildings. The first map that was used for this study dates from 1947, while the last one was from 2004. In total, five snapshots of the city centre were taken in order to obtain stock information for this part of the city. This data was calculated and published in the 4D-GIS paper in 2009 (Tanikawa and Hashimoto, 2009). To calculate the average lifespan, Tanikawa and Hashimoto fitted reliability curves to a logistic curve. We fitted the same data to the five different curves we are analysing, and the results are shown in Table 4.

Table 4 – Wakayama R^2 values expressed as percentage for curve fitting. The left column represent the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best. The logistic curve R^2 are derived from Tanikawa and Hashimoto, 2009.

Wakayama R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=12428)	88.5%	99.9%	99.9%	98.9%	99.9%	88.3%
1958 (n=16842)	85.9%	99.9%	99.9%	99.1%	99.9%	84.6%
Average R^2	87.2%	99.9%	99.9%	99.0%	99.9%	86.5%
R^2 std dev	1.9%	0.04%	0.04%	0.2%	0.04%	2.7%

In the case of Wakayama empirical data, the best overall curve fit is the Weibull distribution, closely followed by the gamma and log-normal distributions. Differences among these curves are in the other of hundredths of percentage point. An order of magnitude above is the Gompertz curve, with and R^2 of 99.0%. The normal and logistic curves represent the data least well, scoring 87.2% and 86.5% respectively. These results confirm what we have previously seen in the case of the Nagoya data, where all the right-skewed distributions perform better than the left-skewed ones, and even better than the symmetric distributions. While the 1947 cohort is best fitted by the Weibull curve, the 1958 cohort is best represented by the log-normal distribution. Unfortunately, the available data did not allow for more cohorts to be studied, diminishing the validity of the results because of a limited number of available vintages.

Table 5 –*Wakayama average lifespan and, between parenthesis, standard deviation for two different cohorts and six different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number. The logistic curves values are taken from Tanikawa and Hashimoto 2009.*

Wakayama lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=12428)	26.7 (25.7)	20.5 (46.6)	20.6 (42.4)	22.5 (n/a)	19.6 (122.6)	23.0 (28.2)
1958 (n=16842)	28.7 (25.2)	24.3 (54.9)	24.4 (49.4)	25.5 (n/a)	23.9 (154.2)	27.0 (28)

Table 5 shows the calculated average lifespans using different curves. The right-skewed curves, which are the ones with the lowest errors, present smaller values than the other curves. The highest lifespans are calculated from those curves which present symmetrical tails. There is a 28% difference between the best (log-normal) and worst (normal) fitting curves.

A detailed description on the R^2, average lifespans, and standard deviation for different building groups (residential, commercial, etc.), and the parameters used to calculate the reliability functions can be found in the Supporting Information (SI 2.3).

3.2.4.3 Salford, Greater Manchester (UK)

Salford was the second case study described in the 4D-GIS paper (Tanikawa and Hashimoto, 2009). This case, compared to Wakayama, covered a much longer time span, starting in 1849 and ending in 2004, and included nine different time steps. The number of buildings included, however, was smaller than in the other studies with 3,240 buildings standing in 2004, which represents 12% of the number of buildings included in the Wakayama sample.

Table 6 – *Salford* R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best. The logistic curve R^2 are *derived* from Tanikawa and Hashimoto, 2009.

Salford R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=98)	98.0%	97.9%	97.3%	98.3%	96.5%	97.9%
1896 (n=947)	95.8%	95.7%	95.8%	96.1%	95.8%	95.9%
1908 (n=220)	88.0%	87.5%	85.9%	89.3%	85.0%	88.8%
1932 (n=1228)	95.8%	95.1%	94.8%	95.8%	94.2%	95.5%
1953 (n=509)	97.9%	99.0%	99.4%	97.8%	99.6%	97.1%
Average	95.1%	95.1%	94.6%	95.5%	94.2%	95.0%
Standard dev	4.1%	4.5%	5.2%	3.6%	5.5%	3.6%

Table 6 displays the results of the curves fitting. Contrary to the results for Nagoya and Wakayama, the distribution that best and most consistently fits the data is the Gompertz distribution, followed by the normal, logistic, and Weibull distributions, while gamma and log-normal scored last. Despite this, the absolute difference between the best and worst fitting distributions is very small, at 1.231%. The reason why the Gompertz distribution best fit the data might be found in the way the City of Salford developed. After a quick development phase thanks to a local coal mine, the city entered a period of stagnation due to the great economic crisis of the 1930s, when many people lived on the verge of poverty in apartments that would nowadays be considered slums. By 1933, a decision to demolish and sanitise the area was taken. What occurred in Salford is hence not natural demolition due to aging, but a deliberate external intervention that terminated the life of many buildings prematurely, a historical specificity which is better modelled by a left-skewed distribution.

The calculated lifespan shows relatively consistent results across the five different distributions, with the exception of the values reported in the 2009 paper by Tanikawa and Hashimoto, which shows values that are on average 20% higher than the rest of the distributions. The calculations for each single cohort are shown in Table 7.

Table 7 - Salford average lifespan and, between parenthesis, standard deviation for two different cohorts and six different distributions. The logistic curves values are taken from Tanikawa and Hashimoto 2009.

Salford lifespan and std dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=98)	92.4 (49.8)	90.3 (48.2)	88.4 (52.6)	93.3 (46.2)	86.5 (61.6)	103 (54.3)
1896 (n=947)	80.7 (7.4)	80.5 (10.4)	80.6 (7.3)	80.2 (13.7)	80.6 (7.3)	104 (8.8)

1908 (n=220)	88.4 (37.6)	88.2 (36.6)	88.8 (45.7)	88.2 (31.8)	88.7 (55.3)	94 (39.6)
1932 (n=1228)	93.9 (40.6)	99.3 (50.2)	103.3 (68)	91.5 (32.5)	108 (117.7)	103 (40.4)
1953 (n=509)	44.8 (22.2)	44.6 (24.1)	44.3 (27.9)	45.4 (20.4)	44.1 (38.2)	55 (24.2)

These findings suggest that, in general, right skewed distributions, especially the log-normal, represent the dynamics of stock accumulation and demolition in cities well but does not cater so much for unexpected events such as natural hazards, climate impacts and planning decisions that shorten building lifespans. Do these findings at the city scale hold when we move to the national scale? We aim to address this question by using long-term national stock accumulation data for Japan and the United States.

3.3 Sensitivity analysis of different distribution curves and input parameters to a material stock accumulation and forecast demolition waste model

A previous study (Fishman et al., 2014) introduced a novel methodology to estimate the accumulated material stock of a nation based on data for material inflows and assumptions about lifetime distribution (top-down inflow driven stock accumulation model). The model uses construction material inflows as input; median, standard deviation, and a normal distribution as exogenous variables; material stock and demolition waste are the outputs. In the following sections, we will perform a sensitivity analysis on the model to assess its response to random inputs and variables.

3.3.1 Sensitivity to distribution choice

3.3.1.1 Material stock accumulation

In the following we test how the model responds to different distributions, modelling them so they have the same median and standard deviation. As inputs we have chosen the inflow material dataset for Japan (Krausmann et al., 2011), which spans from 1878 to 2006, and for the United States (Gierlinger and Krausmann, 2012), which spans from 1870 to 2005. We chose to apply a median of 30 years in the case of Japan, and to double this value in the case of the US, in line with the existing literature about lifespan of construction in Asia and North America (Cai et al., 2015; Hu et al., 2010; Tanikawa and Hashimoto, 2009). The standard deviation has been arbitrarily set at 50% of the average lifespan with the intention of avoiding truncating the normal and Gompertz distributions (cf. Figure 8a and Figure 8b).

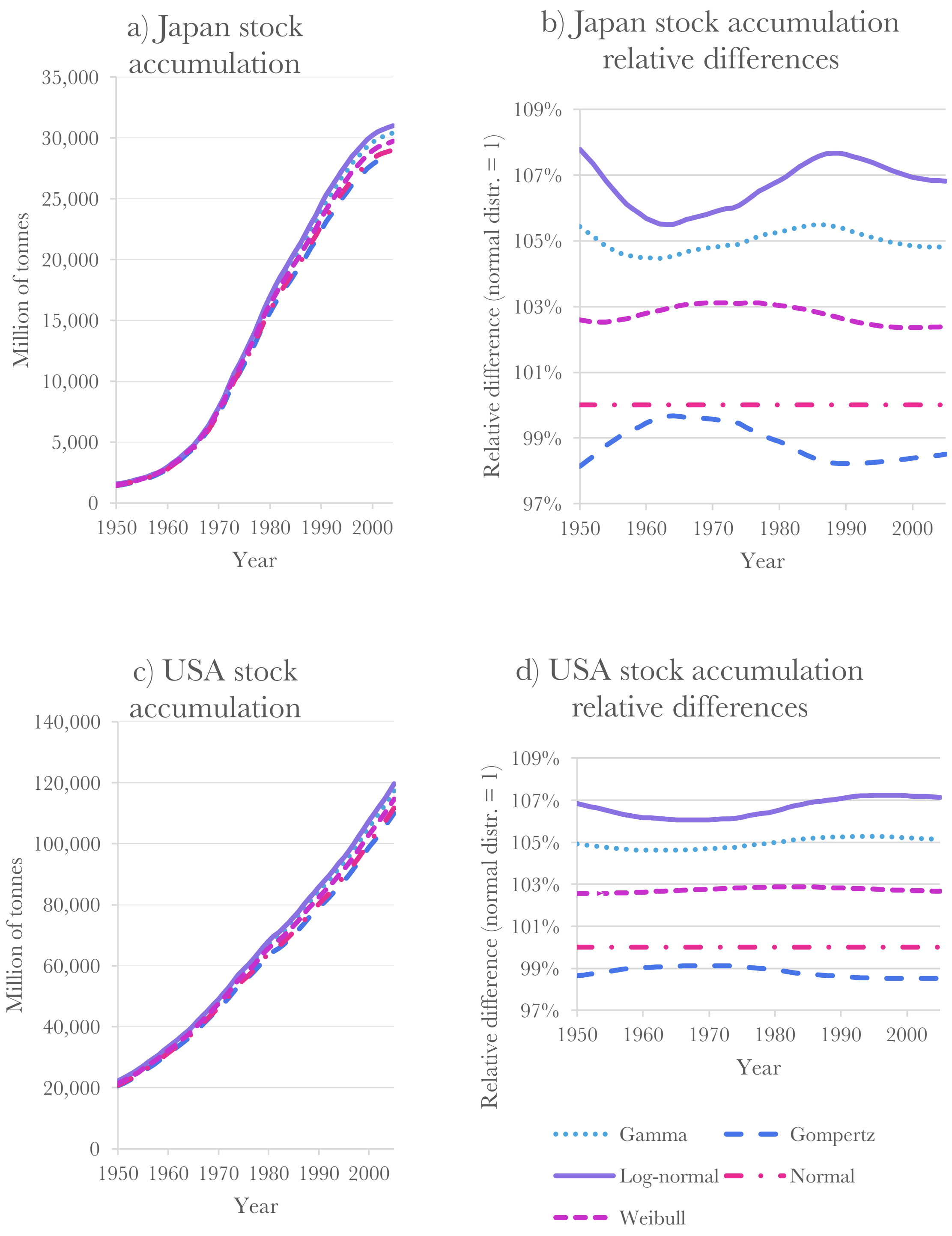

Figure 10 – a) Japan stock accumulation from year 1950 to 2005. b) Relative differences of the Japan stock accumulation, baseline = normal distribution. c) USA stock accumulation from year 1950 to 2005. d) Relative differences of the USA stock accumulation, baseline = normal distribution. All the distributions have been modelled to have median = 30 years, and standard deviation = 15 years. Note that the ordinate axis of chart a) and c) have different scales.

Figure 10a depicts the stock accumulation of Japan from 1950 to 2005. The chart shows the stock accumulation from 1950 because the model needs to run for a number of decades to ensure that the unknown stock that was present before the start year of the model – 1878 – would be completely demolished or negligible when our account starts.

Figure 10b represents the relative differences in stock accumulation assuming the normal distribution as baseline, as chosen by Fishman and colleagues in their research. The Gompertz distribution, accounting for approximately 98% of the 29.0 Gt accounted for through the normal distribution, estimates the total stock of Japan at 28.6 Gt. The log-normal distribution estimates 31.0 Gt, approximately +7% compared to the baseline. In between sit the Gamma distribution (30.4 Gt, +5%) and Weibull distribution (29.7 Gt, +2.5%).

Figure 10c shows the same estimation procedure for accumulated stock in the United States. Figure 10d illustrates the relative differences between the five different distributions using the normal as baseline. Despite showing very different patterns of inflow, and relative stock accumulation, the results for the United States display very similar results to those found for Japan (cf. Figure 10a). The normal distribution accounts for 111.6 Gt, the log-normal for 119.6 Gt (+7%), the gamma for 117.4 Gt (+5%), the Weibull for 114.6 Gt (+2.6%), and the Gompertz for 110.0 Gt (–1.5%).

3.3.1.2 Demolition waste outflow

Since the stock accumulation model calculates depreciation of stock, it is possible to estimate the demolition flows that come from the construction sector. The formula to estimate demolition outflows is:

$$Outflow_{y_i} = Stock_{y_{i-1}} + Inflow_{y_i} - Stock_{y_i} \quad (3)$$

Yearly stock values are calculated from the model, while the material inflows are taken from the previously mentioned studies.

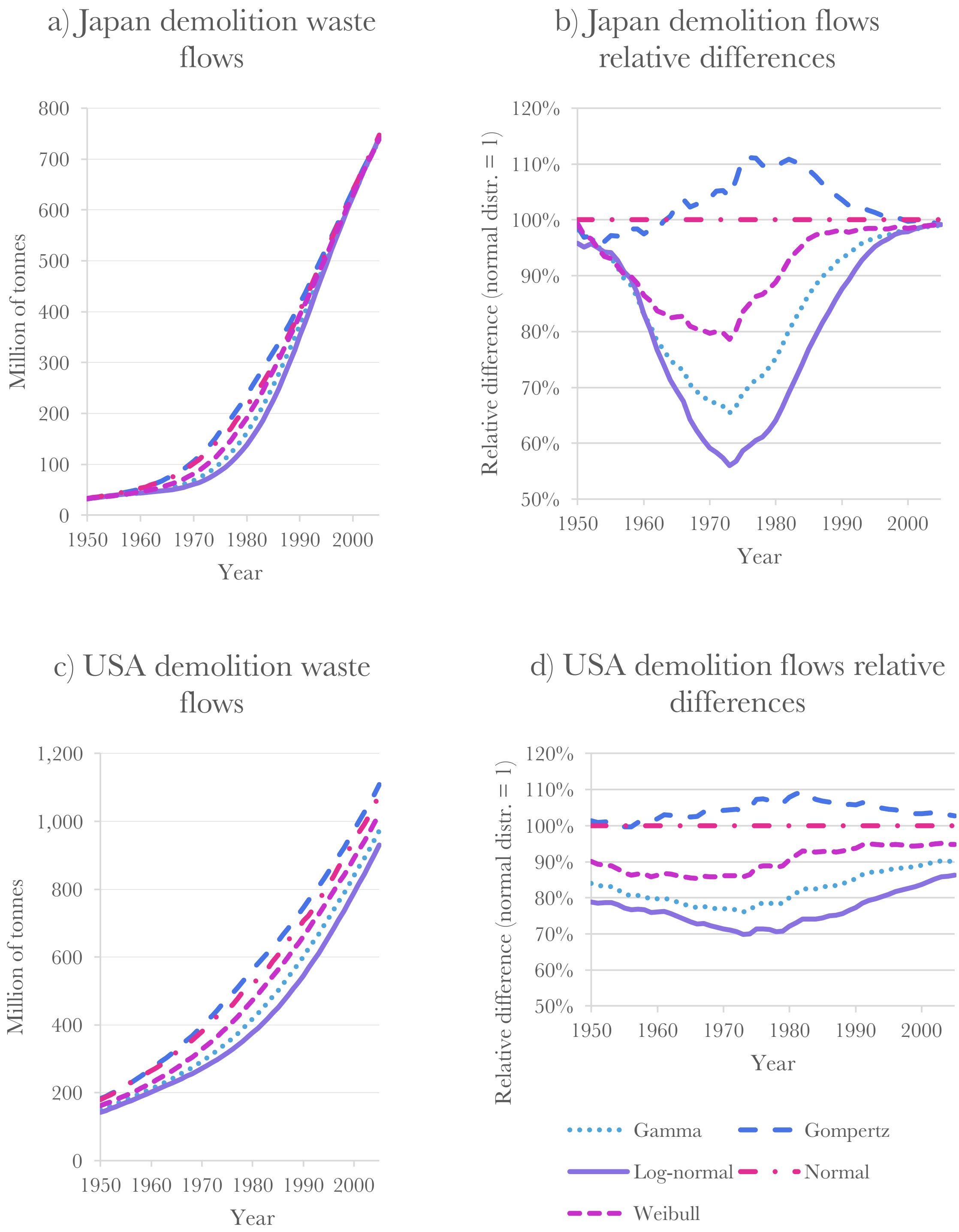

Figure 11 – a) Japan construction waste flows from year 1950 to 2005. b) Japan relative differences of the demolition waste flows, baseline = normal distribution. c) USA construction waste flows from year 1950 to 2005. d) USA relative differences of the demolition waste flows, baseline = normal distribution. All the distributions have been modelled to have median = 30 years, and standard deviation = 15 years. Note that the ordinate axis of chart a) and c) have different scales.

Figure 11a graphs the forecast for demolition waste flows for Japan. While all the flows in 1950 are around 30 Mt/year, they grow 25-fold, reaching approximately 740 Mt/year by 2005. Figure 11b shows that the different distributions result in a similar level of construction demolition waste in 1950 and 2005 with the 1970s being the time with the largest difference between different models. In the 1970s, the log-normal distribution was 43% below the reference case of normal distribution. The Gompertz distribution was 12% above the base case. Japan experienced a period of very fast construction growth after WWII, a time at which Japan saw its yearly inflows of construction material grow 15-fold (Krausmann et al., 2011). In 1973, the time of the first oil price shock, Japan experienced an abrupt stop to its construction expansion era, resulting in the different distribution functions cohering and producing similar outflow rates.

Figure 11c and Figure 11d indicate the results for the case of the US. While Japan shows decreasing inflows from the 1990s onward (Krausmann et al., 2011), allowing the different distributions to cohere and reach similar outflow values, the US presents progressively growing inflows (Gierlinger and Krausmann, 2012), thus keeping the results of the distributions separate. The normal distribution, taken as the reference curve, estimates 1,078 Mt for 2005. The log-normal distribution shows the lowest flow value, 931 Mt for 2005, which is 86% of what the normal distribution showed. At the opposite end, the Gompertz distribution estimates 1,108 Mt of outflows, 103% of the normal account.

In contrast to the urban examples shown in section 3.2.4 Case studies, the top-down stock accumulation model for the two national studies of Japan and the United States presents consistent results for the different distributions. In both cases the Gompertz distribution delivers the lowest stock accumulation result, followed by normal, Weibull, gamma, and log-normal. This order is reversed when looking at outflows. On the stock account side, the choice of one distribution over another does not affect the results excessively, resulting in a difference of 9% when comparing the highest to the lowest result. When estimating demolition waste flows, however, the choice is much more important, resulting in a difference of 55% between the highest and lowest estimate in the case of Japan.

The United States Environmental Protection Agency reported for the year 2003 a total of 170 Mt of construction and demolition (C&D) materials coming from the building sector (USEPA, 2009). Our model, which estimates not only the building sector but also infrastructure, estimated a flow of 873÷1,053 Mt of C&D materials for the same year. This indicates that demolition quantities coming from the infrastructure sector outweigh building demolition materials by a ratio of 4:1. This discrepancy of fivefold is in line with the findings of Kapur and colleagues, who accounted for the year 1996 cement discards from the construction sector equal to 26÷29 Mt, while, limited to the building sector, the USEPA accounted for 6 Mt of discarded cement for the same year (Kapur et al., 2008).

3.3.2 Sensitivity of stock estimate to inflows uncertainties

While inflows, being usually calculated a priori, should not be considered a variable of the model, they are often subject to inherent uncertainties (Fischer-Kowalski et al., 2011; Patrício et al., 2015). These uncertainties derive from compilation errors, underreporting in official statistics, missing data, etc. It was thus decided to extend the sensitivity analysis to the inflows, in order to see how results might change due to errors present in the source data found in statistical yearbooks and databases.

To test the sensitivity of the model to random inflows, we first applied normally distributed random noise to the Japanese material inflows, and then performed 10,000 Monte Carlo simulations to assess the stock accumulation results.

The parameters for the Monte Carlo simulations are calculated for each single year, applying a normally distributed uncertainty which has the mean set as the known value, and the standard deviation equal to 30% of that year's value.

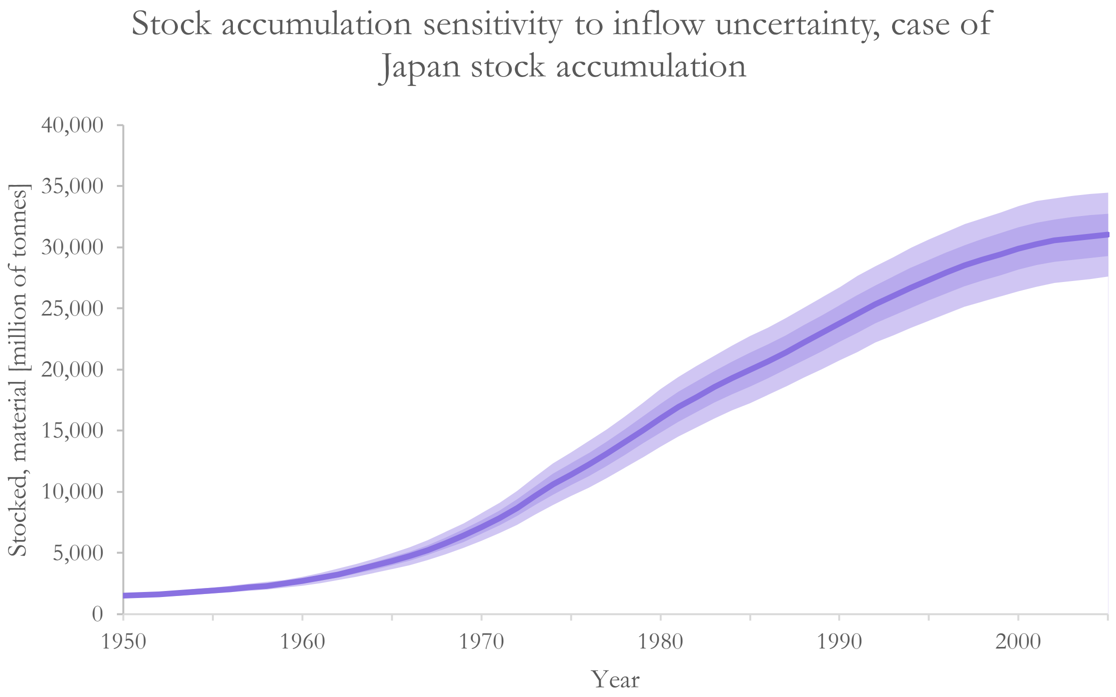

Figure 12 – Construction material stock sensitivity analysis to inflow uncertainties, case of Japan. The main line indicates the average of the Monte Carlo simulation. The coloured bands represent confidence intervals. The model is calculated using a log-normal distribution with median = 30 years, and standard deviation = 15 years. The coloured bandwidths represent one (68%) and two (95%) standard deviations of uncertainty, respectively.

The results of the simulation are shown in Figure 12. The calculated material stock is 31.0 Gt, exactly matching the amount we previously calculated through a deterministic approach (cf. Figure 3). The coloured bands are calculated by adding and subtracting a single and a double standard deviation respectively. The lowest case accounts for 27.6 Gt, equal to 89% of the average account, while the highest case accounts for 34.5 Gt, equal to 111% of the average, resulting in ±11%.

3.3.3 Sensitivity of stock estimate to the uncertainties of the median parameter of the model distribution function

In order to test how the model responds to random medians, we first applied normally distributed random noise (mean = 30 years, standard deviation = 10 years) to the set median of 30 years, and then performed 10,000 Monte Carlo simulations to assess the stock accumulation results.

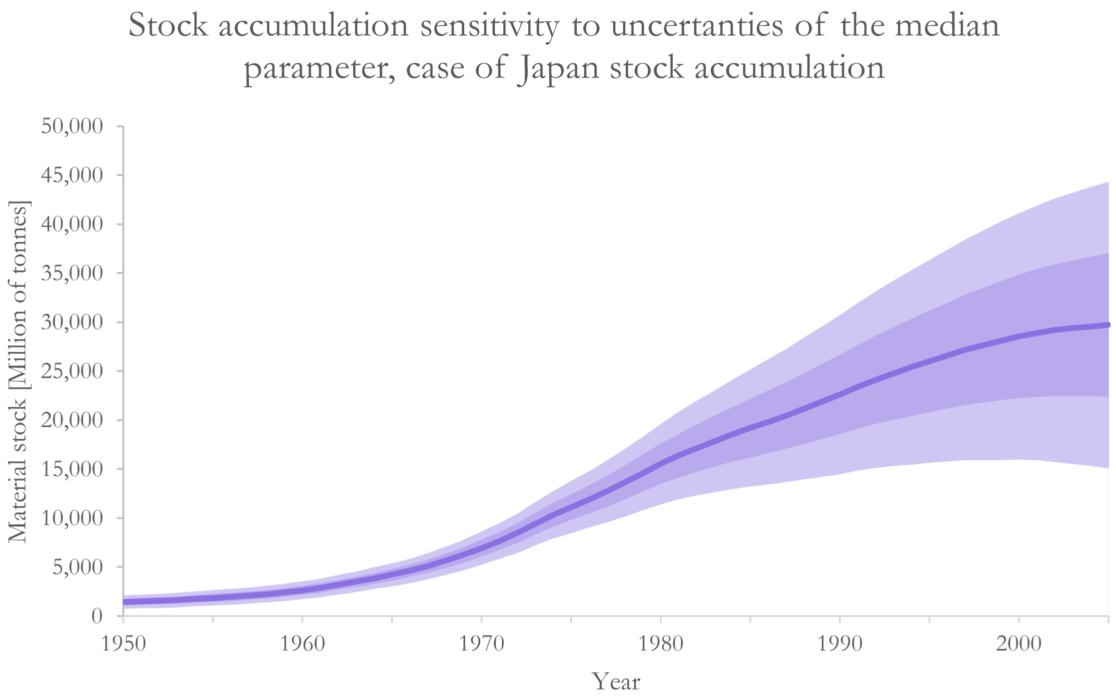

Figure 13 – Stock accumulation sensitivity analysis to uncertainty of the median parameter of the distribution function used in the stock accumulation model. The main line indicates the average of the Monte Carlo simulation. The coloured bands represent confidence intervals. The model is calculated using a log-normal distribution with random median, and standard deviation = 15 years. The coloured bandwidths represent one (68%) and two (95%) standard deviations of uncertainty, respectively.

The results of this simulation are plotted in Figure 13. The material stock accounts for 29.7 Gt, missing 1.3 Gt compared to the deterministic account. The bands of confidence show a high degree of uncertainty, ranging from a minimum of 15.1 Gt to a maximum of 44.4 Gt, a difference of ±49%.

3.3.4 Sensitivity of stock estimate to standard deviation parameter of the model distribution function

In order to test the how the model responds to standard deviation, we applied normally distributed random noise (mean = 0.434, standard deviation = 0.145) to the scale (σ) parameter of the log-normal distribution. Ideally we would have applied it directly to the standard deviation, but this was not possible without affecting the median. Nonetheless, modifying the scale parameter permits us to alter the standard deviation without affecting the median. We performed 10,000 iterated Monte Carlo simulations to assess the stock accumulation results.

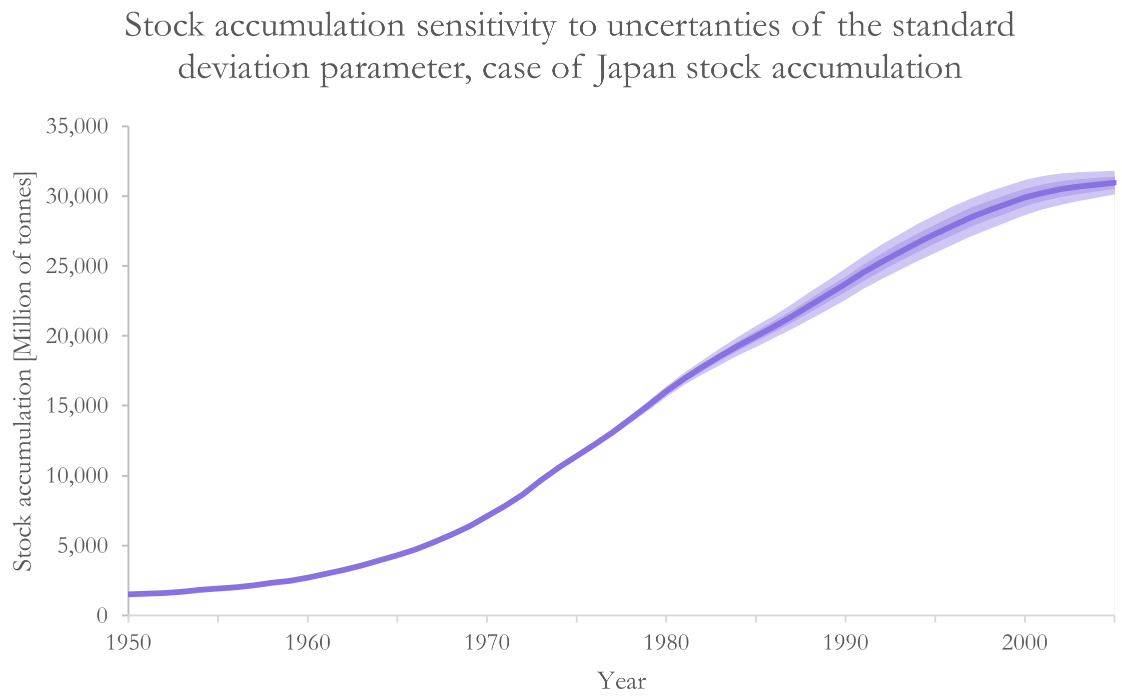

Figure 14 – Stock accumulation sensitivity analysis to uncertainty of the standard deviation parameter of the distribution function used in the stock accumulation model. The main line indicates the average of the Monte Carlo simulation. The coloured bands represent confidence intervals. The model is calculated using a log-normal distribution with median = 30 years, and random standard deviation. The coloured bandwidths represent one (68%) and two (95%) standard deviations of uncertainty, respectively.

Figure 14 depicts the results when applying a random standard deviation to the model. The average accounts for 31.0 Gt, matching the deterministic model. The lowest end of the bands of confidence accounts for 30.1 Gt, while the highest reaches 31.8 Gt, resulting in ±3% to the average results.

3.4 Discussion

3.4.1 Estimating lifespan of real building data

The curve fitting model showed, unsurprisingly, how the choice of a different distribution can affect the precision of the average lifespan calculation. Short-lived buildings, such as in the case of Nagoya and Wakayama, matched the theoretical assumption that building reliability curves follow a log-normal distribution. The Salford study case showed mixed results: while the Gompertz distribution fits better overall, different building typologies and cohorts are best modelled by different curves (cf. Supporting Information tables S16, S17, S18, S19). It appears that high density residential buildings are best fitted by a log-normal distribution, in the case of industrial buildings the normal distribution shows the lowest results variance and fits the data almost as well as the Gompertz distribution, while the Weibull distribution presents the most consistent results for the tertiary sector. These mixed results might be caused by intrinsically different behaviours of different building typologies when facing longer lifespans, but may also be due to the small numbers of buildings considered in the Salford case study compared to the Japanese studies. Further research in the field of long-lived buildings is necessary to unpack the relation between typology and modelling curve.

Compared to long-lived buildings, short-lived buildings showed greater lifespan estimation differences among different curves. Plotting demolitions per year on a frequency chart relative to a single building cohort, short-lived buildings show a very long right tail, which matches much better right-skewed distributions (log-normal, gamma, and Weibull). This skewness is much less accentuated in long-lived buildings, smoothing the overall differences between curves, thus making the choice of one distribution over another less significant.

Symmetric distributions showed the poorest fits of all the tested curves, and generally resulted in longer lifespan estimations. While these differences were small in the case of Salford – 80.6 years ±0.8% on average – in the case of short-lived buildings the differences are more pronounced: 18.7 years ±5.0% for the case of Nagoya, and 23.7 years ±9.1% for the case of Wakayama. In the latter case, the difference between the best fitting curve (log-normal) and the poorest one (normal distribution), was equal to 6 years, or 27% of the first account. This could lead to very poor estimations when researchers try to estimate future waste flows from the construction sector, therefore it is advisable to perform a fitting test of several distributions.

In our research, for the Japanese cases, we have been able to calculate lifespan for the past 50-60 years of a fairly wide area, while in the case of Salford we have been able to assess the past 160 years of a limited central area. It is important to remark that recent findings on the whole city of Zurich for the past 170 years by Aksözen and colleagues showed how the lifespan of buildings has decreased over time (Aksözen et al., 2016a), thus researchers interested in modelling long-term stock accumulation should not overlook this aspect.

From a purely mathematical point of view, because of the higher number of data points, the earlier cohorts are drawn more precisely than the latter. The 1960 cohort uses 7 data points to draw the best fitting curve, while the 1990 cohort uses only 4, the minimum amount that we can use to fit a curve[6]. In the case of functional differences between cohorts, modellers are thus advised to have greater confidence in earlier curves than later ones.

3.4.2 Top-down inflow driven stock accumulation and waste flow forecast model: sensitivity to uncertainties and different lifetime distributions through Monte-Carlo simulation

The top-down inflow driven model was proved to be a viable tool in estimating the total of accumulated construction materials present in a society. The five different distributions showed consistent and relatively close results relative to stock accumulation. They showed, however, very different results when accounting for demolition flows. If policy makers are to plan where to allocate this kind of waste, uncertainty of up to 50% in the sheer quantity of materials needing to be disposed of would lead to terrible outcomes – either greatly underestimating or overestimating total waste amounts.

The reason behind this very different impact of the selection of a specific lifetime distribution function on the stock accumulation and waste flows account is the buffer effect of

[6] All the distributions considered in this study are characterised by two parameters, and this means that it is necessary to have a minimum of two points to characterise their parameters. Yet, independently of their parameters, the curves generally start at the point (0,1), which means that a third point it is necessary. Finally, a fourth point is required to have an estimation of the fitting error.

lifespan. After the end of WWII most developed countries experienced rapidly increasing material inflows (Schaffartzik et al., 2014). These inflows are immediately recorded by the stock accumulation model, and, after an initial period with no depreciation, start to be slowly converted into demolition waste. Lifespan, acting as a buffer between inflows and outflows, delays the transformation of construction materials into waste by a number of years equal to its average. Thus, the outflow of demolition waste recorded today stems from the inflows which entered the system perhaps decades ago. A relative difference of 100 million tonnes between two different lifespan distributions, for instance, represents 0.1% of the US construction material stock in recent years, but almost 10% of the demolition waste.

The model proved to be mainly sensible to median uncertainties (±49%), followed by inflows uncertainties (±11%), and lastly by the standard deviation uncertainties (±3%). Considering the results, modellers should mainly focus on choosing a realistic average lifespan, without worrying too much about the chosen standard deviation. Inflows are inherently subject to account uncertainties, but even so the model responded pretty consistently, proving to be a suitable tool for macro analysis. Standard deviation plays a minor role in the stock accounting model, and any value between 0.75·median and 0.20·median would return realistic results. These results match the findings of Chen and Shi's research about aluminium stocks in China (Chen and Shi, 2012).

Since the model is mainly affected by lifespan (i.e. median parameter), this is where most efforts should be concentrated. Unfortunately, up to today a large-scale analysis on the lifespan of buildings is still missing, and we can only rely on a small set of case studies which have adopted very different accounting methods. A bottom-up approach, as done in the cases of Nagoya, Wakayama, and Salford, can give very reliable results, and even show how lifespan has evolved over time, but these studies are extremely time consuming in terms of data compilation, and require long computation time to be processed. In some cases researchers have been able to estimate national averages from data in statistical yearbooks (Cai et al., 2015), but only a few nations provide enough data to conduct this type of analysis. Some studies provide yearly demolition rates rather than lifespan (Bradley and Kohler, 2007; Deilmann et al., 2009; Lichtensteiger and Baccini, 2008; Petersdorff et al., 2006; Reyna and Chester, 2015; Thomsen and van der Flier, 2011; Wiedenhofer et al., 2015), but it is not possible to convert yearly demolition rates to an average lifespan without knowing the composition of each cohort, making it impossible to use this information with the top-down inflow driven stock accumulation model. More extensive and detailed research about lifespan is therefore advisable.

3.4.3 Estimating construction material stocks and related waste flows. Is there a best lifespan distribution?

We found that the log-normal distribution best fitted the cases of Nagoya and Wakayama, matching the theoretical assumption that buildings, when they have passed their peak of hazard, would last for quite a long time. Our results match recent findings on the analysis of lifespan for life cycle inventories (LCI) (Qin and Suh, 2016), showing an interesting correlation between findings in the field of material flow analysis (MFA) and LCI, which could be investigated in future research aiming to link material consumption to environmental impacts. While it might be tempting to immediately jump to the conclusion that the log-normal distribution should be standard, the case of Salford, best fitting a Gompertz distribution, proved that any external factor such as a natural disaster, a sudden economic crisis, or deliberate massive demolitions, invalidate the assumption, and other distribution functions may better fit the reality. Moreover, the lifespan distribution analysis performed in chapter 3.2.4 Case studies, investigating central areas of three dense cities, showed that in several cases other right skewed distributions performed very well. Further confirmation of our findings requires be supported by future studies assessing wider and more diverse areas (e.g. rural, peripheral, low density, etc.

From this research, we know that the normal distribution does not reflect the reality of building lifespans well, yet we still do not have sufficient data to determine if this distribution could well represent the total stock (building + infrastructure). We also know that the impact of choosing a certain lifetime distribution function on final stock accumulation numbers is negligible, thus researches on construction material stocks conducted by Fishman and colleagues or Vásquez and colleagues, which were performed applying a normal distribution, resulted in verisimilar accounts (Fishman et al., 2014; Vásquez et al., 2016). Had these studies been focused on waste flow accounts as well, their choice of distribution function would have distorted the final result considerably. This demonstrates that both the context of the analysis and the focus on results needs to be considered when choosing a specific lifetime distribution.

Tanikawa and Hashimoto (Tanikawa and Hashimoto, 2009) calculated the average lifespan of buildings for Wakayama and Salford, fitting the data to a logistic distribution, creating results that are on average 15% higher than those estimated by the best fitting distribution for both cities.

These are just some examples where, in light of this study, a more judicious choice of distribution could bring results more rooted in reality. This would allow them to be used by decision makers with greater confidence, e.g. for planning the disposal of demolition waste, a waste stream that will rapidly grow throughout the twenty-first century (Müller, 2006).

Nevertheless, modellers should be aware that, whereas the log-normal distribution seems to be the most realistic choice out of the five proposed, unpredictable events, such as earthquakes or civil wars, would completely invalidate this assumption. Furthermore, our results come from the analysis of buildings. In order to verify whether this evidence would hold true for infrastructure, future research should aim to assess the lifespan of infrastructure.

3.5 Conclusions

In this research, we investigated how different lifespan distributions and uncertainties affect the results of a top-down stock accumulation model. Using data from urban case studies we assessed how well different lifespan distributions match real world data. The results showed that the log-normal distribution, and in general right-skewed distributions, works the best for short-lived buildings, which are very typical of Asian cities. The case of Salford showed that its buildings are best matched by a Gompertz distribution, but also gave different results for different building typologies (cfr. SI 2.2), perhaps due to the small size of the study area, or due to the peculiarity of the economical evolution of the specific case study. The results match the theoretical assumption derived from analysis of the hazard rate that the “best individuals” of a single cohort will live much longer than the average.

We then tested how the lifespan model was affected by different distribution choices using national datasets for Japan and the United States and showed how uncertainties in exogenous variables affect results, comparing stock accumulation and demolition waste flow accounts. The results show that different distribution functions lead to very similar figures for stock accumulation, but very different demolition waste flows. Distribution functions that are right skewed, with the majority of demolition happening in the later stage of life, best represent the reality of built environment, indicating a slight preference for log-normal distribution for estimating accumulated stock in buildings.

Applying the most realistic curve becomes vital if researchers are to provide policy makers with robust estimations in order to proper allocate this type of waste. At the same time, modellers should keep in mind that venturing into long-term projection of waste production is a stretch as natural disasters and deliberate demolitions can completely invalidate projections.

Material inflow data have a intrinsic uncertainty, especially in the non-metallic minerals category (cfr. Fischer-Kowalski et al., 2011), and – with the exclusion of the metallic materials category – accounting discrepancies are very common even within the same database. Uncertainty in inflow parameters did not excessively affect the top-down stock accumulation model, proving its viability for macro scale analysis.

We showed that the top-down inflow driven stock accumulation model is mainly sensitive to the average lifespan, and almost insensitive to the choice of lifespan distribution function. This clearly suggests a direction for future research: calculating realistic lifespans for different typologies of buildings. While there is already solid proof that Asian cities have very short lifespans, in the order of 25 to 30 years, more research on European and American lifespan trends is still needed, and future research should aim to fill this knowledge gap.

Decision makers who are striving to move towards a material sound society should use the analysis of the mean lifespan over time as an indicator to assess and promote policies that encourage reuse, refurbishment, and adaptation of buildings over demolition and reconstruction. While this latter practice might have short-term benefits to the economy, it would, in the long run, deplete the natural environment of irreplaceable natural resources and increase the emissions of pollutants, resulting in a much worse scenario than a slow construction sector.

4 Modelling material flows and stocks of the road network in the United States 1905-2015

4.1 Introduction

Construction minerals, including cement, bitumen, as well as sand and gravel, represent by far the largest fraction of all materials that are annually extracted and accumulate in buildings and various infrastructures as in-use stock (Krausmann et al., 2017). For many nations, they make up 50% of their domestic material consumption and up to 90% of material stock (Heinz Schandl et al., 2017). Their extraction and processing, especially of cement for concrete, is an energy-intensive activity and as a result the embodied greenhouse gas emissions of this material flow category are also significant (Müller et al., 2013).

Despite the fact that non-metallic minerals, such as cement, bitumen, sand and gravel, are relatively benign environmentally, their sheer magnitude poses severe problems with local availability, transportation, land use change and landfilling of construction and demolition waste (Clark et al., 2006; Yoshida et al., 2016). To manage these materials and to improve recycling, it is essential to understand the magnitude of materials accumulated in buildings and transport infrastructure and to assess the dynamics of end-of-life flows to quantify the potential for recycling and for closing of loops (Haas et al., 2015; Wiedenhofer et al., 2015). Existing research has often focused on quantifying construction and demolition waste directly from on-site visits or via waste generation rates, while dynamic material flow approaches utilizing lifetimes have been much rarer (Wu et al., 2014). Recently methods were proposed to directly quantify in-use stocks accumulated within societies to allow to investigate the dynamics of material inputs and waste flows (see Augiseau and Barles, 2016 for a review). Assessing the recyclability of construction minerals waste (Pappu et al., 2007; Schiller et al., 2017), directly linked to in-use stock dynamics and input flows is hence an important step towards investigating the circular economy potential (Haas et al., 2015; Schiller et al., 2016).

Many studies on buildings stocks and flows are available (Augiseau and Barles, 2016), yet road networks tend to be understudied despite their quantitative relevance (Hashimoto et al., 2009, 2007, Kapur et al., 2009, 2008; Schiller et al., 2016; Wiedenhofer et al., 2015), and researchers advocate the importance of focussing on civil and infrastructure networks (Wu et al., 2014). Some studies explicitly discern the stock of buildings and infrastructure, but do not provide information about related material flows; others calculate both stocks and flows, but limit their analysis to specific materials (Shi et al., 2012), while others estimate total material stocks and waste flows, but do not differentiate between buildings and roads (Fishman et al., 2014). So far, material stocks and flows for roads and residential buildings combined have been investigated for the European Union (Wiedenhofer et al., 2015), and for the United States for several types of stocks, but only for cement (Kapur et al., 2008). The main reason why available models that calculate stocks and flows cannot be directly applied to road infrastructure is the different nature of transport infrastructure compared to buildings. While buildings get renovated for many different reasons, and are eventually demolished, cases of actual road removal are extremely rare, and in most cases roads are 'removed' simply by impeding vehicle access through gates or barriers (Switalski et al., 2004).

Buildings and roads are also very different with regard to where investment and operational spending comes from and in terms of ownership. Roads are usually common property, require public investment for building and maintenance and fall under different legislative control, depending on the type of road. They only generate an income if they are toll roads and operating models that include private ownership are the exception.

Roads also pose a difficulty for material flow accounting research because establishing the amount of materials required for the construction of roads and their maintenance is far from simple. Most studies so far adopt rule-of-thumb accounting strategies based on a limited number of factors and often without specifically referring to changing technical construction standards over time; additionally differences in road types and the specifics of road construction and renewal need to be taken into account. This study aims to improve the knowledge base about the material requirements of roads, the magnitude of material accumulated in roads and waste flows from road refurbishment, specifically parametrized for the United States.

In this study, we design a stock-driven model that considers the specificities of different road types and the historical changes of technical construction standards. We establish a bottom-up methodology to estimate physical stocks of roads, and derive the related material requirements for road construction and maintenance using best practice engineering knowledge and physical data about the extent of road networks. This methodology permits us to estimate the material composition of the road network over time, the quantity of materials needed for expansion and maintenance and evolution in the ratio of the two. From this, we can estimate the potential of road construction to absorb road maintenance waste as well as building construction and demolition waste.

We apply this methodology to the United States of America, the country with the greatest extent of road network in the world (Central Intelligence Agency, 2013), for the years 1905–2015, to understand the material requirements to maintain in service what is by far the most common mean of transport in the United States (U.S. Department of Transportation, 2015a). For this purpose, we distinguish fourteen different road types and changes of technical construction standards over time. We intend to address the following questions: what is the size and composition of material stock of the US road network? What is the yearly requirement for virgin materials? What amounts of materials are recycled within the system? What is the yearly amount of waste flowing from road renewal? We relate the findings on material accumulation in roads to population, gross domestic product (GDP), and numbers of vehicles in circulation to gain a better understanding of the relationship between provisioning transport and mobility and the material underpinnings.

4.2 Methodology

4.2.1 Conceptual approach

While standard material flow accounts provide data on annual extraction and overall consumption of materials, they commonly do not include information about the specific uses of materials in different economic activities (Fischer-Kowalski et al., 2011; UNEP, 2015). In order to determine which fraction of the national yearly consumption of non-metallic minerals in the United States has been required to establish and maintain the road network we needed to develop an analytical approach which combines information about the evolution of the extent of the road network, of different road surfacing technologies, and of the material characteristics of these road types, to establish the overall inflows, accumulated material stocks, and outflows. This approach is operationalised in a model which is a bottom-up technology-based stock and flow representation of the material requirements of roads. The conceptual framework is schematised in Figure 15.

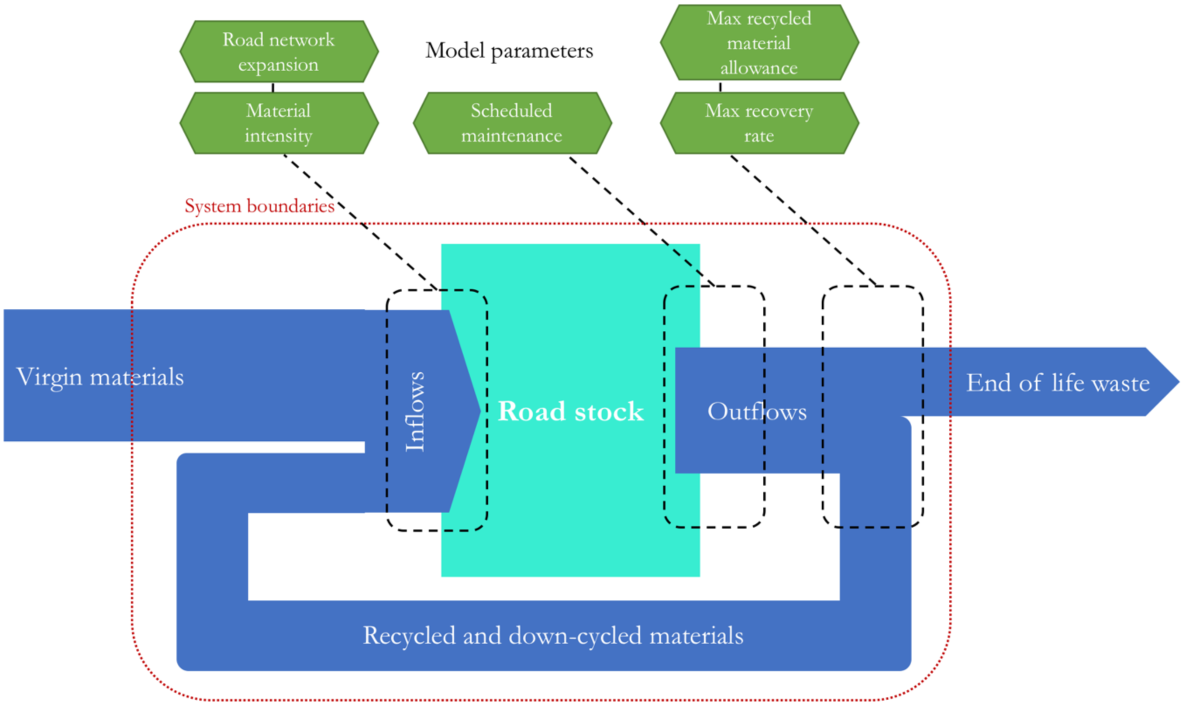

Figure 15 – Conceptual figure of the road material stocks and flows model.

4.2.2 Model

The model aims to calculate the material inflows, stock, and outflows of road networks, tracking the quantity of recycled asphalt and aggregate that is reused to make a new layer of tarmac, and the amount of scrape materials that can be recovered from the wearing layer and used in sublayers of new roads. The main parameter that feeds the model is the annual extension of the road network by road surface type. Four further variables allow calculation of total material inflows, stocks, and outflows of the road network: the maximum percentage of material removed during roadwork that can potentially be retrieved (maximum yearly recovery rate); the maximum percentage of recycled materials that are legally allowed to be used for repaving the wearing layer of a road (maximum yearly allowed recyclable content); scheduled maintenance intervals which vary according to road classification (the maintenance interval); and material intensity per unit length of road (material intensity). The model outputs are: yearly virgin material inflow, yearly recycled and down-cycled[7] material flow, total stock, and end-of-life waste.

[7] By recycled flows we mean those materials which are removed during scheduled maintenance from road wearing layers and are reused in the same layer. With down-cycled flows, we refer to those materials which are collected from wearing layer rubble, and are used in sublayers in the construction/improvement of roads.

A conceptual flowchart of the model is depicted in Figure 16. Different shapes have different meanings: parallelograms indicate data inputs and outputs; ovals indicate model variables; rectangles indicate internal operations; and hexagons indicate internal datasets. To keep this manuscript lean, we will limit the description of the model to its visual conceptualisation. Interested readers can find a detailed explanation in the Supporting Information §1.

Note that the model will calculate outflows coming only from the wearing layer and not count any outflows coming from sublayers. This is because, in most cases, when a road is 'removed' and disappears from statistics, it often means that it has been closed to traffic rather than being physically removed. Thereby these no longer used roads are obsolete or hibernating stocks (Hashimoto et al., 2007). Only in very rare cases, mostly in protected areas, have a few kilometres of roads actually been removed (Switalski et al., 2004).

Figure 16 – Flowchart of the model. Note that different shapes indicate different functions: parallelograms for inputs/outputs, ovals for variables, rectangles for operations, and hexagons for internal data.

4.2.2.1 *Road material intensity*

Our model simulates the road network in the United States from 1905 to 2015, and uses seven different road types: non-surfaced pavement, surfaced non-paved pavement, low-type pavement, intermediate-type pavement, flexible high-type pavement, rigid high-type pavement, and composite high-type pavement. These types make up the whole road network in the history of the United States road transport system.

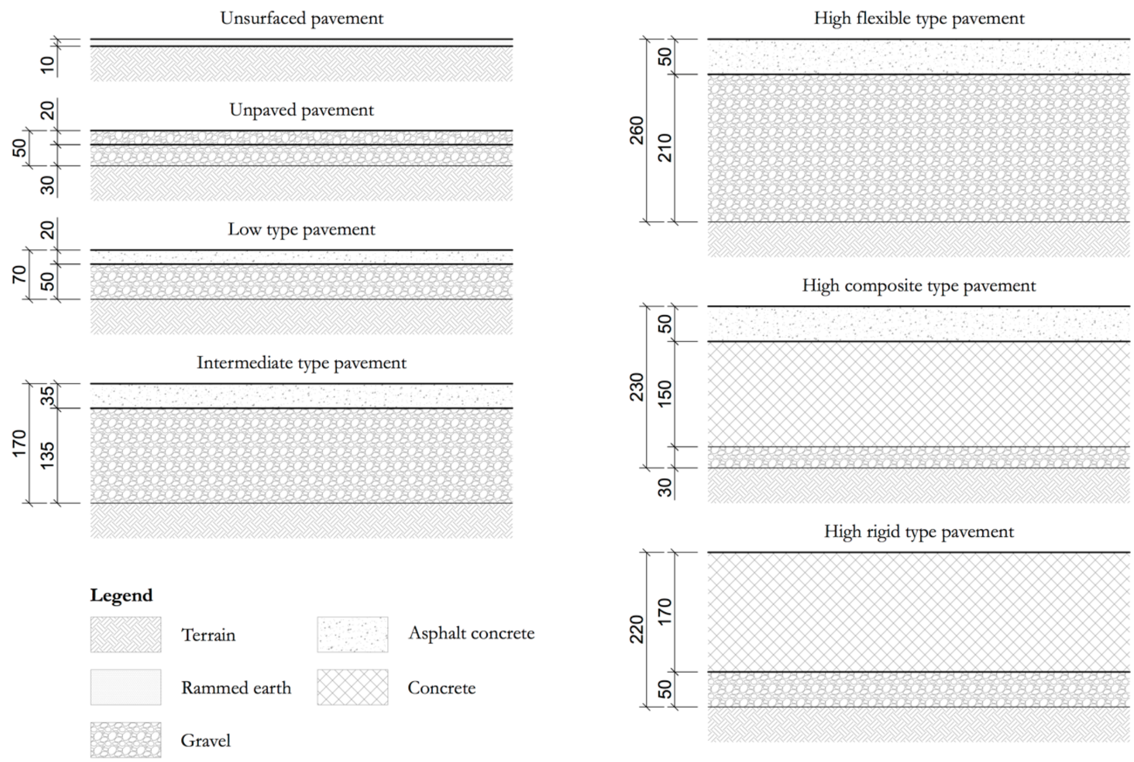

Figure 17 – Cross section of pavement typologies. The measurements represent the height of each layer, and are expressed in millimetres.

A visual representation of the cross section of these seven pavement types is displayed in Figure 17. Thickness of layers have been derived from the detailed descriptions available in the Highway Statistic Summaries (U.S. Department of Transportation, Various years). Note that the bold lines present in each pavement in Figure 17 denote the limit between the wearing layer and, where present, a sublayer. A more detailed description of the different pavement types can be found in the SI §2.

4.2.3 Dataset

The dataset used for this study is sourced from the US Department of Transportation and covers the period from 1905 to 2015. The first report on the extent and type of roads was compiled by the US Office of Public Roads in 1904, separating roads into surfaced and non-surfaced. The report was updated in 1909 and 1914, and is available on a yearly basis from 1921 to 1979. A more detailed classification of road surface types has been available since 1941, and the classification system remained mostly unchanged until 2008. Roads were initially divided into: unpaved, low and intermediate types, high flexible and composite types, and a high rigid type. They were further categorised into rural and urban roads. Since 1996 the previous categories have been further disaggregated into: unpaved, low type, intermediate type, high flexible type, high composite type, and a high rigid type. The years 2009 and 2010 are not reported in the statistics, while from 2011 to 2015 the reports categorised urban and rural roads into the following four surface types: unpaved, bituminous surfaced, composite surfaced, and concrete surfaced (U.S. Department of Transportation, Various years). A detailed description of the material intensities of different surface types can be found in section §2.1 of the Supporting Information.

The data compilation method employed by the Department of Transportation changed over time: in the early years, roads were estimated at the national level through a survey. Following the 1916 Federal Aid Road Act, each State was required to have a highway department to take charge of monitoring, administering, and maintaining its road network. From 1921 onwards, it has been possible to receive more precise data on the extent and condition of roads for all US States. From 1980, the Federal Highway Administration (FHWA) started accounting only for 'public roads' as defined by the 23 USC 402, resulting in a slight 'artificial' decrease in the total length of the road network (about 1.5% of roads were excluded). Continuous changes in accounting methodology over time have allowed for a progressive increase in the accuracy of the data and, despite being somewhat difficult to harmonise, our overall assessment is that the whole time-series is very well suited for the purpose of this study.

Given the composition of the available data, we decided to disaggregate the total road infrastructure into fourteen categories: seven types of road surfaces (non-surfaced pavement, surfaced non-paved pavement, low-type pavement, intermediate-type pavement, flexible high-type pavement, rigid high-type pavement, and composite high-type pavement), and two functional types (urban and rural roads). For the missing years, such as between 1904 and 1909, we linearly interpolated the missing values, while for those years where categories were grouped (e.g. low- and intermediate-type pavement) we applied shares of types from neighbouring years.

4.2.4 Sensitivity analysis

While the available data and literature provides a large amount of information and confidence in the parameters that have been used in our model, we decided to verify the accuracy of our results by conducting a sensitivity analysis. We tested which model parameters would have the strongest effect on the overall results, and to which extent. By altering each parameter individually, we determine the overall effects of those changes on the model.

Out of all the parameters in the model, the only one that affects the account of the stock is the material intensity of roads. Using a bottom-up model, all it requires to calculate the stock is an object inventory (in our case the length of roads), and a parameter that acts as the density of these objects (in our case the material intensity of roads per unit of length).

The remaining three parameters of the model (maintenance interval, max yearly allowed recyclable content, and max yearly recovery rate) will affect only the inflows and outflows of materials, but are expected to have no effect on overall stock.

4.2.5 Limitations of the approach

The model relies on official statistical information for the total extent of the road network, and on engineering knowledge on best practices in construction and maintenance to infer the overall material requirements of this fundamental infrastructure. In simulating the evolution of the material consumption over the past 110 years, we had to use the following assumptions:

The model categorises 14 types of roads (7 types of pavements divided into urban and rural), and for each type of road assumes cyclical renovation at a certain interval. While we apply different periodic maintenance, it must be assumed that in reality shorter or longer lifespans occur, or that these intervals change over time. Furthermore, economic conditions, weather patterns, calamities, or unpredicted alterations in local traffic can shorten or increase the maintenance intervals. This means that the chosen maintenance schedules bear a level of error for which we can't control.

The total height and width of the road types have been calculated according to technology assumptions and road types, and are based on information provided in official statistics (see SI §2 for a detailed description of this). It is impossible, however, to determine the exact thickness of each road since this greatly depends on traffic and soil composition, which can only be estimated through on-site surveys. Other parameters that affect design requirements of roads are specific weather patterns (e.g. seasonal heavy rains) and the gradient of the terrain. This creates additional uncertainty for the overall results.

It is also difficult to judge the accuracy of the historical road length data found in the statistics. While we can assume that in recent years, with the progress of technologies for surveying and mapping, the dataset should be very precise, the same cannot be assumed for older statistics.

Roads are recorded in official statistics once they are open for transit, and not during their progressive construction. Relying on reported statistics for the model means a road that took 5 years to be completed will be recorded in the year of completion and not progressively during its construction. That may create certain shifts in material requirements between years but will not affect the overall amount.

The model reports the inflows of 'virgin' materials required for the construction and maintenance of new roads. We need to point out that often roads are used to accommodate large amounts of building demolition waste. While this practice is formally a way of down-cycling, in this research we calculate down-cycled materials that stem from the wearing layer of roads and are moved to sublayers. It is hard to judge how much material recycling of building construction waste has occurred historically in the United States. Supporting structures for roads such as bridges and tunnels, for instance, also require large amounts of construction materials which are excluded from this analysis.

Despite these limitations, we trust that this account is the most detailed and robust analysis of material flows in the road sector available to date.

4.3 Results

4.3.1 Material stock

This study quantifies material stocks and flows for constructing and maintaining the road network of the United States of America from 1905 to 2015. The model discerns the five materials that are the main constituents of roads: rammed earth, gravel, sand, cement, and bitumen.

The material stock of the United States road network is plotted in Figure 18. The two decades from 1905 to 1925 saw a rapid extension of the road network from 3.8 million to 5.2 million kilometres, which was followed by a long period of incremental growth, including the upgrading of existing roads. The material stock in roads in 1905 was 0.7 billion tonnes and the quantity of materials stocked in each kilometre of road was 180 tonnes. The last century saw material stocks in roads growing rapidly at a compound annual growth rate of 2.8%, reaching 15.1 billion tonnes in 2015. At that time, the total extent of roads was about 6.6 million km, with in an average material content of 2,268 tonnes per km, i.e. more than ten times the level in 1905.

Gravel used in road base dominates material accumulation in roads and the share of materials has shifted somewhat over time. In 1905, the most used material was gravel (65%), followed by rammed earth (16%), and sand (14%). Over time roads increased their average depth to carry more traffic and heavier vehicles. The share of gravel rose to 92%, followed by sand (6%), and cement (2%). Bitumen, which is used as a top layer, never accounted for more than 1% of total stock since asphalt concrete is composed of 95% gravel and only a small share of bitumen (excluding air and other minor components). With bitumen density much lower than gravel, this explains the very low share of this material in the overall stock.

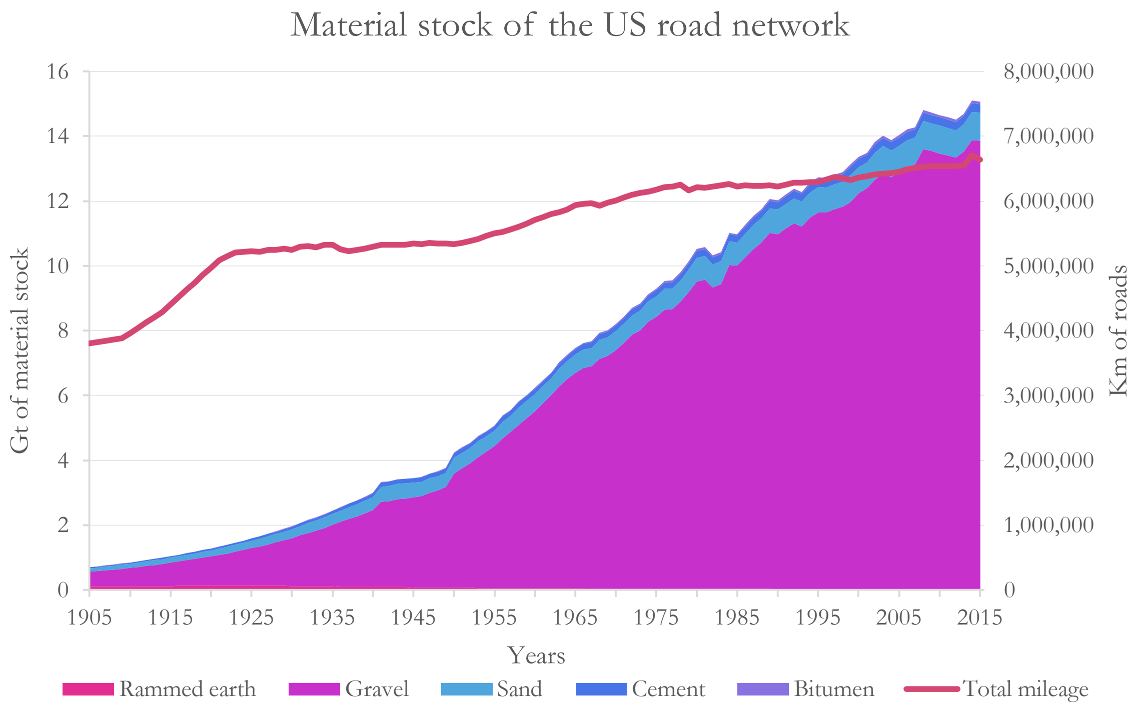

Figure 18 – Material stock of the US road network, years 1905–2015. The left ordinate axis plots the material content in gigatonnes (1 Gt = 10^{15} g = 1 Pg), while the right ordinate axis plots the total length of roads in km.

4.3.2 Material flows

4.3.2.1 Material inflows

We account for the yearly quantities of materials that are required for building and maintaining the road network, i.e. all materials coming from any source other than scraping from existing roads, with no distinction between materials coming from quarrying (properly labelled as virgin materials) and demolition rubble (formally down-cycled materials). We are labelling them as virgin materials, in the sense that they come from outside of our system boundaries (cf. Figure 15).

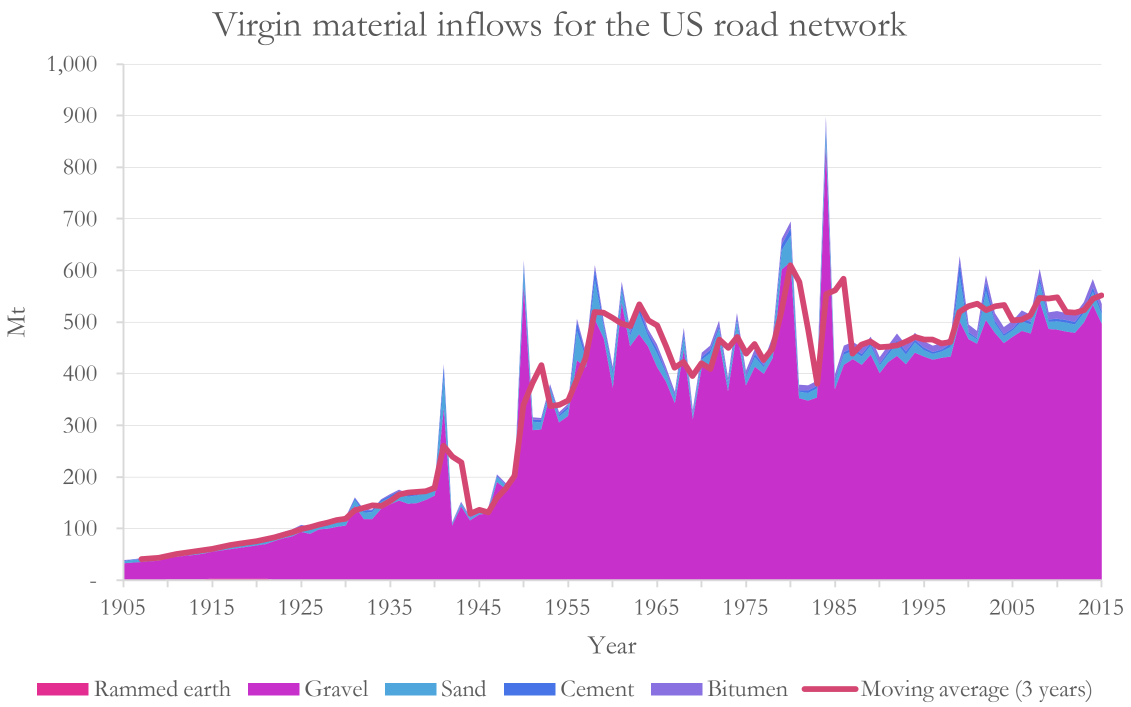

Figure 19 – Virgin material inflows for constructing and maintaining the US road network. The units are megatonnes (1 Mt = 10^{12} g = 1 Tg = 1 million of tonnes).

Figure 19 shows that in 1905 the yearly material requirements for roads were 38.6 million tonnes of mainly gravel (83%), sand (12%), and cement (3%). The yearly inflows progressively grew to 535.4 million tonnes in 2015, composed mainly of gravel (93%), sand (3%) and bitumen (3%). While the absolute peak of material requirements for roads was recorded in 1984 with 898.8 million tonnes, it appears that the inflows grew in a roughly linear fashion, at a compound annual growth rate of 2.4%. The peaks of 1980 and 1984 were caused by two large reported increases in flexible paved roads over a steep decrease of unsurfaced and unpaved roads (cf. Figure SI 10), hinting that during those years the US Department of Transportation was investing heavily in improving rather than expanding the existing road network. As reported in the Summary for 1985 'Although changes in total mileage are small, there have been many changes in the quality of highways, such as surfacing roads, widening existing pavements, reducing grades, minimising curves, eliminating railroad grade crossings, and other improvements to provide safer, more efficient use' (U.S. Department of Transportation, 1985). An additional reason is that the model is coded to notice new construction once this has been reported in the official statistics, and accounts for all inflows required for construction in that same year. In reality, the actual construction process might have lasted for a number of years, which creates distortion in yearly inflows, especially for very large projects. To moderate the potential error, Figure 19 displays a 3-year moving average that levels peaks and troughs. Using the 3-year moving average, the highest peak appears in 1980, when around 610 million tonnes of materials were required.

4.3.2.2 Recycled and down-cycled material flows

The large material requirements for road construction and maintenance come from two sources, as explained above, and they are hard to distinguish in the absence of reliable data.

Materials collected during the maintenance of the wearing (upper) layer of roads are often reused in the newly renovated layer but the share of reused material is determined by technical constraints. Less restricted is the use of recovered materials from the wearing layers for beddings (sublayers) of newly constructed roads. The model accommodates these different types of reuse by dynamically changing the shares of usage of these materials.

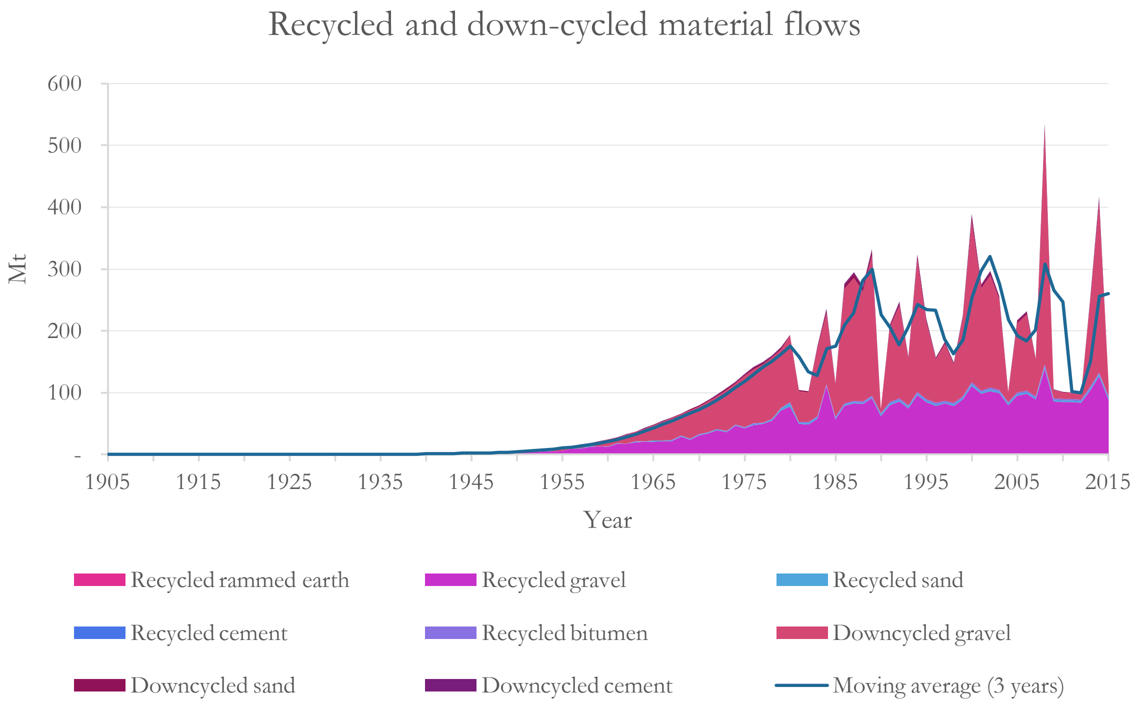

Figure 20 – Recycled and down-cycled flows differentiating construction materials into eight different categories, from year 1905 to 2015. The units are megatonnes (1 Mt = 10^{12} g = 1 Tg = 1 million of tonnes).

Flows of recycled and down-cycled materials are displayed in Figure 20. These flows were practically irrelevant in the early 20th century (0.007 Mt in 1905), and start being noticeable around 1955, when flows reached 11.9 million tonnes of which 6.5 million tonnes were recycled into new top layers of roads and 5.3 million tonnes were down-cycled. In 2015, the total flows were 111.2 million tonnes but, as is clear from the chart, the down-cycled component has been very erratic since 1980. This reflects the fact that in more recent years there has been hardly any construction of new roads but merely a focus on road upgrading, extension and refurbishment, hence the model does not allocate any down-cycled materials for some years. For this reason, we believe that the moving average, showing a flow of 259.8 million tonnes for 2015, is a more realistic value than the actual modelled data. A figure showing the share of recycled and down-cycled materials from roads, as well as the share of material inflows for other sources (virgin and construction demolition), is available in the SI §4.

4.3.2.3 End-of-life outflows

Those materials which are demolished from the wearing layer, and are not reallocated in renovated pavement (recycled flows) or new road beddings (down-cycled flows), are considered as waste heading for waste disposal (cf. Figure 15).

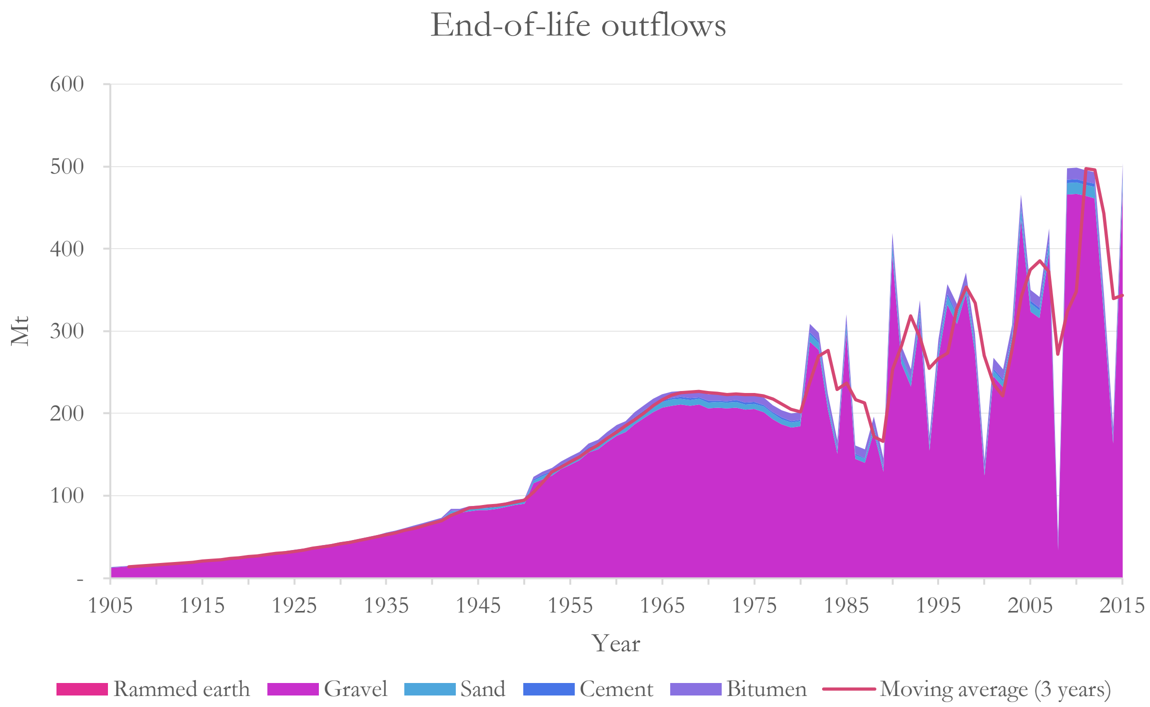

Figure 21 – End-of-life outflows for five building materials, from 1905 to 2015. The units are megatonnes (1 Mt = 10^{12} g = 1 Tg = 1 million of tonnes).

The waste flows are shown in Figure 21. In 1905, the end-of-life (EoL) flows were 13.3 million tonnes, which then grew steadily until 1967 reaching 227.2 million tonnes. Since then the yearly EoL flows have fluctuated, peaking at 504.4 million tonnes in 2015, but also showing values as low as 48.3 Mt in 2008 caused by the nature of the statistical reporting and the model's behaviour. The moving average, on the other hand, shows an overall increasing trend in waste flows, peaking at 497.4 million tonnes in 2011.

4.3.3 Socio-economic indicators

In this section, we present how the road network has evolved over time in comparison to the growth of its material stock, population, and number of vehicles using the road network.

The number of registered vehicles was 78,800 in 1905, and grew massively to 263,610,219 for the year 2015, at a compound annual growth rate of 7.7%, much faster than the road network itself or the material accumulated in roads.

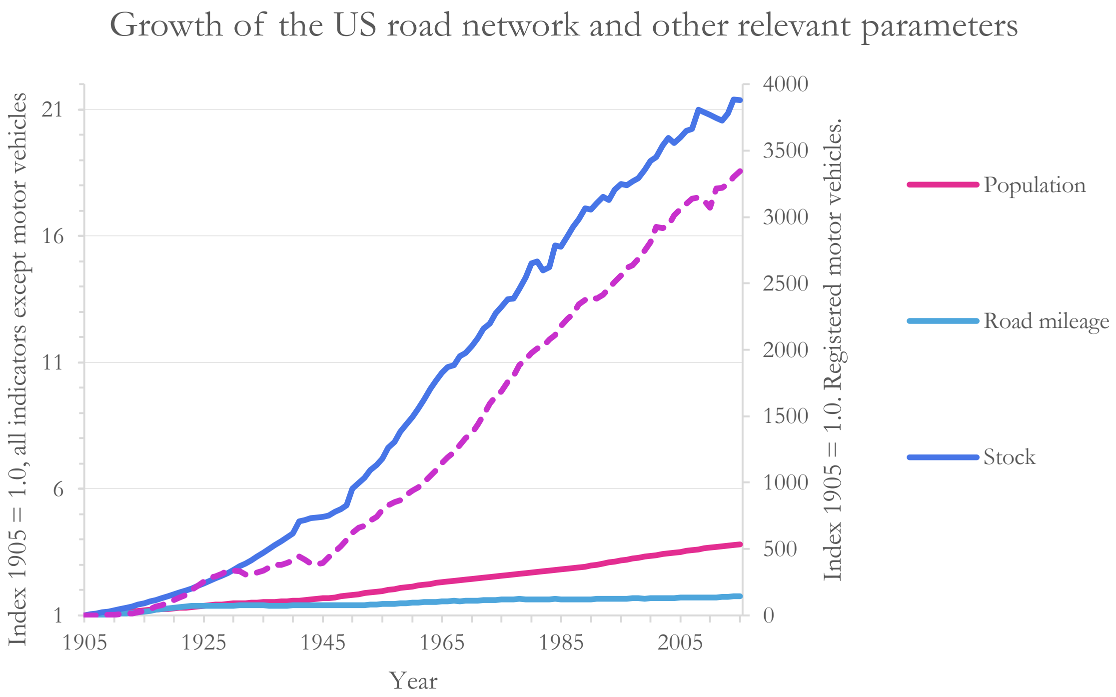

Figure 22 – Indicators of population, road mileage, material stock, and number of registered motor vehicle. Indexed as 1905 = 1. Note that the number of registered motor vehicles is indexed on the right vertical axis, while all the other parameters are plotted on the left axis.

Figure 22 shows growth in population, road mileage, road stock, and registered vehicles in the United States (indexed to 1905 = 1). The overall road network grew slowest at 0.5% per year on average pointing to a much higher utilisation of roads today than in the past. Population in the United States was 84 million in 1905 and grew to 321 million in 2015, a factor of 3.8 with a compound yearly growth rate of 1.2%. The material stock of roads, as already mentioned in 4.3.1, was 0.7 Gt in 1905, and 15.1 Gt in 2015, increasing over 21-fold, at a rate of 2.8% per year. The parameter which grew the most was the number of registered vehicles. It was 78,800 in 1905 (about 1 vehicle per 1000 persons), and soared to 263,610,219 for the year 2015 (about 820 vehicles per 1000 persons), growing 3345.3 times in 110 years, with a compound annual growth rate of 7.7% (note that in Figure 22 this is plotted on the right axis, while material stock is plotted on the left axis). The rapid growth of circulating motor vehicles required existing roads to be overhauled and improved to sustain increasing loads and travel speed, but this also posed new issues such as traffic management and increased congestion (Owen, 1958).

4.3.4 Sensitivity analysis results

The model's sensitivity has been tested as described in 4.2.4. The account of the stock is linearly affected by alterations in the material intensity parameters. This is because, continuing the analogy described in 4.2.4, if we interpret road length as a volume, and material intensity as a density, the total weight is calculated as volume per unit of density. The results of this test are shown in Table 8. The overall stock in 2015 accounted for 15.1 Gt. An alteration of ±1 m to the width of roads generated a difference of ±1.7 Gt (from 13.4 Gt to 16.8 Gt), while a change in the layer thickness of ±30% showed a change of ±4.5 Gt (from 10.5 Gt to 19.6 Gt). While these differences might seem relevant at a first glance, the Highway Statistics give ranges of thickness that strengthen confidence in the values we adopted.

Table 8 – Sensitivity analysis of stock, virgin inflows, and waste outflows for the parameter 'material intensity'.

	Default parameters		Road width ±1m		Material intensity ±30%		Combined (extreme cases)	
Stock	1905	0.7 Gt	1905	0.6 Gt 0.8 Gt	1905	0.5 Gt 0.9 Gt	1905	0.4 Gt 1.1 Gt
	2015	15.1 Gt	2015	13.4 Gt 16.8 Gt	2015	10.5 Gt 19.6 Gt	2015	9.4 Gt 21.8 Gt
Virgin inflows	1905	38.6 Mt	1905	34.1 Mt 43.2 Mt	1905	27 Mt 50.2 Mt	1905	23.9 Mt 56.1 Mt
	2015	535.4 Mt	2015	485.7 Mt 585.2 Mt	2015	374.8 Mt 696.1 Mt	2015	340 Mt 760.7 Mt
Waste outflows	1905	13.3 Mt	1905	11.9 Mt 14.7 Mt	1905	9.3 Mt 17.3 Mt	1905	8.3 Mt 19.1 Mt
	2015	504.4 Mt	2015	457.7 Mt 551 Mt	2015	353.1 Mt 655.7 Mt	2015	320.4 Mt 716.3 Mt

Changes in the remaining three model parameters (maintenance interval, max yearly recovery rate, and max yearly allowed recyclable content) have no effect on the calculation of the total stock, but change the results for inflows and outflows. The results are displayed in Table 9. The maintenance interval is the only parameter which has immediate effect from the beginning, being due to the other parameters being modelled not to kick in until after World War II, and is the parameter that has the overall highest effect on flows. In the extreme case of all the parameters contributing to reduce/increase overall inflows and outflows, the results show a difference of –29.5% +55.8% of inflows, and –31.2% +59.2% of outflows.

Table 9 – Sensitivity analysis for virgin inflows and waste outflows the parameters maintenance interval, max yearly recovery rate, and max yearly allowed recyclable content.

	Default parameters		Maintenance interval ±30%		Recovery rate median ±20 y		Recyclable content ±10%		Combined (extreme cases)	
Virgin inflows	1905	38.6 Mt	1905	35.6 Mt 44.3 Mt	1905	38.6 Mt 38.6 Mt	1905	38.6 Mt 38.6 Mt	1905	35.6 Mt 44.3 Mt
	2015	535.4 Mt	2015	414.5 Mt 760 Mt	2015	535.4 Mt 535.4 Mt	2015	488.4 Mt 582.5 Mt	2015	377.2 Mt 834.2 Mt
Waste outflows	1905	13.3 Mt	1905	10.2 Mt 19 Mt	1905	13.3 Mt 13.3 Mt	1905	13.3 Mt 13.3 Mt	1905	10.2 Mt 19 Mt
	2015	504.4 Mt	2015	383.5 Mt 728.9 Mt	2015	504.4 Mt 504.4 Mt	2015	457.3 Mt 551.5 Mt	2015	346.1 Mt 803.1 Mt

A more detailed report on the results of the sensitivity analysis, including charts, can be found in the SI §1.6.

4.4 Discussion

4.4.1 Of all the materials yearly consumed and stocked in the US, what proportion goes into road construction and maintenance?

In the absence of other studies that explicitly calculate material stock for the road construction sector of the United States we can refer to other research estimating the share of materials used for roads compared to the overall use of construction materials. In a recent study, Fishman et al. (2014) calculated the stock of construction materials in the United States as 11.8 billion tonnes in 1930 and 107.5 billion tonnes in 2005. Compared to our own calculation, which estimated 2 billion tonnes and 14 billion tonnes of accumulated material in roads for the same period, it appears that the share of materials stocked in roads decreased over time, from 17% to 13% of overall building material accumulated in stocks. While not accounting specifically for the road stock, Kapur et al. (2008) analysed the stocks and flows of cement in the United States from 1900 to 2000. Their research accounted for 3.9 billion tonnes of cement stocked in the country for the year 2000 across all economic sectors. We estimated an in-use cement stock of 0.3 billion tonnes of cement in roads for the same year, accounting for 8% of total stock.

No further studies have calculated the material stock of construction minerals in the US, but numerous studies have calculated national economy-wide material flows. Gierlinger and Krausmann (2012), covering a period from 1870 to 2005, estimated an apparent consumption of 104 million tonnes of non-metallic minerals in 1905, and 3,578 million tonnes in 2005. Our research accounted for an inflow of 38.6 million tonnes in 1905 and 502.5 million tonnes in 2005, showing a decreasing importance of construction materials for roads, from 37% to 14%. A global study on the apparent consumption of non-metallic minerals from 1970 to 2010 (Miatto et al., 2016) recorded a domestic material consumption for the United States of 1,760 million tonnes for 1970 and 2,654 million tonnes for 2005. Compared to this study, this reflects inflows of 441 million tonnes and 503 million tonnes for the respective years, showing shares of 25% and 19%. A third available dataset reported the apparent consumption of non-metallic minerals in the USA as 1,493 Mt and 3,683 Mt for the years 1970 and 2005 respectively (Heinz Schandl et al., 2017). Compared to our findings, the share that is used for streets and highways is 30% and of 14% respectively. Similar shares of road related material use in economy-wide material consumption have been reported for the EU25 (Wiedenhofer et al., 2015)

It appears that, despite having some variability, all studies accord in pointing out that while total material inflows into the road network are increasing, these flows constitute a decreasing share of the economy-wide domestic material consumption in the United States. This is likely due to a priority on improving and upgrading the quality and safety of existing roads, over an increase in the overall network coverage over the past 40 years (cf. Figure 18) (U.S. Department of Transportation, Various years). This trend might be also explained by the stark decrease of road length per capita (46 m/person in 1905 to 21 m/person), paired with the increased urban population (United Nations, Department of Economic and Social Affairs, Population Division, 2015) and decrease of average household size (U.S. Census Bureau, 2016). While this can be interpreted as a positive thing for the environment, in the sense that roads require a decreasing share of materials, our findings also show that absolute demand does not show signs of decrease.

4.4.2 For how much longer can roads be used to down-cycle demolition rubble?

In many countries, roads have been used as a convenient place to down-cycle construction demolition waste. The slow pace at which new roads were constructed in the United States during the second half of the twentieth century still proved to be sufficient to absorb a good part of the construction and demolition rubble that was produced during those years (U.S. Environmental Protection Agency, 1998). Yet, recent research points out that the twenty-first century will be characterised by unprecedented flows of demolition waste from ageing building stock built in the post-war era (Müller, 2006).

A recent report by the US Environmental Protection Agency calculated that in the years 2012 to 2014 an average of 160.4 million tonnes of C&D were produced from demolished buildings, of which 81.4 million tonnes (51%) were concrete (U.S. Environmental Protection Agency, 2016). For the same years, our model shows an average requirement of 145.4 million tonnes of materials to construct the sublayers of new and upgraded roads. Considering that construction demolition waste in the United States is forecast to double every 16 years (Miatto et al., 2017) the absorptive capacity of road construction and maintenance for this waste flow will reach its limits. Our model shows a slowly decreasing overall trend in the requirement for new road bedding since the 1950s. At an average requirement of around 150 billion tonnes per year we estimate that by 2033 the waste absorption potential of roads for construction and demolition waste will lie below waste disposal. This number is purely theoretical, and does not take into account the locations at which the construction demolition waste occurs and where it could be used. It is important to note that shipping rubble can quickly become uneconomical, making local quarrying a more viable choice (Robinson Jr and Brown, 2002).

4.4.3 Changing technological construction standards for roads in the United States

Contrary to what might be commonly assumed, the total length of the road network in the United States did not even double over the last 110 years (cf. Figure 18), and was not linked to the spread and surge of the popularity of motor vehicles (cf. Figure 22). Yet, despite not changing significantly in terms of extent, paving technology has seen a dramatic technological leap: in face of a 1.75-fold extension in the network, the amount of non-metallic minerals that has become part of the road network has increased 21-fold (cf. Figure 22). The average material intensity of roads shifted from 180 t/km in 1905 to 2,268 t/km in 2015.

This huge change of material intensity has been triggered by the incredibly rapid diffusion of motor vehicles at the start of the twentieth century, increasing haulage and travel speed to a point that was not contemplated by contemporaries (Lay and Vance, 1992). At the start of 1900 the majority of roads were simple ways cleared of obstacles to allow the passage of horses and caravans, and they soon proved unsuitable for sustaining the mechanical stress induced by the much faster and heavier new motor vehicles. Engineers had to face the challenge of renovating existing road infrastructure to make it suitable for the new requirements. The answer was an increase in depth of road beds to better distribute and absorb heavy loads, a rapid diffusion of bitumen concrete to stabilise sublayers to allow high speed travel, and the improvement of roads to reduce steep grades and increase curve radiuses (Steinberg, 1926). This is evident when looking at the change in the share of pavement types (cf. Figure SI 9 and Figure

SI 10) over time. In 1905, unsurfaced roads made up 91% of the total road network. By the end of WWII unsurfaced roads were less than 50%, and by 2015 only 6% of the whole mileage.

The United States, similar to other countries, has experienced a co-evolution of vehicle technology and road engineering requirements. This has especially been the case for heavy vehicles for freight transport, which have increasingly replaced other means of transport such as shipping and rail (U.S. Department of Transportation, 2015b). Further increases in transport volume and vehicle tonnage may require further technical upgrades of roads in a context where the cost, both financial and material, for roads has been dominated by maintenance rather than for new roads (cf. Figure SI 12 and U.S. Department of Transportation, Various years). Using this model and the data collected, these issues could be explored further.

4.5 Conclusions

Roads provide an invaluable service to modern societies: they allow people and goods to move quickly and efficiently, while at the same time offering a useful way to dispose of construction demolition waste originating from the building sector. Until today a detailed longitudinal report of the material requirements, waste production, and absorption potential of this important in-use stock, as well as an estimation of its share of the total yearly consumption of construction minerals, was not available for the United States.

This research has introduced a novel methodology to investigate the material stocks and flows of road networks. The material stock has been calculated through a bottom-up approach, and the flows have been derived using a series of technical parameters that estimate materials required to extend and maintain the network. These technical parameters were sourced from national specific construction standards. The results show that the United States road stock increased 21-fold over 110 years, growing from 0.7 billion tonnes in 1905 to 15.1 billion tonnes in 2015. This massive growth of in-use materials has not only been driven by the extent of roads, but rather more by technical improvements including greater road base depth and better surfacing. This is reflected in a 13-fold increase in the construction materials intensity of road construction, which was on average across 14 different road types, 180 t/km in 1905 and 2,268 t/km in 2015.

With regard to material flows, we estimate that, by 2015, 615 million tonnes of non-metallic minerals were used every year to maintain existing roads in operation, which amounts to approximately 15 to 20% of the economy-wide domestic consumption of non-metallic minerals in the United States. Of these, about 520 million tonnes were sourced from quarries or construction demolition. An additional 115 million tonnes are consumed every year, on average, to build new roads or upgrade existing ones. At the same time, we estimate that the average yearly amount of materials being treated as road waste had reached 350 million tonnes in 2015.

The sheer values that characterise the twenty-first century are very different from the early twentieth century. 17 million tonnes of materials, practically all coming from virgin natural resources, were necessary to maintain the network. On average, but with a clear growing trend over time, 33 million tonnes of materials were required yearly to grow and improve the road network, while end-of-life flows accounted for 17 million tonnes of waste, reflecting the very low recycling potential at that time. The majority of the material requirements shifted from new construction and upgrades to maintenance.

While we are now, for the first time, able to sense the scale of material flows and stocks of road networks in relation to the consumption of the whole United States economy, a series of unresolved questions arise. Firstly, the dynamics of the building stock are an important factor for the quantities of down-cycled materials that end up in road construction. This information would enable more directly linking economy-wide material consumption to their specific uses and in-use stocks. Secondly, the potential for greater circularity of materials in the economy could be further explored if different in-use stock dynamics would be investigated jointly, to infer potentials towards closing regional material loops also between different stock types (Schiller 2016, 2017, Wiedenhofer et al. 2015, Tanikawa et al. 2015). Furthermore, it would have been be interesting to also include the current energy requirements to maintain, extend, and improve the road network, and how would this would change in case of a mode shift in transportation away from roads? How would a change in current practices affect CO_2 emissions and related reductions in maintenance turnover? What are the financial requirements for road maintenance and who is going to pay? Despite these obvious further research needs, we now have a methodology that can be applied at a national level to improve accounts for non-metallic minerals for road construction using more detailed information about the extent of the road network and characteristics of different types of roads. In this regard, this study marks an important advancement in the pursuit of measuring the metabolic performance of economies to provide headline indicators and policy guidance for sustainable material management.

5 Conclusion

5.1 Contributions to Industrial Ecology

While the research on non-metallic minerals presented in this dissertation has been stylistically divided into three strands, this is a mere didactic choice that does not influence the unity of the discourse. Understanding the inflows, stocks, and outflows of non-metallic minerals is a very extensive and challenging topic, and practicality indicates the necessity of subdividing the research question into several smaller and more easily manageable tasks. This should not beguile the reader into thinking that one stands independent of the other, since they are merely multiple faces of the very same object.

The analysis of the metabolism of non-metallic minerals was tackled from three distinct directions. Firstly, we deemed necessary to have a clear and sound perception of the magnitude of consumption, thus developed a novel methodology that considers engineering requirements for the production of key construction components to infer the related consumption of non-metallic minerals. We recorded the apparent consumption of cement, bitumen, and bricks for the years 1970-2010 for the whole world, and calculated suitable conversion factors to find the related requirement of raw non-metallic minerals that are used to produce concrete, roads, railways, brick constructions, and building sublayers. We have been able to distinguish non-metallic minerals into their very basic components (gypsum, limestone, clay, sand, and gravel), and we have been able to allocate them to their sector of use (buildings and infrastructure, roads, and railways). We discovered that our account is in line with previous studies with regard to the most recent decades, but it appeared that the consumption of the '70s and '80s had been heavily underestimated. In 2010, the world consumption of non-metallic minerals was 35 Gt, two thirds of which have been utilised in the Asia-Pacific region.

Secondly, we performed a probabilistic analysis on the demolition patterns of buildings to understand which mathematical function best approximates them, and how this choice reflects on stocks and waste flow estimations. We discovered how the demolition of residential buildings tends to naturally follow a lognormal distribution, but that exterior factors, such as planned demolitions of clearances of city blocks, can significantly alter this pattern. We also discovered that material stock accumulation models do not show major differences on the choice of one distribution function over another, and are mostly sensitive to the choice of median lifespan, but virtually uninfluenced by the standard deviation parameter. On the other hand, when analysing waste forecast, the choice of the most appropriate distribution plays a pivotal role, since it can affect the results by ±50%. Since waste management and planning is one of the more relevant topics to policy makers and city planners, researchers need to pay the utmost attention to identifying the most verisimilar distribution function.

Finally, we used the information discovered in the previous two steps of the research to build a new model that accounts material stocks and flows of road networks. This has made possible to calculate the share of this sector over the total yearly consumption of non-metallic minerals, and to estimate for how long roads will be able to be used as sinks of construction and demolition waste. We have discovered how the share of non-metallic minerals stocks and flows in this sector has reduced over time, and that, despite having been used for down-cycling large amounts of C&D waste, we risk to saturate this potential sink in only 20 years. A careful evaluation of viable alternatives, such as increasing the recyclability of concrete straight into fresh concrete admixtures, is necessary to find useful ways to downstream C&D waste other than landfilling.

During our research, we aimed to be as precise and realistic as possible. Yet, when modelling, researchers always necessarily have to compromise and accept some simplifications, abstractions, and assumptions. While we adopted any reasonable means to ensure that our postulations not influence the goodness of our results, we listed the limitations of each approach in each relative sub-research. We strongly believe that, despite these limitations, our results are sound and beneficial to policy makers and the general research community involved in sustainability of the built environment.

5.2 Next frontiers

The findings of this three years of research have increased the understanding of the flows and stocks of one of the most understudied group of materials of our economies. Nevertheless, whenever we push a little further our scientific understanding, we encounter a new set of questions and unresolved issues.

The yearly consumption and stock accumulation of non-metallic minerals is growing exponentially, yet these materials are paramount of societal change, development, and economic traction. It is not only unrealistic to imagine that this growth can continue endlessly, but it is also fundamental – from a sustainability point of view – to consider how long this large amount of materials will remain in use, and when and where they will be disposed. In what way can we proceed in increasing human wellbeing without being so dependent upon non-metallic materials? In there a way through which we can extend the lifetime of buildings and infrastructure without compromising their safety and usability? What is the amount of C&D waste that can be recycled without dampening technological and aesthetical qualities of buildings and roads? How can we increase this amount? Where can we dispose the large flows of C&D materials that are forecasted to happen during the latter part of the XXI century? Is there a way to make use of all these materials other than landfilling? All these questions will need to be addressed if we seriously intend to pursue a sound material cycle society, and closing the material loops within out economies.

Widening the physical perspective of flows and stocks of non-metallic minerals, we can identify other critical sustainability issues that needs to be studied, quantified, and understood to propose alternative measures. What are the hidden material flows associated with quarrying non-metallic minerals and construction activities? What is the energy required for extracting, processing, manufacturing, and disposing these materials? What is the relative carbon dioxide emission? Can we identify alternative materials that can perform equivalently or better than current standard of the industry? What are the best indicators that we can use to evaluate our environmental performance? This set of questions greatly broaden the perspective of impacts and influence that the use of non-metallic minerals has on the natural environment. While it will surely take decades to investigate and find sound answers all these issues, even a single improvement will contribute fighting climate change, especially in consideration to the prevalence of these materials in national material flow accounts.

NOTE: Section 2 and 3 of this thesis have been published in peer-review journals (Miatto et al., 2017, 2016) as per PhD requirements.

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7 List of figures

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9 References

Adriaanse, A., Bringezu, S., Hammond, A., Moriguchi, Y., Rodenburg, E., Rogich, D., Schütz, H., 1997. Resource flows: the material basis of industrial economies. World Resources Institute Washington, DC.

Aksözen, M., Hassler, U., Kohler, N., 2016a. Reconstitution of the dynamics of an urban building stock. Build. Res. Inf. 0, 20. doi:10.1080/09613218.2016.1152040

Aksözen, M., Hassler, U., Rivallain, M., Kohler, N., 2016b. Mortality analysis of an urban building stock. Build. Res. Inf. 0, 1–19. doi:10.1080/09613218.2016.1152531

Allen, S., Hinks, J., 1996. How long should housing last? Some implications of the age and probable life of housing in England. Constr. Manag. Econ. 14, 531–535.

Allenby, B., 2006. The ontologies of industrial ecology? Prog. Ind. Ecol. Int. J. 3, 28–40. doi:10.1504/PIE.2006.010039

Augiseau, V., Barles, S., 2016. Studying construction materials flows and stock: A review. Resour. Conserv. Recycl. doi:http://dx.doi.org/10.1016/j.resconrec.2016.09.002

Baccini, P., Brunner, P.H., 2012. Metabolism of the anthroposphere: analysis, evaluation, design. MIT Press.

Banneheka, B.M.S.G., Ekanayake, G.E.M.U.P.D., 2009. A new point estimator for the median of gamma distribution. Vidyodaya J. Sci. 14, 95–103.

Bradley, E.P., Kohler, N., 2007. Methodology for the survival analysis of urban building stocks. Build. Res. Inf. 35, 529–542.

Brunner, P.H., Rechberger, H., 2004. Practical handbook of material flow analysis. Int. J. Life Cycle Assess. 9, 337–338.

BSI, 2013. Concrete. Specification, performance, production and conformity.

Cai, W., Wan, L., Jiang, Y., Wang, C., Lin, L., 2015. Short-Lived Buildings in China: Impacts on Water, Energy, and Carbon Emissions. Environ. Sci. Technol. 0, 8. doi:10.1021/acs.est.5b02333

Cembureau, 2014. World Statistical Review 2001-2011 - Cement Production, Trade, Consumption Data. CEMBUREAU The European Cement Association, Brussels, Belgium.

Central Intelligence Agency, 2013. The World Factbook 2013-14. Washington, D.C.

Chang, J., Koetter, T., 2004. From landscape consumption to landscape protection, in: Wang, Y., Ge, S., Guo, G. (Eds.), Mining Science and Technology: Proceedings of the 5th International Symposium on Mining Science and Technology, Xuzhou, China 20-22 October 2004. Taylor & Francis, London, UK, pp. 691–695.

Chen, W.-Q., Shi, L., 2012. Analysis of aluminum stocks and flows in mainland China from 1950 to 2009: Exploring the dynamics driving the rapid increase in China's aluminum production. Resour. Conserv. Recycl. 65, 18–28. doi:http://dx.doi.org/10.1016/j.resconrec.2012.05.003

China Building and Industrial Materials Yearbook, 1982. Almanac of China Building Materials Industry. China Building Material Industry Yearbook, Beijing, China.

Clark, C., Jambeck, J., Townsend, T., 2006. A Review of Construction and Demolition Debris Regulations in the United States. Crit. Rev. Environ. Sci. Technol. 36, 141–186. doi:10.1080/10643380500531197

Daly, H., 1977. Steady state economy. San Franc.

Dannenberg, A., Zitzelsberger, S., Tavoni, A., 2017. Climate negotiators/'and scientists/'assessments of the climate negotiations. Nat. Clim. Change 7, 437–442.

Deilmann, C., Effenberger, K.-H., Banse, J., 2009. Housing stock shrinkage: vacancy and demolition trends in Germany. Build. Res. Inf. 37, 660–668.

Dietz, R., O'Neill, D.W., 2013. Enough is enough: Building a sustainable economy in a world of finite resources. Routledge.

Dittrich, M., Giljum, S., Polzin, C., Lutter, S., Bringezu, S., 2011. Resource use and resource efficiency in emerging economies. Working Paper 12). Vienna: Sustainable Europe Research Institute.

Ekmekci, M., 1990. Impact of quarries on karst groundwater systems. IAHS Publ. 207, 3–6.

European Norm, B.S., 2011. 197-1 (2011) Cement: composition, specifications and conformity criteria for common cements. Br. Stand. Inst. Lond.

Eurostat, 2013. Economy-wide Material Flow Accounts (EW-MFA).

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and indicators of economy-wide material flow accounting. J. Ind. Ecol. 15, 855–876.

Fishman, T., Schandl, H., Tanikawa, H., 2016. Stochastic Analysis and Forecasts of the Patterns of Speed, Acceleration, and Levels of Material Stock Accumulation in Society. Environ. Sci. Technol. 0. doi:10.1021/acs.est.5b05790

Fishman, T., Schandl, H., Tanikawa, H., Walker, P., Krausmann, F., 2014. Accounting for the material stock of nations. J. Ind. Ecol. 18, 407–420.

Gierlinger, S., Krausmann, F., 2012. The physical economy of the United States of America. J. Ind. Ecol. 16, 365–377.

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. J. Ind. Ecol. 19, 765–777. doi:10.1111/jiec.12244

Hashimoto, S., Moriguchi, Y., Tasaki, T., Masaharu, M., 2006. Comparative Analysis on Images of Cycle-Oriented Society. J. Jpn. Soc. Waster Manag. Experts 17, 204–218.

Hashimoto, S., Tanikawa, H., Moriguchi, Y., 2009. Framework for estimating potential wastes and secondary resources accumulated within an economy – A case study of construction minerals in Japan. Waste Manag. 29, 2859–2866. doi:10.1016/j.wasman.2009.06.011

Hashimoto, S., Tanikawa, H., Moriguchi, Y., 2007. Where will large amounts of materials accumulated within the economy go?–a material flow analysis of construction minerals for Japan. Waste Manag. 27, 1725–1738.

Hatayama, H., Daigo, I., Matsuno, Y., Adachi, Y., 2010. Outlook of the World Steel Cycle Based on the Stock and Flow Dynamics. Environ. Sci. Technol. 44, 6457–6463. doi:10.1021/es100044n

Hayakawa T., 2013. A study on establishment of a construction material stock GIS-database on all buildings in Japan (Master's thesis). Nagoya University, Nagoya.

Hu, M., Bergsdal, H., Voet, E. van der, Huppes, G., Müller, D.B., 2010. Dynamics of urban and rural housing stocks in China. Build. Res. Inf. 38, 301–317. doi:10.1080/09613211003729988

Huuhka, S., Lahdensivu, J., 2016. Statistical and geographical study on demolished buildings. Build. Res. Inf. 44, 73–96.

International Energy Agency, 2014. Oil Information.

Kahle, L.R., Gurel-Atay, E., 2013. Communicating sustainability for the green economy. ME Sharpe.

Kapur, A., Keoleian, G., Kendall, A., Kesler, S.E., 2008. Dynamic Modeling of In-Use Cement Stocks in the United States. J. Ind. Ecol. 12, 539–556.

Kapur, A., van Oss, H.G., Keoleian, G., Kesler, S.E., Kendall, A., 2009. The contemporary cement cycle of the United States. J. Mater. Cycles Waste Manag. 11, 155–165. doi:10.1007/s10163-008-0229-x

Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. The Changing Metabolism of Cities. J. Ind. Ecol. 11, 43–59. doi:10.1162/jie.2007.1107

Kitzes, J., 2013. An Introduction to Environmentally-Extended Input-Output Analysis. Resources 2. doi:10.3390/resources2040489

Krausmann, F., Fischer-Kowalski, M., Schandl, H., Eisenmenger, N., 2008. The global sociometabolic transition. J. Ind. Ecol. 12, 637–656.
Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., Fischer-Kowalski, M., 2009. Growth in global materials use, GDP and population during the 20th century. Ecol. Econ. 68, 2696–2705.
Krausmann, F., Gingrich, S., Nourbakhch-Sabet, R., 2011. The metabolic transition in Japan. J. Ind. Ecol. 15, 877–892.
Krausmann, F., Richter, R., Eisenmenger, N., 2014. Resource Use in Small Island States. J. Ind. Ecol. 18, 294–305. doi:10.1111/jiec.12100
Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., Haberl, H., 2017. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc. Natl. Acad. Sci. doi:10.1073/pnas.1613773114
Lawless, J.F., 2011. Statistical models and methods for lifetime data, Second edition. ed. John Wiley & Sons.
Lay, M.G., Vance, J.E., 1992. Ways of the World: A History of the World's Roads and of the Vehicles that Used Them. Rutgers university press.
Liang, H., Tanikawa, H., Matsuno, Y., Dong, L., 2014. Modeling in-use steel stock in China's buildings and civil engineering infrastructure using time-series of DMSP/OLS nighttime lights. Remote Sens. 6, 4780–4800.
Lichtensteiger, T., Baccini, P., 2008. Exploration of urban stocks. J. Environ. Eng. Manag. 18, 41–48.
Lotteau, M., Loubet, P., Pousse, M., Dufrasnes, E., Sonnemann, G., 2015. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Build. Environ. 93, Part 2, 165–178. doi:10.1016/j.buildenv.2015.06.029
Martinico-Perez, M.F.G., Fishman, T., Okuoka, K., Tanikawa, H., 2016. Material Flow Accounts and Driving Factors of Economic Growth in the Philippines. J. Ind. Ecol. n/a-n/a. doi:10.1111/jiec.12496
Matthews, E., Amann, C., Bringezu, S., Hüttler, W., Ottke, C., Rodenburg, E., Rogich, D., Schandl, H., Van, E., Weisz, H., others, 2000. The weight of nations-material outflows from industrial economies, in: World Resources Institute. Citeseer.
Miatto, A., Schandl, H., Fishman, T., Tanikawa, H., 2016. Global Patterns and Trends for Non-Metallic Minerals used for Construction. J. Ind. Ecol. n/a–n/a. doi:10.1111/jiec.12471
Miatto, A., Schandl, H., Tanikawa, H., 2017. How important are realistic building lifespan assumptions for material stock and demolition waste accounts? Resour. Conserv. Recycl. 122, 143–154. doi:http://doi.org/10.1016/j.resconrec.2017.01.015
Ministry of Economy, Trade and Industry, Japan, 1986. Yearbook of Current Production Statistics, Mineral Resources and Petroleum Products, Ceramics and Building Materials [WWW Document]. URL http://www.meti.go.jp/statistics/tyo/seidou/result/ichiran/08_seidou.html (accessed 9.23.15).
Ministry of Land, Infrastructure, and Transport of Japan, 2002. Construction and Demolition Waste Census 2000 [WWW Document]. URL http://www.mlit.go.jp/sogoseisaku/recycle/index.html (accessed 2.18.16).
Müller, D.B., 2006. Stock dynamics for forecasting material flows—case study for housing in The Netherlands. Ecol. Econ. 59, 142–156.
Müller, D.B., Liu, G., Løvik, A.N., Modaresi, R., Pauliuk, S., Steinhoff, F.S., Brattebø, H., 2013. Carbon Emissions of Infrastructure Development. Environ. Sci. Technol. 47, 11739–11746. doi:10.1021/es402618m

Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014. Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. Environ. Sci. Technol. 48, 2102–2113. doi:10.1021/es403506a
Nisbet, M., 1996. The Reduction of Resource Input and Emissions Achieved by Addition of Limestone to Portland Cement. Portland Cement Association.
OECD, 2001. Measuring Capital – OECD Manual. doi:http://dx.doi.org/10.1787/9789264193260-en
Owen, W., 1958. Automotive Transport in the United States. Ann. Am. Acad. Pol. Soc. Sci. 320, 1–8.
Pappu, A., Saxena, M., Asolekar, S.R., 2007. Solid wastes generation in India and their recycling potential in building materials. Build. Environ. 42, 2311–2320. doi:https://doi.org/10.1016/j.buildenv.2006.04.015
Patrício, J., Kalmykova, Y., Rosado, L., Lisovskaja, V., 2015. Uncertainty in Material Flow Analysis Indicators at Different Spatial Levels. J. Ind. Ecol. 19, 837–852. doi:10.1111/jiec.12336
Pauliuk, S., Milford, R.L., Müller, D.B., Allwood, J.M., 2013. The steel scrap age. Environ. Sci. Technol. 47, 3448–3454.
Petersdorff, C., Boermans, T., Harnisch, J., 2006. Mitigation of CO2 emissions from the EU-15 building stock. Beyond the EU directive on the energy performance of buildings. Environ. Sci. Pollut. Res. 13, 350–358.
Pianon M., 2015. Typical requirement for road production.
Piccin S., 2015. Typical concrete requirements for the construction industry.
Qin, Y., Suh, S., 2016. What distribution function do life cycle inventories follow? Int. J. Life Cycle Assess. 1–8. doi:10.1007/s11367-016-1224-4
Rauch, J.N., 2009. Global mapping of Al, Cu, Fe, and Zn in-use stocks and in-ground resources. Proc. Natl. Acad. Sci. 106, 18920–18925. doi:10.1073/pnas.0900658106
Reyna, J.L., Chester, M.V., 2015. The Growth of Urban Building Stock: Unintended Lock-in and Embedded Environmental Effects. J. Ind. Ecol. 19, 524–537. doi:10.1111/jiec.12211
Robinson Jr, G.R., Brown, W.M., 2002. Sociocultural dimensions of supply and demand for natural aggregate—examples from the Mid-Atlantic Region, United States. US Geol. Surv. Open-File Rep. 2, 350.
Russi, D., Gonzalez-Martinez, A.C., Silva-Macher, J.C., Giljum, S., Martínez-Alier, J., Vallejo, M.C., 2008. Material Flows in Latin America. J. Ind. Ecol. 12, 704–720. doi:10.1111/j.1530-9290.2008.00074.x
Sandberg, N.H., Sartori, I., Brattebø, H., 2014. Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock. Energy Build. 82, 287–295. doi:http://dx.doi.org/10.1016/j.enbuild.2014.07.005
Sarkar, S., Chamberlain, J.F., Miller, S.A., 2011. A Comparison of Two Methods to Conduct Material Flow Analysis on Waste Tires in a Small Island Developing State. J. Ind. Ecol. 15, 300–314. doi:10.1111/j.1530-9290.2010.00323.x
Schaffartzik, A., Mayer, A., Gingrich, S., Eisenmenger, N., Loy, C., Krausmann, F., 2014. The global metabolic transition: Regional patterns and trends of global material flows, 1950–2010. Glob. Environ. Change 26, 87–97.
Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Schaffartzik, A., 2017. Global Material Flows and Resource Productivity. Assessment Report for the UNEP International Resource Panel. Pre-publication final draft.
Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Schaffartzik, A., Krausmann, F., Gierlinger, S., Hosking, K., Lenzen, M., Tanikawa, H., Miatto, A., Fishman, T., 2017. Global Material Flows and

Resource Productivity: Forty Years of Evidence. J. Ind. Ecol. n/a-n/a. doi:10.1111/jiec.12626
Schandl, H., Müller, D.B., Moriguchi, Y., 2015. Socioeconomic Metabolism Takes the Stage in the International Environmental Policy Debate: A Special Issue to Review Research Progress and Policy Impacts. J. Ind. Ecol. 19, 689–694. doi:10.1111/jiec.12357
Schandl, H., West, J., 2012. Material Flows and Material Productivity in China, Australia, and Japan. J. Ind. Ecol. 16, 352–364. doi:10.1111/j.1530-9290.2011.00420.x
Schandl, H., West, J., 2010. Resource use and resource efficiency in the Asia–Pacific region. Glob. Environ. Change 20, 636–647. doi:http://dx.doi.org/10.1016/j.gloenvcha.2010.06.003
Schiller, G., Gruhler, K., Ortlepp, R., 2017. Continuous Material Flow Analysis Approach for Bulk Nonmetallic Mineral Building Materials Applied to the German Building Sector. J. Ind. Ecol. doi:10.1111/jiec.12595
Schiller, G., Müller, F., Ortlepp, R., 2016. Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. Resour. Conserv. Recycl. doi:10.1016/j.resconrec.2016.08.007
Shi, F., Huang, T., Tanikawa, H., Han, J., Hashimoto, S., Moriguchi, Y., 2012. Toward a Low Carbon–Dematerialization Society. J. Ind. Ecol. 16, 493–505. doi:10.1111/j.1530-9290.2012.00523.x
Singh, S.J., Krausmann, F., Gingrich, S., Haberl, H., Erb, K.-H., Lanz, P., Martinez-Alier, J., Temper, L., 2012. India's biophysical economy, 1961–2008. Sustainability in a national and global context. Ecol. Econ. 76, 60–69.
Steinberg, S.S., 1926. Building American Highways for Safety. Sci. News-Lett. 10, 85–86.
Steinberger, J.K., Krausmann, F., Eisenmenger, N., 2010. Global patterns of materials use: A socioeconomic and geophysical analysis. Ecol. Econ. 69, 1148–1158.
Stocker, T., 2014. Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Switalski, T., Bissonette, J., DeLuca, T., Luce, C., Madej, M., 2004. Benefits and impacts of road removal. Front. Ecol. Environ. 2, 21–28. doi:10.1890/1540-9295(2004)002[0021:BAIORR]2.0.CO;2
Takiguchi, H., Takemoto, K., 2008. Japanese 3R policies based on material flow analysis. J. Ind. Ecol. 12, 792–798.
Tanaka K., 2014. A study on improvement of a material stock database and indicators toward stock-type society. (Master's thesis). Nagoya University, Nagoya.
Tanikawa, H., Fishman, T., Okuoka, K., Sugimoto, K., 2015. The Weight of Society Over Time and Space: A Comprehensive Account of the Construction Material Stock of Japan, 1945–2010. J. Ind. Ecol. n/a–n/a. doi:10.1111/jiec.12284
Tanikawa, H., Hashimoto, S., 2009. Urban stock over time: spatial material stock analysis using 4d-GIS. Build. Res. Inf. 37, 483–502. doi:http://dx.doi.org/10.1080/09613210903169394
Thomsen, A., van der Flier, K., 2011. Understanding obsolescence: a conceptual model for buildings. Build. Res. Inf. 39, 352–362.
Thomsen, A., van der Flier, K., 2009. Replacement or renovation of dwellings: the relevance of a more sustainable approach. Build. Res. Inf. 37, 649–659.
Thuvander, L., Österbring, M., Mangold, M., Mata, É., Wallbaum, H., Johnsson, F., 2015. Spatial exploration of the refurbishment dynamics of urban housing stocks, in: Proceedings of the Computers in Urban Planning and Urban Management Conference, CUPUM.
Tukker, A., 2000. Life cycle assessment as a tool in environmental impact assessment. Environ. Impact Assess. Rev. 20, 435–456. doi:10.1016/S0195-9255(99)00045-1
UN Comtrade, 2014. Ceramic Building Products.

UN General Assembly, 2005. World summit outcome. Sixtieth Sess.
UN Statistics Division, 2011a. Industrial Commodity Production Statistics Database 1950-2008.
UN Statistics Division, 2011b. Commodity Trade Statistics Database UN.
UNEP, 2015. Global material flow and resource productivity dataset. [WWW Document]. URL (accessed 11.5.15).
United Nations, Department of Economic and Social Affairs, Population Division, 2015. World Urbanization Prospects: The 2014 Revision (No. ST/ESA/SER.A/366).
U.S. Census Bureau, 2016. Changes in household size 1940-2016.
U.S. Department of Transportation, 2015a. Weight of Shipments by Transportation Mode [WWW Document]. URL https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/data_and_statistics/by_subject/freight/freight_facts_2015/chapter2/table2_1 (accessed 5.19.17).
U.S. Department of Transportation, 2015b. Freight Facts and Figures 2015.
U.S. Department of Transportation, 1985. Highway Statistic Summary to 1985. U.S. Department of Transportation, Washington, D.C.
U.S. Department of Transportation, Various years. Highway Statistic Summary. U.S. Department of Transportation, Washington, D.C.
U.S. Environmental Protection Agency, 2016. Construction and demolition debris generation in the United States, 2014.
U.S. Environmental Protection Agency, 1998. Characterization of building-related construction and demolition debris in the United States (No. EPA530-R-98-010). United States Environmental Protection Agency.
U.S. Geological Survey, U.S. Department of the Interior, 2013. 2012 Minerals Yearbook: Mining and Quarrying Trends.
USEPA, 2009. Estimating 2003 Building-Related Construction and Demolition Materials Amounts (No. EPA530-R-09-002). United States Environmental Protection Agency.
Vásquez, F., Løvik, A.N., Sandberg, N.H., Müller, D.B., 2016. Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock. Energy Build. 111, 37–55. doi:http://dx.doi.org/10.1016/j.enbuild.2015.11.018
Weisz, H., Krausmann, F., Eisenmenger, N., Schütz, H., Haas, W., Schaffartzik, A., 2007. Economy-wide material flow accounting. A compilation guide. Eurostat Eur. Comm.
West, J., Schandl, H., 2013. Material use and material efficiency in Latin America and the Caribbean. Ecol. Econ. 94, 19–27.
West, J., Schandl, H., Heyenga, S., Chen, S., 2013. Resource Efficiency: Economics and Outlook for China. UNEP Bangk. Thail.
West, J., Schandl, H., Krausmann, F., Kovanda, J., Hak, T., 2014. Patterns of change in material use and material efficiency in the successor states of the former Soviet Union. Ecol. Econ. 105, 211–219. doi:http://dx.doi.org/10.1016/j.ecolecon.2014.06.013
Wiedenhofer, D., Steinberger, J.K., Eisenmenger, N., Haas, W., 2015. Maintenance and expansion: modeling material stocks and flows for residential buildings and transportation networks in the EU25. J. Ind. Ecol. 19, 538–551. doi:DOI: 10.1111/jiec.12216
Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Spec. Sect. Anal. Glob. Hum. Appropr. Net Prim. Prod. - Process. Trajectories Implic. 69, 211–222. doi:10.1016/j.ecolecon.2009.08.026
Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proc. Natl. Acad. Sci. 112, 6271–6276.
World Bank, 2015. Rail lines (total route-km).
World Steel Association, 2014. Crude steel production, 1980-2013.
WU, 2014. Global material flows database.

Wu, Z., Yu, A.T.W., Shen, L., Liu, G., 2014. Quantifying construction and demolition waste: An analytical review. Waste Manag. 34, 1683–1692. doi:10.1016/j.wasman.2014.05.010
Yoshida, K., Fishman, T., Okuoka, K., Tanikawa, H., 2016. Material stock's overburden: Automatic spatial detection and estimation of domestic extraction and hidden material flows. Resour. Conserv. Recycl. doi:http://dx.doi.org/10.1016/j.resconrec.2016.09.010
Zinoviev D., 2012. Railroad Gauge Width [WWW Document]. Railr. Gauge Width. URL http://parovoz.com/spravka/gauges-en.php (accessed 11.4.15).

10 Appendix to How important are realistic building lifespan assumptions for material stock and demolition waste accounts?

10.1 Functions and equations

10.1.1 Equations parameters

The equations that we used for our analysis are all 1.1characterised by two parameters. They are:

Normal	$\boldsymbol{\mu} \in \mathbb{R}$ – Location $\boldsymbol{\sigma^2 > 0}$ – scale
Gompertz	$\eta > 0$ – Shape $b > 0$ – Location
Weibull	$\lambda > 0$ – Scale $k > 0$ – Shape
Gamma	$\theta > 0$ – Scale $k > 0$ – Shape
Log-normal	$\mu \in \mathbb{R}$ – Location $\sigma > 0$ – Scale of associated normal distribution

10.1.2 Reliability functions

In order to construct the reliability curves used in the maximum likelihood estimation, we used the following equations.

Normal	$\boldsymbol{R_{Normal}(x) = 0.5\left[1 - \text{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right]}$	(1)
Gompertz	$R_{Gompertz}(x) = \exp\left[-\eta(e^{bx} - 1)\right]$	(2)
Weibull	$R_{Weibull}(x) = e^{-\left(\frac{x}{\lambda}\right)^k} \qquad x \geq 0$	(3)
Gamma	$R_{Gamma}(x) = \frac{1}{\Gamma(k)}\Gamma\left(k, \frac{x}{\theta}\right)$	(4)
Log-normal	$R_{Log-normal}(x) = 0.5\left\{1 - \text{erf}\left[\frac{\ln(x-\mu)}{\sigma\sqrt{2}}\right]\right\}$	(5)

10.1.3 Median and standard deviation

The median of the equation is used for estimating the average lifetime of the buildings, while the standard deviation is used to appraise how spread or concentrated the demolitions are.

Reminding that the notation $\tilde{x}$ typically represents the median of the random variable x, the characterising equations are:

Normal	$\tilde{x}_{Normal} = \mu$	(6)
Gompertz	$\tilde{x}_{Gompertz} = \left(\frac{1}{b}\right) \ln\left[\left(-\frac{1}{\eta}\right) \ln\left(\frac{1}{2}\right) + 1\right]$	(7)
Weibull	$\tilde{x}_{Weibull} = \lambda(\ln 2)^{\frac{1}{k}}$	(8)
Gamma	There is not a simple closed form to calculate the median. An approximation. Banneheka and Ekanayake (2009) calculated an approximation formula to estimate the median of the Gamma distribution for values of $k \geq 1$. $$\tilde{x}_{Gamma} \approx k\theta \frac{3k - 0.8}{3k + 0.2}$$	(9)
Log-normal	$\tilde{x}_{Log-normal} = e^{\mu}$	(10)

Reminding that the notation σ typically represents the standard deviation of the random variable x, the standard deviation is calculated as:

Normal	$\sigma_{Normal} = \sigma$	(11)
Gompertz	$$\sigma_{Gompertz} = \left(\frac{1}{b}\right) e^{\frac{\eta}{2}} \left\{-2\eta\ {}_3F_3(1,1,1;2,2,2;-\eta) + \gamma^2 + \left(\frac{\pi^2}{6}\right) + 2\gamma \ln(\eta) + [\ln(\eta)]^2 - e^{\eta}[\mathrm{Ei}(-\eta)]^2\right\}^{1/2}$$	(12)
	where γ is the Euler constant: $$\gamma = -\psi(1) = 0.577215 \cdots$$ and	(13)

$$ {}_3F_3(1,1,1;2,2,2;-\eta) = \sum_{k=0}^{\infty} \left[\frac{1}{(k+1)^3}\right] (-1)^k \left(\frac{\eta^k}{k!}\right) $$

and **Ei** denotes the exponential integral (14)

$$ Ei(x) = -\int_{-x}^{\infty} \frac{e^{-t}}{t} dt $$

(15)

Weibull	$\sigma_{Weibull} = \lambda\left[\Gamma\left(1+\frac{2}{k}\right) - \left(\Gamma\left(1+\frac{1}{k}\right)\right)\right]^{\frac{1}{2}}$	(16)
Gamma	$\sigma_{Gamma} = \theta\sqrt{k}$	(17)
Log-normal	$\sigma_{Log-normal} = \sqrt{\left(e^{\sigma^2}-1\right)e^{2\mu+\sigma^2}}$	(18)

10.1.4 Skewness

Many times in the main manuscript we talk about skewness. It is defined as the measure of the asymmetry of the probability distribution of a real-valued random variable about its mean.

Some functions, such as the case of the normal distribution, are symmetrical, thus their skewness is equal to 0.

In the case the right tail of the function is longer than the left one, i.e. when the majority of the mass is concentrated on the left side of the distribution, the function is said to be skewed to the right, right-tailed, right-skewed, or to have positive skewness.

In the case the left tail of the function is longer than the right one, i.e. when the majority of the mass is concentrated on the right side of the distribution, the function is said to be skewed to the left, left-tailed, left-skewed, or to have negative skewness.

A graphical example of this description can be found in Figure S23.

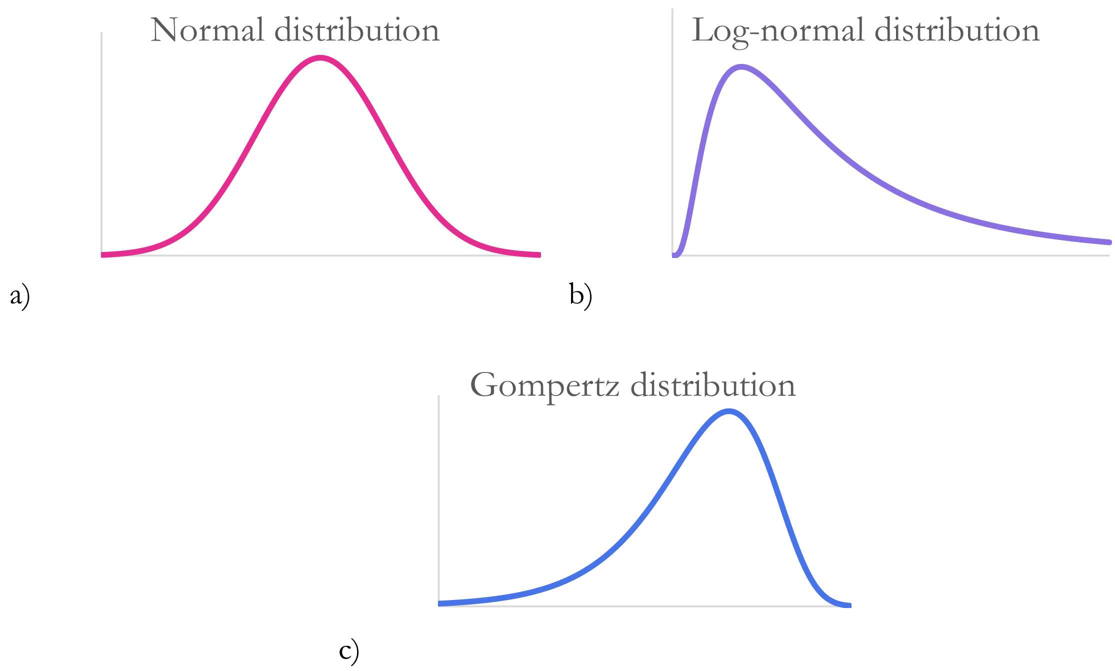

Figure S23 – Three examples of distribution skewness. a) Normal distribution, with its null skewness, is symmetrical. b) Log-normal distribution is an example of a right skewed distribution. c) Gompertz distribution is an example of a left skewed distribution.

10.2 Average lifespan and relative parameters

In this chapter we will show the detailed results relative to the lifespan analysis for the cases of Nagoya, Wakayama, and Salford, showing not only the gross results relative to the totality of buildings, but also their division according to their typology.

10.2.1 Nagoya, Japan

10.2.1.1 R^2 values

We here report the R^2 values for five categories of buildings in Nagoya: commercial, commercial proximities (e.g. sport facilities, parking facilities, etc.), residential, industrial, and the totality of buildings.

Table S10 – Nagoya commercial buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Commercial R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=15792)	95.1%	98.1%	98.4%	97.0%	99.0%
1970 (n=15963)	90.6%	99.1%	99.2%	98.8%	98.7%
1980 (n=13112)	95.0%	98.6%	98.6%	98.8%	98.1%
1990 (n=11491)	93.0%	98.0%	98.2%	97.3%	98.8%
Average R^2	93.4%	98.5%	98.6%	98.0%	98.7%
R^2 std dev	2.1%	0.5%	0.4%	0.9%	0.4%

Table S11 – Nagoya commercial proximal buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Commercial proximity areas R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=0)	n/a	n/a	n/a	n/a	n/a
1970 (n=0)	n/a	n/a	n/a	n/a	n/a
1980 (n=3975)	93.9%	97.7%	97.6%	97.9%	97.1%
1990 (n=3580)	92.1%	97.2%	97.5%	96.2%	98.3%
Average R^2	93.0%	97.4%	97.5%	97.0%	97.7%
R^2 std dev	1.2%	0.46%	0.1%	1.2%	0.8%

Table S12 – Nagoya residential buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Residential R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=6189)	92.0%	97.9%	98.0%	97.6%	98.6%
1970 (n=6172)	84.1%	98.4%	98.6%	96.2%	98.1%
1980 (n=4515)	95.6%	97.1%	96.9%	97.3%	96.3%
1990 (n=4425)	90.6%	95.9%	96.3%	94.6%	97.3%
Average R^2	90.6%	97.3%	97.5%	96.4%	97.6%
R^2 std dev	4.8%	1.1%	1.0%	1.4%	1.0%

Table S13 – Nagoya industrial buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Industrial R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=6683)	94.3%	97.5%	97.9%	96.4%	98.4%
1970 (n=6969)	90.2%	98.8%	98.8%	98.4%	98.3%
1980 (n=4896)	93.6%	98.2%	98.2%	98.4%	97.7%
1990 (n=4249)	91.3%	97.4%	97.6%	96.8%	98.3%
Average R^2	92.4%	98.0%	98.1%	97.5%	98.2%
R^2 std dev	1.9%	0.6%	0.5%	1.0%	0.3%

Table S14 – Nagoya buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

All buildings R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=6683)	94. 5%	98.0%	98.3%	97.1%	98.8%
1970 (n=6969)	89.3%	99.0%	99.0%	98.3%	98.5%
1980 (n=4896)	94.8%	98.2%	98.1%	98.4%	97.6%
1990 (n=4249)	92.2%	97.5%	97.7%	96.6%	98.4%
Average R^2	92.7%	98.1%	98.3%	97.6%	98.4%
R^2 std dev	2.5%	0.6%	0.5%	0.9%	0.5%

10.2.1.2 Average lifespan and standard deviation

This section displays the calculated lifespan and standard deviation for the five categories (commercial, commercial proximities, residential, industrial, and the totality of buildings). On some occasions it has not been possible to calculate the standard deviation for the Gompertz distribution being its variance a negative number.

Table S15 – Nagoya commercial buildings average lifespan and, between parenthesis, standard deviation for four different cohorts and five different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number.

Commercial lifespan & standard deviation	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=15792)	26.2 (17.6)	24.3 (18.8)	24 (19.8)	24.8 (17.6)	23.2 (26)
1970 (n=15963)	18.3 (17.4)	14.2 (26.8)	13.9 (25.8)	15.2 (n/a)	13.7 (56.7)
1980 (n=13112)	18.5 (13.7)	17.1 (18)	17 (19.1)	17.4 (15)	16.6 (32.7)
1990 (n=11491)	14.4 (9.6)	13.8 (12.6)	13.7 (13.4)	14 (10.9)	13.5 (22)

Table S16 – Nagoya commercial proximities buildings average lifespan and, between parenthesis, standard deviation for two different cohorts and five different distributions.

Commercial proximity areas lifespan and std dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=0)	n/a	n/a	n/a	n/a	n/a
1970 (n=0)	n/a	n/a	n/a	n/a	n/a
1980 (n=3975)	20.9 (15.1)	19.8 (21.7)	19.7 (23.2)	20.1 (17.3)	19.4 (46.4)
1990 (n=3580)	16.2 (10.2)	16 (13.9)	15.9 (15.1)	16.2 (11.5)	15.7 (26.4)

Table S17 – Nagoya residential buildings average lifespan and, between parenthesis, standard deviation for four different cohorts and five different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number.

Residential lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=6189)	26.3 (21.5)	23.2 (26.6)	23.1 (27.2)	23.2 (24.9)	22.2 (45.4)
1970 (n=6172)	19.6 (20.3)	14 (47.3)	13.1 (39)	16.9 (n/a)	13.7 (177.6)
1980 (n=4515)	22.5 (14.2)	22 (17.7)	21.9 (19.9)	22.4 (14.1)	21.6 (33.5)
1990 (n=4425)	16 (10)	15.7 (13.2)	15.6 (14.3)	16 (11.2)	15.4 (23.9)

Table S18 – Nagoya industrial buildings average lifespan and, between parenthesis, standard deviation for four different cohorts and five different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number.

Industrial lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=6683)	30.8 (19.9)	29 (22.5)	28.7 (24.2)	29.7 (20)	27.8 (35)
1970 (n=6969)	21.2 (19.5)	17.3 (33.6)	17 (31.9)	18.3 (n/a)	16.7 (87.1)
1980 (n=4896*)*	20.1 (15)	18.8 (22.3)	18.6 (23.4)	19 (18.2)	18.3 (47.9)
1990 (n=4249)	15.7 (10.4)	15.3 (15)	15.2 (16)	15.5 (n/a)	15 (29.8)

Table S19 – Nagoya all buildings average lifespan and, between parenthesis, standard deviation for four different cohorts and five different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number.

All buildings lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=6683)	27.3 (19)	25.2 (21.1)	24.9 (22.3)	25.6 (19.3)	24 (31.2)
1970 (n=6969)	19.3 (18.5)	14.8 (31.5)	14.5 (29.5)	16.3 (n/a)	14.4 (76.7)
1980 (n=4896)	19.8 (14.3)	18.6 (19.3)	18.5 (20.7)	18.9 (15.7)	18.1 (37.5)
1990 (n=4249)	15.2 (9.9)	14.7 (13.3)	14.6 (14.3)	15 (11.4)	14.4 (24.3)

10.2.1.3 Distribution parameters

In this part of the supporting information we report the parameters that we used to generate the reliability curves, and to estimate the average lifespan and standard deviation.

Table S20 – Equation parameters for Nagoya commercial buildings.

Commercial parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=15792)	μ=26.2 σ=17.6	k=1.513 λ=31	k=2.07 θ=13.8	b=0.02916 η=0.7	μ=3.14 σ=0.74
1970 (n=15963)	μ=18.3 σ=17.4	k=0.868 λ=21.6	k=0.78 θ=29.2	b=0.00056 η=81.4	μ=2.62 σ=1.24
1980 (n=13112)	μ=18.5 σ=13.7	k=1.213 λ=23.1	k=1.35 θ=16.5	b=0.02365 η=1.4	μ=2.81 σ=0.96
1990 (n=11491)	μ=14.4 σ=9.6	k=1.337 λ=18.2	k=1.62 θ=10.6	b=0.03998 η=0.9	μ=2.6 σ=0.89

Table S21 – Equation parameters for Nagoya proximal commercial buildings.

Commercial proximity areas parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=0)	n/a	n/a	n/a	n/a	n/a
1970 (n=0)	n/a	n/a	n/a	n/a	n/a
1980 (n=3975)	μ=20.9 σ=15.1	k=1.181 λ=27	k=1.27 θ=20.6	b=0.02062 η=1.4	μ=2.96 σ=1.04
1990 (n=3580)	μ=16.2 σ=10.2	k=1.388 λ=20.8	k=1.69 θ=11.6	b=0.04483 η=0.6	μ=2.75 σ=0.9

Table S22 – Equation parameters for Nagoya residential buildings.

Residential parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=6189)	μ=26.3 σ=21.5	k=1.146 λ=31.9	k=1.27 θ=24.1	b=0.00791 η=3.4	μ=3.1 σ=0.98
1970 (n=6172)	μ=19.6 σ=20.3	k=0.68 λ=24.1	k=0.54 θ=52.9	b=0.00006 η=637.3	μ=2.61 σ=1.61

1980 (n=4515)	μ=22.5 σ=14.2	k=1.472 λ=28.2	k=1.79 θ=14.9	b=0.04361 η=0.4	μ=3.07 σ=0.87
1990 (n=4425)	μ=16.0 σ=10.0	k=1.421 λ=20.3	k=1.77 θ=10.7	b=0.04726 η=0.6	μ=2.73 σ=0.87

Table S23 – Equation parameters for Nagoya industrial buildings.

Industrial parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=6683)	μ=30.8 σ=19.9	k=1.511 λ=37.0	k=1.99 θ=17.2	b=0.028 η=0.5	μ=3.32 σ=0.79
1970 (n=6969)	μ=21.2 σ=19.5	k=0.856 λ=26.5	k=0.77 θ=36.3	b=0.00053 η=71.3	μ=2.81 σ=1.32
1980 (n=4896)	μ=20.1 σ=15.0	k=1.122 λ=26.0	k=1.18 θ=21.5	b=0.01522 η=2.1	μ=2.91 σ=1.07
1990 (n=4249)	μ=15.7 σ=10.4	k=1.271 λ=20.5	k=1.48 θ=13.2	b=0.03055 η=1.1	μ=2.71 σ=0.97

Table S24 – Equation parameters for Nagoya buildings.

All buildings parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*
1960 (n=6683)	μ=27.3 σ=19.0	k=1.423 λ=32.6	k=1.84 θ=16.4	b=0.02404 η=0.8	μ=3.18 σ=0.80
1970 (n=6969)	μ=19.3 σ=18.5	k=0.823 λ=23.2	k=0.72 θ=34.7	b=0.00052 η=81.1	μ=2.67 σ=1.33
1980 (n=4896)	μ=19.8 σ=14.3	k=1.224 λ=25.1	k=1.36 θ=17.8	b=0.02449 η=1.2	μ=2.90 σ=0.98
1990 (n=4249)	μ=15.2 σ=9.9	k=1.346 λ=19.4	k=1.63 θ=11.2	b=0.0401 η=0.8	μ=2.67 σ=0.90

10.2.2 Salford, Greater Manchester, UK

10.2.2.1 R^2 values

We here report the R^2 values for five categories of buildings in Salford, Greater Manchester (UK): high density residential buildings, mid/low density residential buildings, industrial buildings, other buildings (e.g. commercial, religious), and the totality of buildings. In this case we also report the R^2 values for the logistic curve since Tanikawa and Hashimoto, in their 2009 publication, calculated the lifespan of buildings through a logistic curve.

Table S25 – Salford high density residential buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

High density residential R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=40)	95.0%	95.1%	94.8%	94.9%	94.4%	94.7%

1896 (n=710)	98.4%	98.4%	98.4%	97.2%	98.4%	98.4%
1908 (n=140)	81.5%	80.7%	82.9%	78.4%	83.5%	80.5%
1932 (n=258)	89.5%	89.3%	89.0%	89.5%	88.7%	89.1%
1953 (n=80)	94.1%	95.7%	96.6%	93.3%	97.2%	93.0%
Average R^2	91.7%	91.9%	92.3%	90.7%	92.4%	91.1%
R^2 std dev	6.5%	7.0%	6.3%	7.4%	6.2%	6.8%

Table S26 – Salford mid and low density residential buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Mid/low density residential R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=43)	97.7%	97.8%	97.3%	98.6%	96.4%	97.3%
1896 (n=103)	97.9%	98.0%	97.0%	98.4%	96.5%	98.1%
1908 (n=14)	84.3%	84.5%	84.3%	86.6%	82.1%	84.3%
1932 (n=722)	86.1%	85.7%	85.1%	83.4%	82.4%	86.2%
1953 (n=179)	78.8%	95.3%	95.3%	94.9%	95.8%	74.6%
Average R^2	89.0%	92.3%	91.8%	92.4%	90.6%	88.1%
R^2 std dev	8.5%	6.6%	6.5%	7.0%	7.7%	9.8%

Table S27 – Salford industrial buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Factories R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=12)	95.3%	94.7%	96.0%	93.0%	96.3%	95.1%
1896 (n=89)	94.6%	94.6%	93.7%	95.9%	92.7%	93.8%
1908 (n=56)	94.7%	94.9%	94.3%	95.8%	93.4%	94.1%
1932 (n=221)	95.9%	96.1%	95.4%	97.3%	95.2%	96.3%
1953 (n=203)	99.5%	99.4%	99.3%	98.7%	99.0%	99.6%
Average R^2	96.0%	95.9%	95.7%	96.1%	95.3%	95.8%
R^2 std dev	2.0%	2.0%	2.2%	2.1%	2.5%	2.4%

Table S28 – R^2 values expressed as percentage for curve fitting for other buildings of Salford (e.g. public buildings, religious buildings, etc.). The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Others buildings R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=3)	n/a	n/a	n/a	n/a	n/a	n/a
1896 (n=45)	93.5%	94.5%	95.6%	92.0%	97.5%	93.5%
1908 (n=10)	75.4%	89.1%	89.4%	87.6%	88.2%	73.7%
1932 (n=27)	90.0%	89.6%	87.1%	93.1%	86.2%	91.4%
1953 (n=47)	99.2%	98.8%	97.7%	99.8%	96.8%	99.4%
Average R^2	89.5%	93.1%	92.5%	93.1%	92.2%	89.5%
R^2 std dev	10.1%	4.6%	5.0%	5.0%	5.8%	11.1%

Table S29 – Salford all buildings (of this case study) R² values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R² is the mean of all the cohort R² for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

All buildings R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=98)	98.0%	97.9%	97.3%	98.3%	96.5%	97.9%
1896 (n=947)	95.8%	95.7%	95.8%	96.1%	95.8%	95.9%
1908 (n=220)	88.0%	87.5%	85.9%	89.3%	85.0%	88.8%
1932 (n=1228)	95.8%	95.1%	94.7%	95.8%	94.2%	95.5%
1953 (n=509)	97.9%	99.0%	99.4%	97.8%	99.6%	97.1%
Average R^2	95.1%	95.1%	94.6%	95.5%	94.2%	95.0%
R^2 std dev	4.1%	4.5%	5.2%	3.6%	5.5%	3.6%

10.2.2.2 Average lifespan and standard deviation

This section displays the calculated lifespan and standard deviation for the five categories (high density residential buildings, low/mid density residential buildings, industrial buildings, other buildings, and the totality of buildings). On some occasions it has not been possible to calculate the standard deviation for the Gompertz distribution being its variance a negative number (i.e. being its standard deviation a complex number).

Table S30 – Salford high density residential buildings average lifespan and, between parenthesis, standard deviation for five different cohorts and six different distributions.

High density residential lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=40)	115.5 (46)	114.8 (45.2)	112.9 (51.2)	117.6 (43.2)	111.8 (58.9)	115.8 (50.3)
1896 (n=710)	81 (5.3)	81.4 (5.3)	80.9 (5.3)	82 (8.8)	80.9 (5.4)	81 (5.8)
1908 (n=140)	95 (24.9)	95.3 (24)	94.8 (27)	95.4 (23.3)	94.7 (29.2)	95 (27.5)
1932 (n=258)	80.1 (36.5)	82 (41.5)	83.4 (52.4)	79.6 (30.8)	84.2 (75.4)	79.1 (38.2)
1953 (n=80)	46.1 (21.5)	46 (23.2)	45.6 (26.8)	46.7 (19.9)	45.4 (35.6)	46.1 (23.6)

Table S31 – Salford low/mid density residential buildings average lifespan and, between parenthesis, standard deviation for five different cohorts and six different distributions.

Mid/low density residential lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=43)	70.6 (47.9)	67.5 (45.4)	66.3 (47.8)	69.2 (43.8)	65.1 (54.4)	70.4 (51.9)
1896 (n=103)	85.9 (27.4)	86 (26.1)	85.2 (28.9)	87.1 (26.6)	85 (30.9)	86.1 (29.4)
1908 (n=14)	116.9 (71.9)	154.5 (229.5)	155.4 (237.3)	129.6 (91.8)	189.3 (2930.4)	114 (73.9)
1932 (n=722)	231.2 (86.7)	520.8 (399.5)	806.8 (910.8)	692.8 (341)	4180.2 (445259.9)	187.7 (62.5)
1953 (n=179)	91.2 (52.2)	181.2 (347.2)	173.2 (297.5)	145.3 (606.3)	247.7 (10336.7)	87 (51.6)

Table S32 – Salford industrial buildings average lifespan and, between parenthesis, standard deviation for five different cohorts and six different distributions.

Factories lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=12)	105.2 (26.4)	105.8 (27.4)	104 (26.2)	107.9 (29.6)	103.4 (26.5)	104.8 (28.3)
1896 (n=89)	62.8 (32.4)	61 (31.7)	59.1 (35.4)	63.9 (29.9)	57.8 (41.4)	63.1 (35.3)
1908 (n=56)	60.1 (35.7)	57.8 (37.1)	56.7 (41.9)	59.9 (32.5)	55.3 (56.1)	60.4 (39.2)
1932 (n=221)	51.2 (14.9)	51.4 (14.1)	51 (13.4)	51.8 (15.9)	50.8 (13.5)	51.2 (16.4)
1953 (n=203)	33.5 (12.2)	33.4 (12)	32.9 (12.7)	34.1 (12.2)	32.6 (13.6)	33.4 (13)

Table S33 – Salford other buildings (e.g. public buildings, religious buildings) average lifespan and, between parenthesis, standard deviation for five different cohorts and six different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number.

Other buildings lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=3)	n/a	n/a	n/a	n/a	n/a	n/a
1896 (n=45)	32.2 (13.9)	32.7 (28.2)	32.6 (27.1)	31.4 (32)	31 (34.2)	32.4 (16)
1908 (n=10)	59.4 (58.3)	48.1 (182.3)	44.7 (138.8)	53.8 (n/a)	46.4 (1354)	59.5 (65.7)
1932 (n=27)	65.6 (25.8)	65.1 (22.9)	65.2 (27.6)	65.4 (21.3)	64.9 (30.5)	65.5 (27.4)
1953 (n=47)	42.2 (16.5)	42 (16)	41.5 (18.8)	42.9 (15)	41.2 (22)	42.3 (17.9)

Table S34 – Salford all buildings (of this case study) average lifespan and, between parenthesis, standard deviation for five different cohorts and six different distributions.

All buildings lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=98)	92.4 (49.8)	90.3 (48.2)	88.4 (52.6)	93.3 (46.2)	86.5 (61.6)	92.6 (54.3)
1896 (n=947)	80.7 (7.4)	80.5 (10.4)	80.6 (7.3)	80.2 (13.7)	80.6 (7.3)	80.6 (8.8)
1908 (n=220)	88.4 (37.6)	88.2 (36.6)	88.8 (45.7)	88.2 (31.8)	88.7 (55.3)	88 (39.6)
1932 (n=1228)	93.9 (40.6)	99.3 (50.2)	103.3 (68)	91.5 (32.5)	108 (117.7)	91.1 (40.4)
1953 (n=509)	44.8 (22.2)	44.6 (24.1)	44.3 (27.9)	45.4 (20.4)	44.1 (38.2)	44.9 (24.2)

10.2.2.3 Distribution parameters

In this part of the supporting information we report the parameters that we used to generate the reliability curves, and to estimate the average lifespan and standard deviation.

Table S35 – Equation parameters for Salford high density residential buildings.

High density residential parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=40)	μ=115.5 σ=46	k=2.793 λ=130.9	k=5.51 θ=21.8	b=0.02409 η=0.043	μ=4.72 σ=0.45	μ=115.8 s=27.7
1896 (n=710)	μ=81 σ=5.3	k=18.998 λ=83	k=232.13 θ=0.3	b=0.14647 η=0.000004	μ=4.39 σ=0.07	μ=81 s=3.2

1908 (n=140)	μ=95 σ=24.9	k=4.451 λ=103.4	k=12.96 θ=7.5	b=0.05226 η=0.005	μ=4.55 σ=0.29	μ=95 s=15.1
1932 (n=258)	μ=80.1 σ=36.5	k=2.184 λ=97	k=3.15 θ=29.6	b=0.03258 η=0.056	μ=4.43 σ=0.65	μ=79.1 s=21
1953 (n=80)	μ=46.1 σ=21.5	k=2.19 λ=54.3	k=3.53 θ=14.3	b=0.04706 η=0.087	μ=3.82 σ=0.6	μ=46.1 s=13

Table S36 – Equation parameters for Salford low/mid density residential buildings.

Mid/low density residential parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=43)	μ=70.6 σ=47.9	k=1.696 λ=83.8	k=2.53 θ=30.1	b=0.01388 η=0.43	μ=4.18 σ=0.62	μ=70.4 s=28.6
1896 (n=103)	μ=85.9 σ=27.4	k=3.663 λ=95.1	k=9.33 θ=9.5	b=0.04296 η=0.017	μ=4.44 σ=0.33	μ=86.1 s=16.2
1908 (n=14)	μ=116.9 σ=71.9	k=0.984 λ=224.2	k=0.95 θ=243.6	b=0.00561 η=0.648	μ=5.24 σ=1.66	μ=114 s=40.8
1932 (n=722)	μ=231.2 σ=86.7	k=1.524 λ=662.4	k=1.34 θ=785.4	b=0.00241 η=0.161	μ=8.34 σ=2.16	μ=187.7 s=34.4
1953 (n=179)	μ=91.2 σ=52.2	k=0.863 λ=277	k=0.84 θ=323.8	b=0.00017 η=28.281	μ=5.51 σ=1.93	μ=87 s=28.4

Table S37 – Equation parameters for Salford industrial buildings.

Factories parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=12)	μ=105.2 σ=26.4	k=4.327 λ=115.1	k=16.38 θ=6.5	b=0.04003 η=0.009	μ=4.64 σ=0.25	μ=104.8 s=15.6
1896 (n=89)	μ=62.8 σ=32.4	k=2.127 λ=72.5	k=3.41 θ=19.2	b=0.02888 η=0.13	μ=4.06 σ=0.56	μ=63.1 s=19.5
1908 (n=56)	μ=60.1 σ=35.7	k=1.763 λ=71.2	k=2.44 θ=26.8	b=0.02274 η=0.238	μ=4.01 σ=0.7	μ=60.4 s=21.6
1932 (n=221)	μ=51.2 σ=14.9	k=4.083 λ=56.3	k=15.18 θ=3.4	b=0.07153 η=0.017	μ=3.93 σ=0.25	μ=51.2 s=9
1953 (n=203)	μ=33.5 σ=12.2	k=3.072 λ=37.7	k=7.39 θ=4.7	b=0.08622 η=0.039	μ=3.48 σ=0.37	μ=33.4 s=7.2

Table S38 – Equation parameters for other Salford buildings (e.g. public buildings, religious buildings).

Other buildings parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=3)	n/a	n/a	n/a	n/a	n/a	n/a
1896 (n=45)	μ=32.2 σ=13.9	k=1.391 λ=42.5	k=2.04 θ=18.9	b=0.00732 η=2.681	μ=3.43 σ=0.73	μ=32.4 s=8.8
1908 (n=10)	μ=59.4 σ=58.3	k=0.652 λ=84.4	k=0.53 θ=190.5	b=0.0001 η=126.807	μ=3.84 σ=1.84	μ=59.5 s=36.2
1932 (n=27)	μ=65.6 σ=25.8	k=3.129 λ=73.2	k=6.21 θ=11.1	b=0.05229 η=0.023	μ=4.17 σ=0.41	μ=65.5 s=15.1
1953 (n=47)	μ=42.2 σ=16.5	k=2.878 λ=47.7	k=5.51 θ=8	b=0.07122 η=0.034	μ=3.72 σ=0.46	μ=42.3 s=9.9

Table S39 – Equation parameters for all the buildings included in the Salford case study.

All buildings parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1849 (n=98)	μ=92.4 σ=49.8	k=2.077 λ=107.7	k=3.45 θ=28.3	b=0.01767 η=0.165	μ=4.46 σ=0.56	μ=92.6 s=30
1896 (n=947)	μ=80.7 σ=7.4	k=9.164 λ=83.8	k=123.67 θ=0.7	b=0.0929 η=0.0004	μ=4.39 σ=0.09	μ=80.6 s=4.9
1908 (n=220)	μ=88.4 σ=37.6	k=2.65 λ=101.3	k=4.41 θ=21.7	b=0.03314 η=0.039	μ=4.49 σ=0.51	μ=88 s=21.8
1932 (n=1228)	μ=93.9 σ=40.6	k=2.185 λ=117.4	k=2.92 θ=39.8	b=0.03273 η=0.037	μ=4.68 σ=0.73	μ=91.1 s=22.3
1953 (n=509)	μ=44.8 σ=22.2	k=2.058 λ=53.3	k=3.14 θ=15.7	b=0.04394 η=0.109	μ=3.79 σ=0.64	μ=44.9 s=13.4

10.2.3 Wakayama, Japan

10.2.3.1 R^2 values

We here report the R^2 values for four categories of buildings in Wakayama: residential, commercial, industrial, and the totality of buildings.

Table S40 – Wakayama residential buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Residential R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=5878)	84.9%	99.9%	99.9%	97.5%	99.9%	84.4%
1958 (n=4615)	86.2%	99.9%	99.9%	98.6%	99.7%	84.2%
Average R^2	85.5%	99.9%	99.9%	98.1%	99.8%	84.3%
R^2 std dev	0.9%	0.1%	0.1%	0.9%	0.1%	0.1%

Table S41 – Wakayama commercial buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Commercial R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=2667)	87.8%	99.8%	99.7%	85.8%	99.9%	87.9%
1958 (n=7726)	86.1%	99.8%	99.8%	99.1%	99.9%	85.4%
Average R^2	86.9%	99.8%	99.7%	92.5%	99.9%	86.7%
R^2 std dev	1.2%	0.1%	0.1%	9.4%	0.0%	1.8%

Table S42 – Wakayama industrial buildings R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

Industrial R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=3563)	95.4%	99.7%	99.7%	99.8%	99.3%	95.2%
1958 (n=4178)	87.4%	99.8%	99.8%	99.4%	99.9%	86.2%
Average R^2	91.4%	99.8%	99.7%	99.6%	99.6%	90.7%

R^2 std dev	5.7%	0.1%	0.1%	0.3%	0.5%	6.3%

Table S43 – Wakayama all buildings (of this case study) R^2 values expressed as percentage for curve fitting. The left column represents the year of the cohorts and the sample size, the average R^2 is the mean of all the cohort R^2 for a specific distribution. The colours represent the grade of fitting, where red indicates the worst, and blue the best.

All buildings R^2	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=12428)	88.5%	99.9%	99.9%	98.9%	99.9%	88.3%
1958 (n=16842)	85.9%	99.9%	99.9%	99.1%	99.9%	84.6%
Average R^2	87.2%	99.9%	99.9%	99.0%	99.9%	86.5%
R^2 std dev	1.9%	0.1%	0.0%	0.2%	0.0%	2.7%

10.2.3.2 Average lifespan and standard deviation

This section displays the calculated lifespan and standard deviation for the four categories (residential buildings, commercial buildings, industrial buildings, and the totality of buildings). On some occasions it has not been possible to calculate the standard deviation for the Gompertz distribution being its variance a negative number (i.e. being its standard deviation a complex number).

Table S44 – Wakayama residential buildings average lifespan and, between parenthesis, standard deviation for two different cohorts and six different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number.

Residential lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=5878)	29.4 (29.4)	22.3 (67.3)	22.6 (56)	25.1 (n/a)	21.5 (256)	29.2 (32.5)
1958 (n=4615)	35.3 (29)	33.3 (77.8)	33.4 (68)	33 (n/a)	32.8 (332.6)	35.3 (32.3)

Table S45 – Wakayama commercial buildings average lifespan and, between parenthesis, standard deviation for two different cohorts and six different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number.

Commercial lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=2667)	18 (17.9)	12.1 (34.4)	12.1 (30.7)	11.4 (4.5)	12.2 (69.3)	17.7 (19.7)
1958 (n=7726)	25.4 (22.8)	20.5 (46.1)	20.5 (42)	22 (n/a)	20.2 (108.6)	25.1 (25.1)

Table S46 – Wakayama industrial buildings average lifespan and, between parenthesis, standard deviation for two different cohorts and six different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number.

Industrial lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=3563)	29.6 (23.4)	25.8 (31.5)	25.7 (32.6)	26.2 (28.1)	24.5 (61.7)	29.4 (25.4)
1958 (n=4178)	28.6 (24.5)	24.6 (47.4)	24.7 (44.4)	25.4 (n/a)	24 (115.1)	28.4 (27.1)

Table S47 – Wakayama all buildings (of this case study) average lifespan and, between parenthesis, standard deviation for two different cohorts and six different distributions. The standard deviation for the Gompertz distribution is reported as (n/a) when this is a complex number.

All buildings lifespan and standard dev	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=12428)	26.7 (25.7)	20.5 (46.6)	20.6 (42.4)	22.5 (n/a)	19.6 (122.6)	26.4 (28.2)
1958 (n=16842)	28.7 (25.2)	24.3 (54.9)	24.4 (49.4)	25.5 (n/a)	23.9 (154.2)	28.6 (28)

10.2.3.3 Distribution parameters

In this part of the supporting information we report the parameters that we used to generate the reliability curves, and to estimate the average lifespan and standard deviation.

Table S48 – Equation parameters for Wakayama residential buildings.

Residential parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=5878)	μ=29.4 σ=29.4	k=0.71 λ=37.4	k=0.6 θ=72.6	b=0.00017 η=160.2	μ=3.07 σ=1.59	μ=29.2 s=17.9
1958 (n=4615)	μ=35.3 σ=29	k=0.788 λ=53	k=0.71 θ=80.9	b=0.00035 η=60.3	μ=3.49 σ=1.54	μ=35.3 s=17.8

Table S49 – Equation parameters for Wakayama commercial buildings.

Commercial parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=2667)	μ=18.0 σ=17.9	k=0.726 λ=20.0	k=0.58 θ=40.1	b=0.21830 η=0.06	μ=2.50 σ=1.35	μ=17.7 s=10.8
1958 (n=7726)	μ=25.4 σ=22.8	k=0.801 λ=32.4	k=0.70 θ=50.1	b=0.00032 η=99.00	μ=3.01 σ=1.33	μ=25.1 s=13.8

Table S50 – Equation parameters for Wakayama industrial buildings.

Industrial parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=3563)	μ=29.6 σ=23.4	k=1.10 λ=36.0	k=1.16 θ=30.3	b=0.00691 η=3.5	μ=3.20 σ=1.06	μ=29.4 s=14.0
1958 (n=4178)	μ=28.6 σ=24.5	k=0.86 λ=37.6	k=0.79 θ=49.8	b=0.00041 η=66.2	μ=3.18 σ=1.29	μ=28.4 s=15.0

Table S51 – Equation parameters for all Wakayama buildings (of this case study).

All buildings parameters	*Normal*	*Weibull*	*Gamma*	*Gompertz*	*Log-normal*	*Logistic*
1947 (n=12428)	μ=26.7 σ=25.7	k=0.8 λ=32.4	k=0.7 θ=50.6	b=0.00019 η=159.5	μ=2.98 σ=1.38	μ=26.4 s=15.5
1958 (n=16842)	μ=28.7 σ=25.2	k=0.8 λ=38.5	k=0.7 θ=58.7	b=0.00029 η=93.0	μ=3.17 σ=1.39	μ=28.6 s=15.4

11 Appendix 2 to Modelling material flows and stocks of the road network in the United States 1905-2015

11.1 Model description

The main parameter used by the model to estimate the evolution of roads is the annual length of the road network by surface type. Alongside this main driver four additional variables are used to convert this information into material stocks and flows: maximum yearly recovery rate; maximum yearly allowed recyclable content; maintenance interval; and material intensity.

11.1.1 Model variables

Road length: this parameter is differentiated into 7 different surfaces (non-surfaced pavement; surfaced non-paved pavement; flexible low-type pavement; flexible intermediate-type pavement; flexible high-type pavement; rigid high-type pavement; and high composite type pavement), 2 types (urban and rural), and 111 years (1905 to 2015).

Maximum yearly recovery rate: expressed as the percentage of materials that are recovered from the outflow generated by the cyclical maintenance of the wearing layer. The parameter varies by year (1905 to 2015).

Maximum yearly allowed recyclable content: expressed as the percentage of recycled materials that can legally be included in the newly made wearing layer. The parameter varies by year (1905 to 2015).

Maintenance interval: this parameter indicates the average amount of time that elapses between two scheduled maintenance events for the wearing layer of roads. It is differentiated into 7 different surfaces (non-surfaced pavement; surfaced non-paved pavement; flexible low-type pavement; flexible intermediate-type pavement; flexible high-type pavement; rigid high-type pavement; and high composite type pavement), and 2 types (urban and rural).

Material intensity: this parameter calculates the amount of materials that are used to construct a unit of length of road (in our case the unit is tonnes per kilometre). It is differentiated into 7 different surfaces (non-surfaced pavement; surfaced non-paved pavement; flexible low-type pavement; flexible intermediate-type pavement; flexible high-type pavement; rigid high-type pavement; and high composite type pavement), 2 types (urban and rural), 5 materials (cement, gravel, sand, bitumen, rammed earth), and location (bedding layer, and wearing layer).

11.1.2 Calculating material stock

The material stock is a very straightforward calculation: having an explicit database listing the length of roads by surface type, and multiplying this value by the material intensity expressed in tonnes/kilometre, it is possible to calculate the material stock and its composition over time. The conceptual flowchart is shown in Figure SI 1.

$$Material\ stock\ _{m,y} = \ Road\ length_{s,t,y} \cdot Material\ intensity_{s,t,m,l} \tag{1}$$

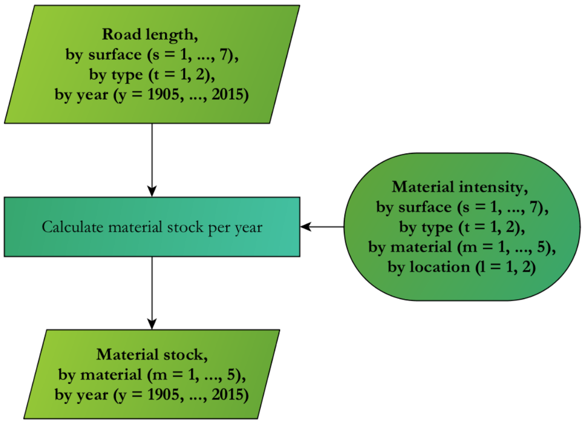

Figure SI 1 – Flowchart of stock model. Different shapes indicate different functions: parallelograms for inputs/outputs, ovals for variables, and rectangles for operations.

11.1.3 Calculating gross inflows

To calculate the net amount of virgin materials[8] required to build and maintain the road network, we first have to assess the gross requirement, i.e. the amount of material that is needed disregarding its origin. A conceptual summary is displayed in Figure SI 2.

To estimate the gross inflows required for new construction, it is firstly necessary to calculate year to year road length changes:

$$\Delta\_Road\_length_{s,t,y} = Road\_length_{s,t,y} - Road\_length_{s,t,y-1} \tag{2}$$

Which can then be multiplied by relative material intensity to estimate the gross inflow requirements for new construction:

$$Gross\_inflow\_(new)_{m,y} = \Delta\_Road\_length_{s,t,y} \cdot Material\_intensity_{s,t,m,l} \tag{3}$$

To estimate the gross inflows required for new maintenance, it is firstly necessary to estimate the length of roads that require maintenance in a specific year:

$$Road\_to\_maint_{s,t,y} = Road\_length_{s,t,y} \cdot Maint\_interval_{s,t}{}^{-1} \tag{4}$$

It is then possible to estimate the gross inflows required to maintain the wearing layer of roads by multiplying the length calculated in Equation (4) by the material intensity:

$$Gross\_inflow\_(maint)_{m,y} = Road\_to\_maint_{s,t,y} \cdot Material\_intensity_{s,t,m,l} \tag{5}$$

[8] When we talk about virgin materials, we refer to any material that comes from outside our system boundaries, regardless of its origin or if it had any previous use (cf. Figure 1 of the main manuscript). With recycled materials we refer to materials which are recovered from scraped wearing layers, and reused in the new admixture with the same function. With downcycled materials we intend those materials that, within our system boundaries, are recovered during the maintenance of the wearing layer of roads, and are used as fillings in new road beds.

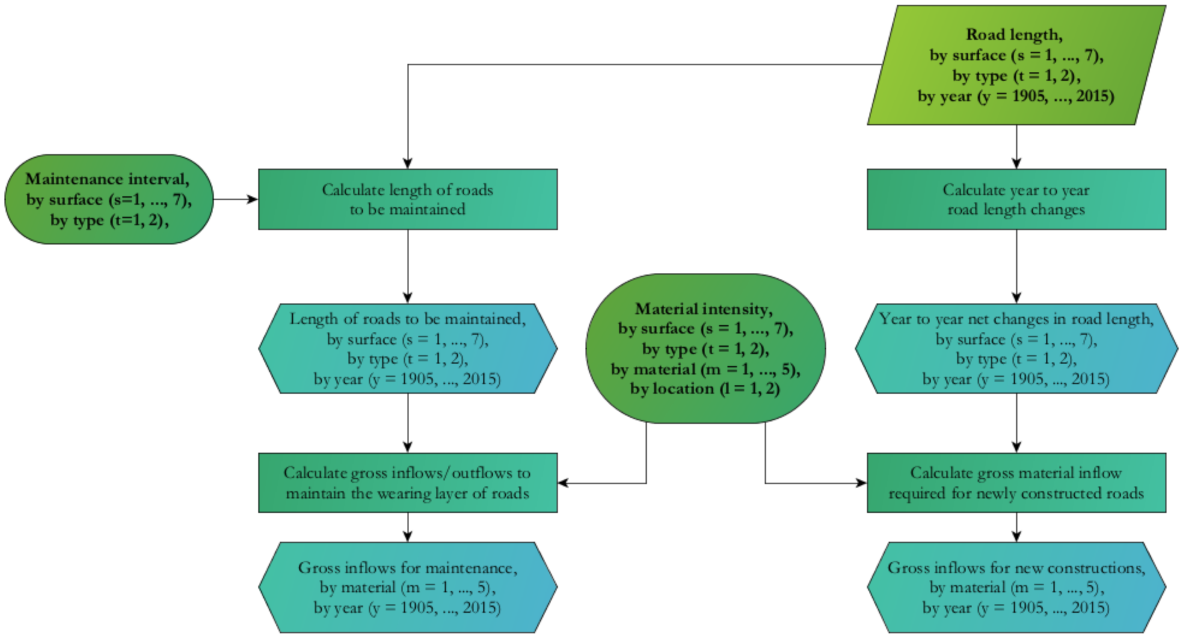

Figure SI 2 – Sub-flowchart of the model to calculate the gross (before recycling and downcycling) inflow of materials required to build and maintain roads. Different shapes indicate different functions: parallelograms for inputs/outputs, ovals for variables, rectangles for operations, and hexagons for internal data.

11.1.4 Recycled and down-cycled flows

The gross inflow requirement for maintenance calculated in 11.1.3 is equivalent to the gross amount of outflows for maintenance, because we assume that maintenance is not used to alter the quality of roads, but simply to restore the roads to their optimal performance.

Once the gross inflow required for maintenance (which is equal to its outflow) is calculated, we can estimate the potential amount of retrieved resources by multiplying this by the Max yearly recovery rate parameter. Multiplying this result by the maximum amount of recycled content allowed in the new wearing layer, we can calculate the yearly amount of recycled materials in the system.

$$Recoverable\_mat_{m,y} = Gross\_inflow\_(maint)_{m,y} \cdot Max\_recovery\_rate_{y} \tag{6}$$

$$Max\_recycled\_mat_{m,y} = Gross\_inflow\_(maint)_{m,y} \cdot Max\_allowed\_rate_{y} \tag{7}$$

$$Recycled\_mat_{m,y} = \begin{cases} Recoverable\_mat_{m,y} \text{ if } Recoverable\_mat_{m,y} \leq Max\_recycled\_mat_{m,y} \\ Max\_recycled\_mat_{m,y} \text{ if } Recoverable\_mat_{m,y} > Max\_recycled\_mat_{m,y} \end{cases} \tag{8}$$

We can then check if there are any materials that have been recovered but have not been recycled in the wearing layer, and verify whether they can be allocated to the sublayer of newly constructed roads.

$$Downcyclable\_mat_{m,y} = Recoverable\_mat_{m,y} - Recycled\_materials_{m,y} \tag{9}$$

$$Downcycled\_mat_{m,y} = \begin{cases} Downcyclable\_mat_{m,y} \text{ if } Downcyclable\_mat_{m,y} \leq Gross\_inflow\_(new\_sub)_{m,y} \\ Gross\_inflow\_(new\_sub)_{m,y} \text{ if } Downcyclable\_mat_{m,y} > Gross\_inflow\_(new\_sub)_{m,y} \end{cases} \tag{10}$$

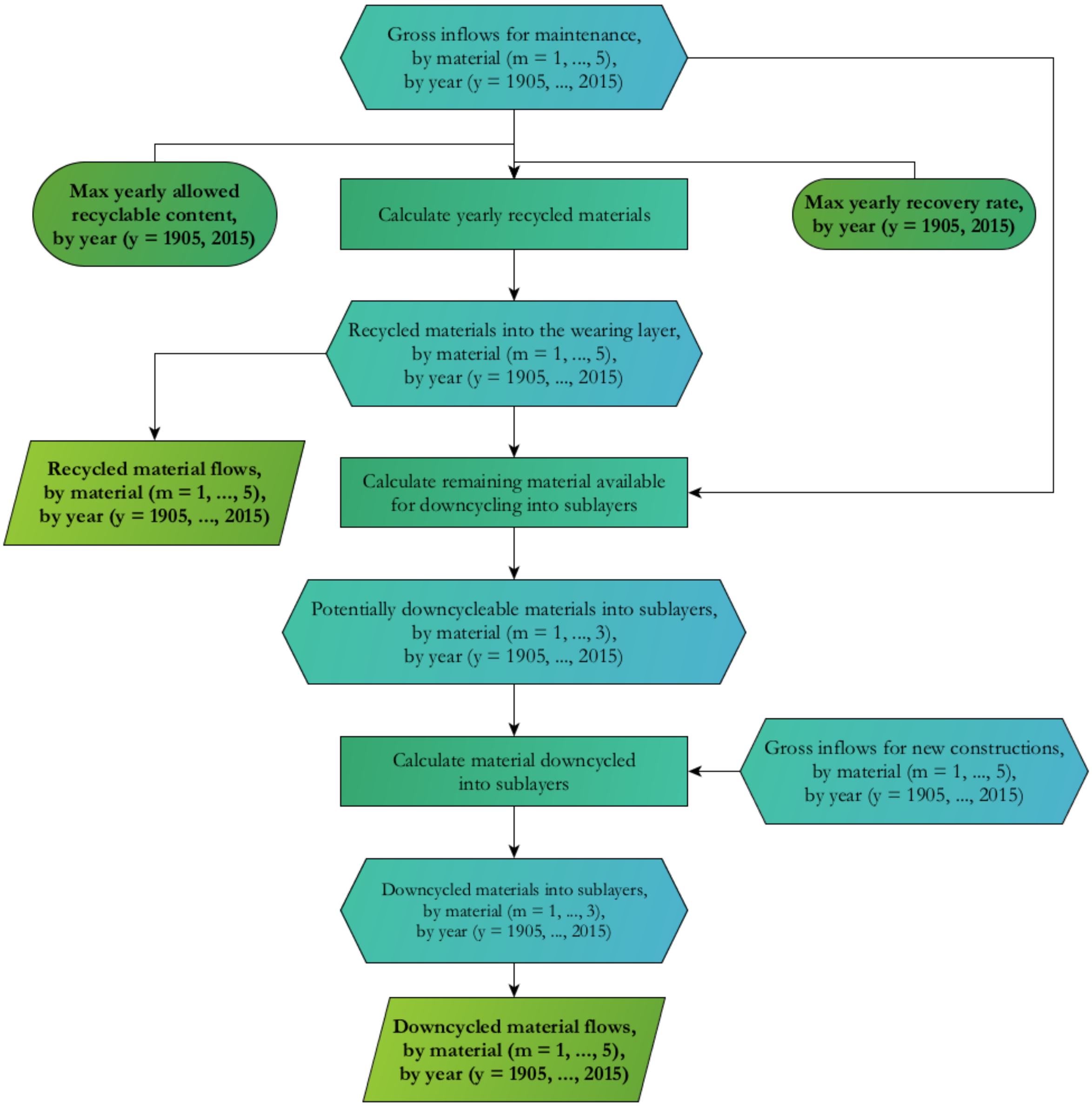

Figure SI 3 – Sub-flowchart of the model to calculate the recycled and downcycled material flows. Different shapes indicate different functions: parallelograms for inputs/outputs, ovals for variables, rectangles for operations, and hexagons for internal data.

11.1.5 Calculating virgin inflows and end of life waste

In its final step, the model uses the datasets generated in §11.1.4 to calculate the amount of virgin materials required for construction and maintenance, and the quantity of waste that is generated from maintenance. This is summarised in Figure SI 4.

Once the material inflow requirements for new construction and maintenance are known (cf. §11.1.3), and the amount of materials being recycled and down-cycled have been made explicit (cf. §11.1.4), calculating the amount of virgin materials can be simply done as:

$$\begin{aligned} Virgin\_inflow_{m,y} &= Gross\_inflow\_(new)_{m,y} + Gross\_inflow\_(maint)_{m,y} - Recycled\_mat_{m,y} \\ &- Downcycled\_mat_{m,y} \end{aligned} \quad (11)$$

Similarly, it is possible to calculate the annual amount of waste materials exiting the system by calculating:

$$Waste\_outflow_{m,y} = Gross\_inflow\_(new)_{m,y} + Gross\_inflow\_(maint)_{m,y} - Recycled\_mat_{m,y} - Downcycled\_mat_{m,y} \quad (12)$$

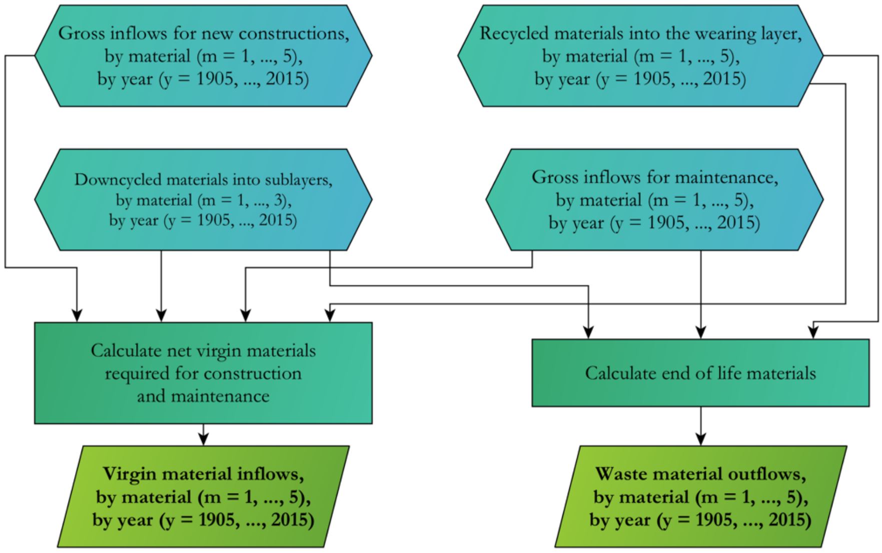

Figure SI 4 – Sub-flowchart of the model to calculate the virgin material inflows, and the end of life waste flows. Different shapes indicate different functions: parallelograms for inputs/outputs, rectangles for operations, and hexagons for internal data.

11.1.6 Model sensitivity analysis

As reported in the main manuscript (cf. §2.4 and §3.4 of the main manuscript), the material stock is linearly dependent on the material intensity and total road length, while inflows and outflows are dependent on all the model parameters. We now report the charts relative to the absolute and relative difference of virgin material inflows and end of life outflows, expanding on the information reported in Table 2 of the main manuscript.

Figure SI 5 displays the difference in absolute terms between the standard parameters that we adopted in our model and variations to those model variables that affect only inflows and outflows without making any difference in the stock. The single parameter that has most influence on the stock is the maintenance interval (+224.5 Mt to -120.9 Mt), followed by the percentage of recycled materials allowed to be included in the new wearing layer (±47.0 Mt). The parameter maximum yearly recovery rate has nearly no influence on the amount of virgin inflows. The relative differences among these parameters are plotted in Figure SI 6.

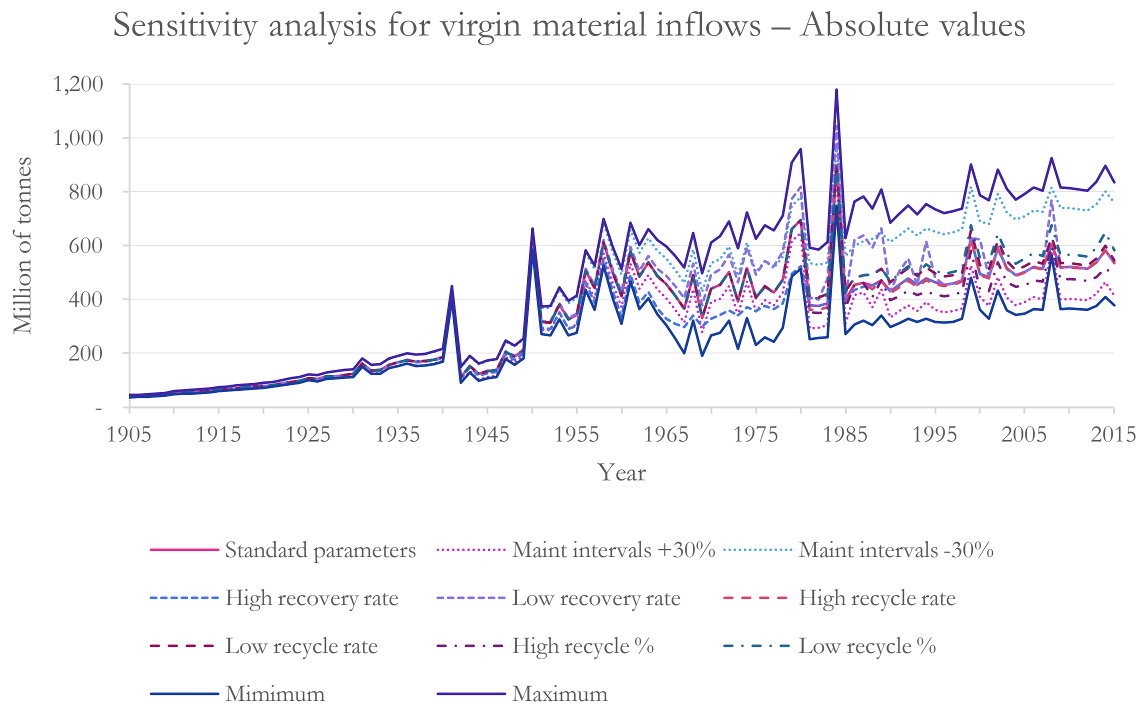

Figure SI 5 – Sensitivity analysis of virgin material inflows for the parameters Maximum yearly recovery rate, Maximum yearly allowed recyclable content, and Maintenance interval. The lines labelled as "minimum" and "maximum" represent the extreme cases in which all the parameters contribute to minimise or maximise virgin material inflows. Note that the same parameter has the same line type, but different colours.

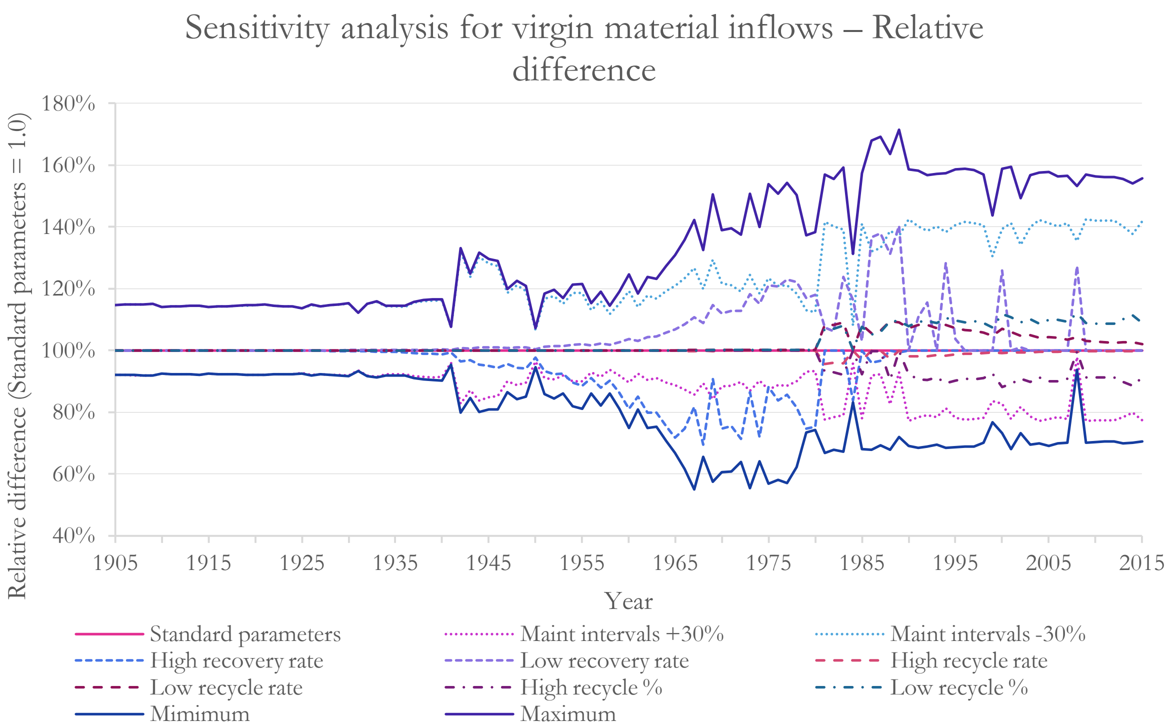

Figure SI 6 – Sensitivity analysis of the relative difference of virgin material inflows. The parameters tested are Maximum yearly recovery rate, Maximum yearly allowed recyclable content, and Maintenance interval. The lines labelled as "minimum" and "maximum" represent the extreme cases in which all the parameters contribute to minimise or maximise virgin material inflows. Note that the same parameter has the same line type, but different colours.

The same analysis has been conducted for the waste outflows, and its results are shown in Figure SI 7. The most influential parameters are the same ones of the virgin inflows, and show the exact same absolute difference. This is because none of these flows affect the material stock, therefore, for the rule of the continuity of mass, an increment of 224.5 Mt of inflows (such as in the case of +30% maintenance intervals) needs to correspond to an increment of outflows of the exact same amount. The relative differences of outflows are shown in Figure SI 8. The peak in year 2008 is due to the very low outflows forecasted by the model (48.3 Mt) compared to the maximum value forecast by the sensitivity analysis (369.3 Mt).

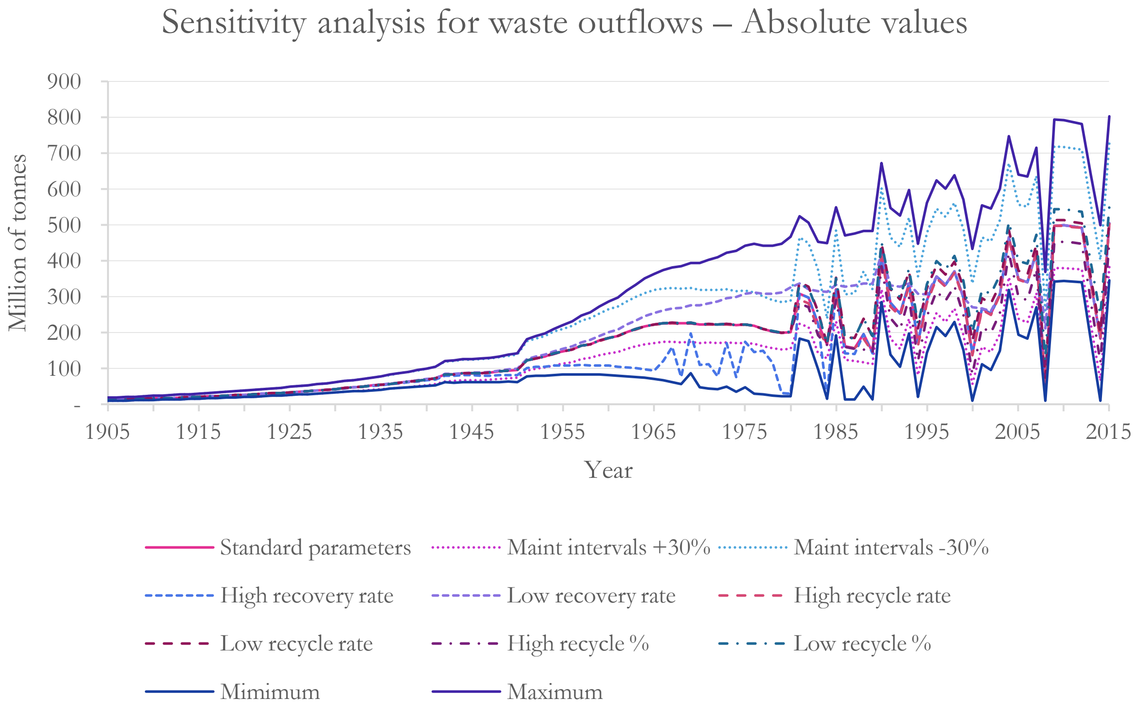

Figure SI 7 – Sensitivity analysis of end of life outflows for the parameters Maximum yearly recovery rate, Maximum yearly allowed recyclable content, and Maintenance interval. The lines labelled as "minimum" and "maximum" represent the extreme cases in which all the parameters contribute to minimise or maximise waste outflows. Note that the same parameter has the same line type, but different colours.

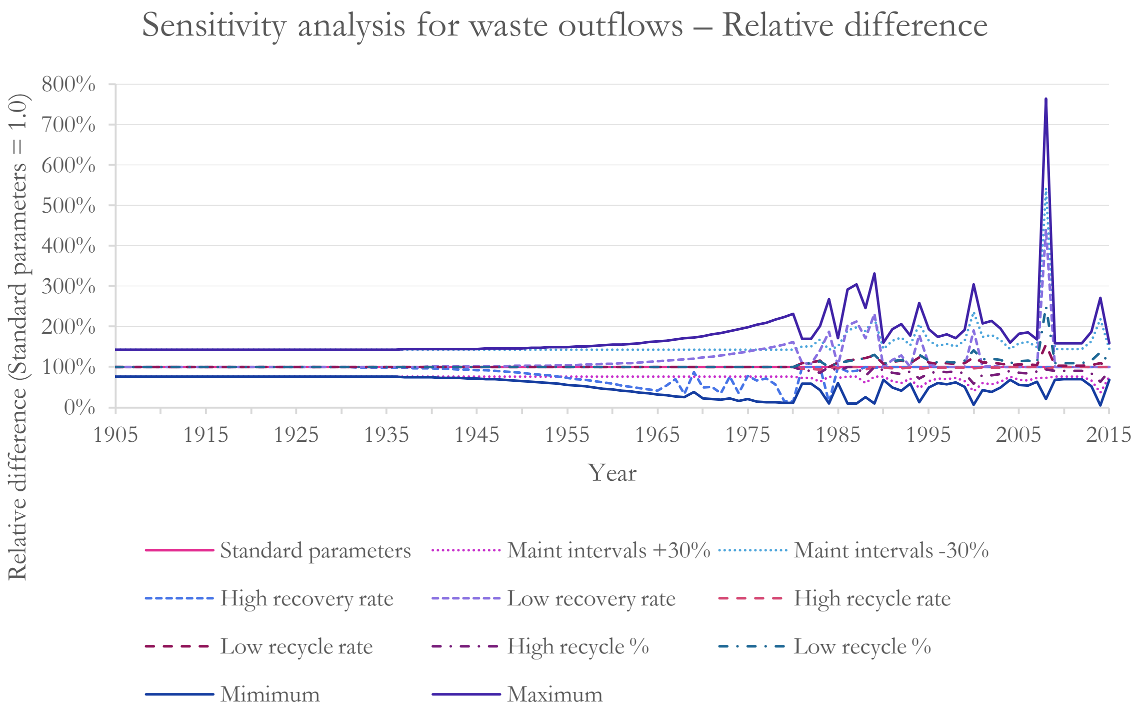

Figure SI 8 – Sensitivity analysis of the relative difference of end of life outflows. The parameters tested are Maximum yearly recovery rate, Maximum yearly allowed recyclable content, and Maintenance interval. The lines labelled as "minimum" and "maximum" represent the extreme cases in which all the parameters contribute to minimise or maximise waste outflows. Note that the same parameter has the same line type, but different colours.

11.2 Road pavements

Our model comprises seven different road types: non-surfaced pavement, surfaced non-paved pavement, low-type pavement, intermediate-type pavement, flexible high-type pavement, rigid high-type pavement, and composite high-type pavement. Their description has been taken from the Highway Statistic reports which have been published regularly by the US Department of Transport since 1945.

We report here the definition of the road surface types as reported by the US Department of Transport.

- Unpaved mileage includes the following categories:
  - Unimproved roadways using the natural surface and maintained to permit passage;
  - Graded and Drained roadways of natural earth aligned and graded to permit reasonably convenient use by motor vehicles and which have adequate drainage to prevent serious impairment of the road by normal surface water— surface may be stabilised;
  - Soil, Gravel, or Stone, a graded and drained road with a surface of mixed soil, gravel, crushed stone, slag, shell, etc.— surface may be stabilised.
- Paved mileage includes the following categories:
  - Low Type, an earth, gravel, or stone roadway which has a bituminous surface course less than 1" (25.4 mm) thick— suitable for occasional heavy loads;
  - Intermediate Type, a mixed bituminous or bituminous penetration roadway on a flexible base having a combined surface and base thickness of less than 7" (177.8 mm);

- o High-Type Flexible, a mixed bituminous or bituminous penetration roadway on a flexible base having a combined surface and base thickness of 7" (177.8 mm) or more— also includes brick, block, or combination roadways;
- o High-Type Composite, a mixed bituminous or bituminous penetration roadway of more than 1" (25.4 mm) compacted material on a rigid base with a combined surface and base thickness of 7" (177.8 mm) or more;
- o High-Type Rigid, a Portland Cement Concrete roadway with or without a bituminous wearing surface of less than 1" (25.4 mm).

While not providing a detailed description of the thickness of each layer, this being dependant on local characteristics such as soil composition and load bearing, traffic, and weather, it gives a very useful indication of minimum and maximum height of the cross section of the pavement. The pavement layers used in our model are the following (cf. Figure 3 of the main manuscript):

- Unsurfaced pavement: this being pavement composed only of soil, we did not consider any sublayer, and assumed 10 mm of wearing layer composed of rammed soil.
- Unpaved pavement: composed of two layers of gravel. The first part (30 mm) is the sublayer, while the upper part (20 mm) is the wearing layer.
- Low type pavement: the sublayer is composed of gravel (50 mm), while the wearing layer is composed of a mixture of bitumen and gravel (asphalt concrete) having a thickness of 20 mm.
- Intermediate type pavement: the sublayer is made of gravel (135 mm), while the wearing layer is made of asphalt concrete (35 mm).
- High flexible type pavement: the sublayer is made of gravel (210 mm), while the wearing layer is made of asphalt concrete (50 mm).
- High composite type pavement: the sublayer is composed first of a layer of gravel (30 mm) on which a slab of cement concrete has been poured (150 mm). The wearing layer is composed of asphalt concrete (50 mm).
- High rigid type pavement: the sublayer is constructed with a layer of gravel (50 mm), and the wearing layer is built out of cement concrete (170 mm).

11.2.1 Material intensity of road pavements

In Table SI 1 we report the material intensity that we used in our model.

Table SI 1 – Material intensity of roads by surface type. The values are expressed in tonnes per kilometre.

	Rammed earth (t/km)	Gravel (t/km)	Sand (t/km)	Cement (t/km)	Bitumen (t/km)	Total (t/km)
Unsurfaced pavement	32	0	0	0	0	32
Unpaved pavement	0	231	0	0	0	231
Low type pavement	0	444	0	0	4	447
Intermediate pavement	0	1722	0	0	11	1732
High flexible pavement	0	4607	0	0	27	4634

High composite pavement	0	3260	1728	522	19	5528
High rigid pavement	0	2862	1958	592	0	5412

11.3 Evolution of the roads in the United States of America

In the main manuscript, we mentioned that the total length of the road network has not even doubled during the past 110 years, going from 3,800,000 km to 6,600,000 km, and the network has mostly seen improvement in its quality rather than a huge expansion. The evolution over time has been plotted in Figure SI 9.

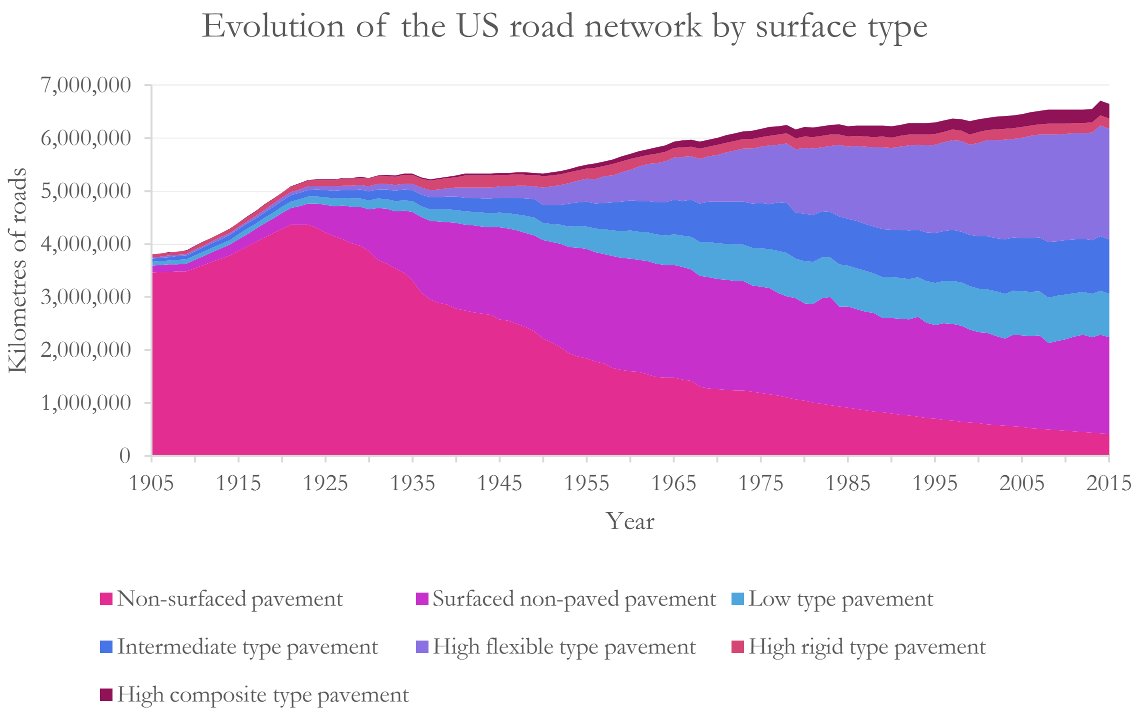

Figure SI 9 – Evolution of the United States road network by surface type. Note that the vertical axis reports the length in kilometres.

The same figure has been plotted normalising it to 100% in Figure SI 10, where it is clear how the amount of non-surfaced roads has drastically decreased, in favour of asphalt concrete roads.

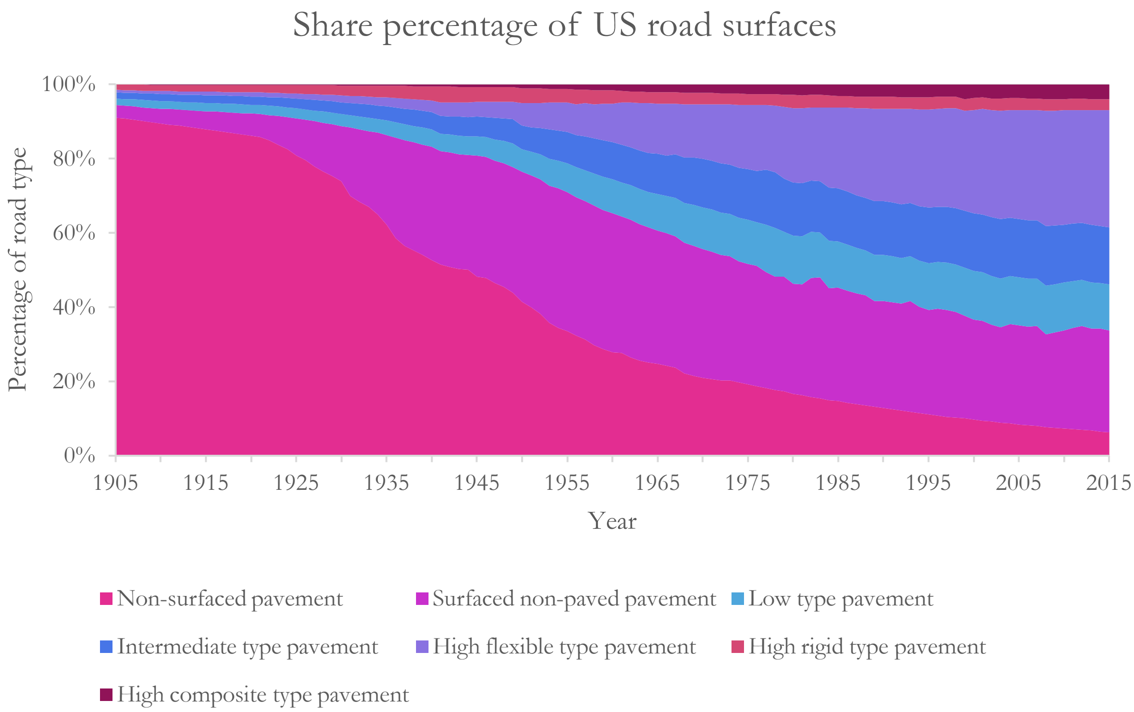

Figure SI 10 – Share of type of surface by year, normalised to 100%.

11.4 Material shares

11.4.1 Share of virgin materials against recycled and down-cycled materials

The chart plotted in Figure SI 11 shows the share of material sources. As expected, at the very beginning almost all materials were sourced as virgin materials coming from outside our system boundaries (cf. Figure 1 in the main manuscript). With the evolution of recycling techniques and increased rubble recovering, the share has shifted. Nowadays on average 70% of materials are sourced from outside the system boundaries, while recycled materials are about 14%, and down-cycled materials comprise about 16%, despite being affected by high yearly oscillations.

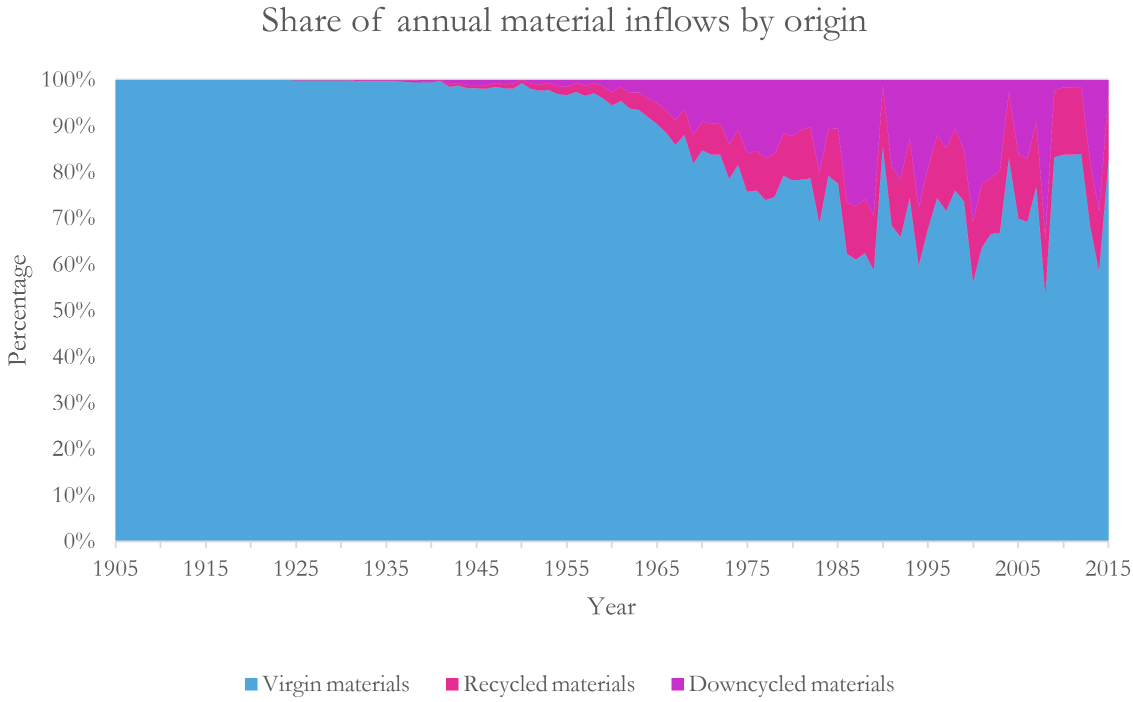

Figure SI 11 – Annual share of materials used for road construction and maintenance according to its source.

11.4.2 Share of materials required for new construction versus maintenance

Figure SI 12 displays how the share of material requirements has progressively shifted from new construction to maintenance. In the early years, we expect that about 70% of the yearly material inflows would have been required for expanding the network. This number progressively diminished, dropping on average below 50% in 1966, and arriving o 2015 at an average share of 20% in 2015.

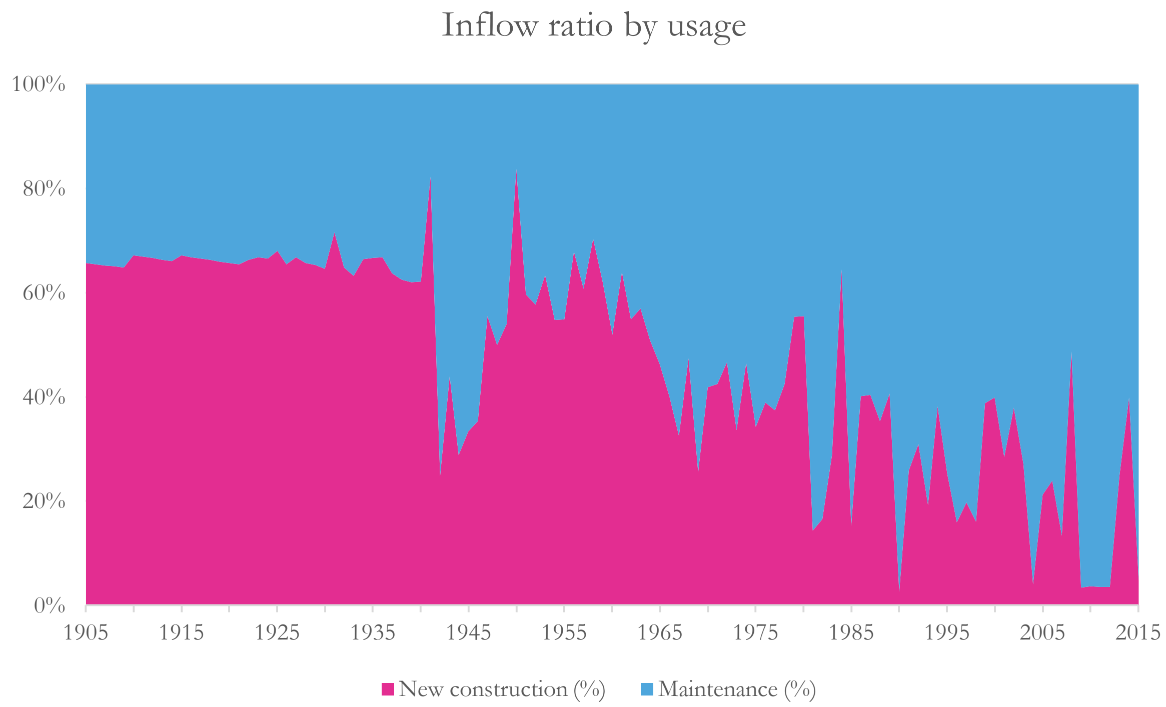

Figure SI 12 – Annual share of gross inflows by destination.