Material stock accumulation in society: modeling, forecasts, and socio-economic drivers

（社会に蓄積されたマテリアルストック：
モデリング・将来予測・社会経済要因）

FISHMAN Tomer
フィッシュマン　トメル

Doctor of Environmental Studies
Graduate School of Environmental Studies, Nagoya University
名古屋大学大学院環境学研究科都市環境学専攻

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Supervised by
Prof. Hiroki Tanikawa
Prof. Heinz Schandl

Summary

In-use material stocks, especially buildings and infrastructure, provide numerous services such as dwelling, transport, and communication, forming the physical foundations of society. The quantity and quality of materials stocks inform their ability to provide such services, and dictate the amounts of material and energy flows necessary to maintain, expand, and provide energy to them. The demands for inflows of materials from the environment into human economic systems are continuously increasing and straining options for resource extraction, which cause harm to natural ecosystems as well as raise the economic costs of extraction. Since the planet has limited material sources and a limited capacity to handle anthropogenic wastes, actions to reduce the strains caused by material stocks on the environment are in order. This work examines the long-term accumulation trends of material stocks in society and their associated material flow dynamics. It describes both deterministic and stochastic methodologies to account and create future projections of stock growth, analyzes historical trends and investigates the socio-economic driving factors of this accumulation in several case studies.

The first chapter introduces the topic of material stocks and related concept of material consumption, with a special focus on construction materials. It presents the problem statement and research objective, and defines the main research question: 'What are the trends of material stock in countries as they mature?'. This is followed by descriptions of the justification, scope and limitations, and structure of the thesis.

The second chapter reviews the theories, principles, and state of the art through a literature review. The theoretical foundations are explored in detail, describing the historical and conceptual background. The roots of this research in the fields of Industrial Ecology, Ecological Economics are described, and the term 'sustainability' as used in this work is defined based on the notions of the steady-state

要旨

建築物や社会基盤として社会に蓄積されている物質（以下、マテリアルストック）は、住居・交通・コミュニケーションなど先進国の人間活動に不可欠なサービスを提供している。環境から社会経済システムへ投入される物質の需要は増加傾向にあり，資源逼迫による経済コスト増大と同時に、資源の大量採取・廃棄により自然生態系へ重大な影響を与えている。本研究は，長期間にわたる マテリアルストックの蓄積傾向と関連したマテリアルフローの動態を検討する。さらに、ストック成長の将来予測に用いる確率論的手法の構築，歴史的傾向の分析，蓄積傾向をもたらす社会経済的な決定要因の分析を行う。

第 1 章では，マテリアルストックとマテリアルフローに関連した概念について整理し，特に建設系資源を対象として、各国のマテリアルストックの蓄積傾向とその要因分析に関する本研究のフレームワークを示す。

第 2 章では，既存研究を整理し、マテリアルストック･フロー理論に関する最先端の手法を纏めた。特に、産業エコロジーや環境経済学の学問領域における本研究の位置づけを明確にし、社会経済のメタボリズム研究とマテリアルストック・フロー分析の最新成果が詳細に示した。既存研究の多くはフローに着目しており，ストックにも着目した研究は少なく、ある単一の素材や，狭い領域及び短期的な内容に限定的である。加えて，マテリアルストックと経済活動の関係を検討する研究や，蓄積傾向の要因を分析した研究は存在しない。そのため、詳細かつ時系列のマテリアルストックデータの

economy. The state of the art of Socio-Economic Metabolism and of Material Stock and Flow Accounting and Analysis is presented in detail. So far, most research has focused on flows, not stocks. The few studies of stocks were limited to one material, or small areas, or short time spans. Furthermore, there are no studies that examine the relations of material stock and economic activity, or studies that look for the drivers of stock accumulation. Therefore, it is necessary to first create an account of long-term national material stock, and then to analyze this new data.

The third chapter explains the overarching methodological framework of the work, including the system boundaries and the flow of research steps. The work is divided into two main sections: material stock accounting and material stock analysis.

The fourth chapter presents the methods, data, results, and discussion of the material stock accounting research done in this work. First, a deterministic top-down method to account for a country's material stocks is described. Using exogenous variables of inflow data and lifetime statistics, this model calculates the material stock, outflow, and net addition to stock for every year. The model is presented with case studies for Japan and the USA, finding that Japan's material stock grew from about 920 million tonnes in 1930 to 38.7 billion tonnes in 2005 and from 11 billion tonnes in 1930 to 107.5 billion in 2005 in the USA. The model is extended using 3 future scenarios until 2050, presenting different cases of accumulation trajectories. This is followed by stochastic forecasts using the ARIMA time series analysis method. The stochastic and deterministic models are compared for Japan and the USA, which show that endogenous statistical forecasts are viable methods. Forecasts for further 44 more countries and the world are done, showing that only 4 growth patterns with unique accumulation patterns and ways to react to external shocks exist for all countries despite their huge differences. Moreover, the relations of material stock levels, speed, and acceleration are formalized using mathematical differences and integrations.

整備を行い、蓄積傾向の要因を明らかにすることが必要である。

第 3 章では，システム上の境界に触れつつ研究全体を通した分析の枠組みについて説明する。本論文の大きな柱は、マテリアルストックの定量化・勘定と蓄積傾向の分析である。

第 4 章では，本研究で実施したマテリアルストック勘定について，分析手法，分析データ，分析結果，及び考察を示す。国レベルのマテリアルストックを推計するトップダウン手法を示した。物質投入量データと耐用年数の統計など外生変数を用いて，マテリアルストック，排出量，及び蓄積純増について毎年のデータを本モデルにより算出する。本モデルを用いて、日本とアメリカのケーススタディを行った結果、1930 年から 2005 年にかけて，日本は 9 億 2 千万トンから 387 億トンに，アメリカは 110 億トンから 1075 億トンに増加したことが明らかになった。さらに，ARIMA(自己回帰和分移動平均モデル)に基づく時系列分析を用いた確率論的予測を行う。このモデルにより日本とアメリカについて比較を行った結果，ARIMA を用いる予測が有効な方法である事を明らかにした。44 ヶ国と世界全体の将来予測を行い、蓄積パターンと外部からの影響により，ただ 4 種の成長パターンが国の大小に関係なく全ての国に当てはまることが明らかになった。さらに，マテリアルストックの蓄積傾向について、数学的な微分や積分等を用い，その水準，速度，加速度の関係を表現することができた。

第 5 章では，本研究で実施した蓄積傾向の分析について，その手法，データ，結果，及び考察を示す。まず，第 4 章の結果を詳しく分析することで，日本の一

The fifth chapter presents the methods, data, results, and discussion of the material stock analysis research done in this work. First a descriptive analysis of the results of chapter 4 is described, showing that material stock per capita in Japan is nearing the USA, both at over 300 tonnes per person. Next a decomposition analysis using the IPAT framework is presented for the USA, Japan, and its prefectures, comparing the influence of population, affluence, and stock productivity on the growth of material stocks in different development phases. The chapter concludes with a panel regression analysis for Japan's prefectures, observing the correlations of population (urban and rural) and economic activity (divided into 3 sectors) with material stock accumulation. The analyses show that economic activity, and especially the tertiary sector, is a main driver, and population has adverse effects depending on the prefecture. It is also implied that government policy has major influence, but its effects as a driver only appear indirectly and are difficult to enumerate.

The sixth chapter concludes the work. A synthesis and summary of the research of chapters 4 and 5 is presented, followed by overall achievements, implications, limitations, and areas for future research. The new method to account for the historical material stock of nations was formulated and used for two countries, and two methods for future projections were tested and found to be viable. Pioneering analysis was conducted on the relations of population, economics, and material stocks, and it was found that the methods produce useful results that complement each other. Further research using these methods is recommended, as well as expansion of research to more detailed spatial resolutions as well as studies into more complex interactions of drivers of material stock growth. The methods developed in this work offer empirical tools to analyze past trends and plan future policies and can be expanded to any region or country.

人あたりマテリアルストックがアメリカの水準まで近づいており，一人あたり 300 トンを超えていることが示された。次に，IPAT の枠組みを用いた要因分析を行い、異なる成長段階のマテリアルストックの増大に対して，人口の影響，及びストック生産性を比較する。ここでは、アメリカ，日本，及び都道府県について詳細な分析を実施する。本章では，パネル回帰分析を用いて、日本の各都道府県におけるマテリアルストック蓄積に対する人口と経済活動の相関性を分析する。その結果，経済活動，特に第三次産業が主要な成長要因であり，県によっては人口増加が蓄積傾向に対して反作用を与えることを明らかにした。

第 6 章では，4 章及び 5 章の研究の総論とまとめに続き，全体のまとめと結果の解釈，政策提言と制約，及び今後の研究について記載する。本研究では、国レベルの時系列マテリアルストック勘定の新しい手法が考案され，さらに将来予測を行い，その適応性が認められた。人口，経済及びマテリアルストックの関係を定量化することで、再現性の高い結果を示すことができた。今後の展望として，より詳細な空間的解像度をもつデータベースを用いることで、各要因の相互作用を考慮したマテリアルストックの成長要因を明らかにすることが期待される。本研究で開発した、過去の蓄積傾向と将来の政策を分析する経験論的ツールは、どの国や地域でも適用可能である。

Table of Contents

1. Introduction

1.1. Background

1.1.1. The flow of materials between the natural environment and the anthroposphere

Human society requires vast amounts of physical materials. These materials are extracted from the natural environment, transformed into beneficial products and into energy, are used, and eventually returned to the natural environment as wastes and emissions. The lifestyles enjoyed in developed countries, and which developing countries are striving to achieve, are characterized by consumption of enormous amounts of materials compared to pre-modern societies (Brunner and Rechberger 2004). The demands for inflows of materials from the environment into human economic systems (i.e. the "anthroposphere") are continuously increasing and straining options for resource extraction, which cause harm to natural ecosystems as well as raise the economic costs of extraction (von Weizsacker et al. 1998). In return, the outflows of used and discarded materials are also increasing (Matthews et al. 2000) causing environmental harms of which pollution and greenhouse gas increases are but a few widely publicized examples. Since the planet has limited material sources and a limited capacity to handle anthropogenic wastes (Meadows et al. 1972; Rockstrom et al. 2009), the material usage practices adopted since the industrial revolution and made common in the consumption-based, growth-oriented societies of the 20th century are unsustainable. Actions to reduce the strains caused by material flows on the environment are in order, which must consider both inputs and outputs of materials to reduce extraction of materials and reduce wastes.

1.1.2. Consumption, throughput, and stock

When materials are input from the natural environment to be used by human society in the anthroposphere, they are said to be "consumed". However, there is a great variance and ambiguity in the meaning of consumption for different classes of materials (Fujii et al. 2014). When biomass and fossil fuels, for example, are consumed, they are irreversibly transformed into wastes and emissions and in an economical sense "disappear" the moment their energy potential is used. The consumption of other materials, such as minerals and metals, is decidedly different- the act of consumption only signals the beginning of their persistent service as goods and products in society, and in a economical sense they “appear” thanks to their consumption. The former type of materials are used within a short timespan while the latter spend more time in use by society and accumulate as physical stocks (Eurostat 2001). Energy carrying fossil materials and biomass are examples of materials with short-term throughput flow profiles, whose inflow amounts are dictated by current demands and leave the economy as soon as they are used, and even if these materials are stocked they don’t perform any economic function until when used. On the other hand, other materials accumulate in society as long-term stocks whose function is to provide society with continuous economic services during their period of usability. These are materials that compose the physical space of human society- from buildings and infrastructure, to vehicles, to consumption products such as clothes, computers and cellphones. The demand for inflows of raw materials to produce these objects consists of two factors (Wiedenhofer et al. 2015): new increases to the existing stock, as well as the maintenance or replacement of old stock due to depreciation which reached its end of life, i.e. it lost its ability to provide its intended service to the economy. Hence, these two groups of materials also have different outflow dynamics. Throughput materials become wastes and emissions by the act of their consumption, while the factors of aging and depreciation dictate the outflows of the stocked materials back to the environment. Finally, the question of thresholds (Haberl et al. 2004) should be approached differently for these two categories. While top thresholds of throughput material may be defined as consumption per person per year, for example, and be based on demand and technology, the yearly consumption of stocked materials is virtually meaningless as it may have no top limit- in rapid development phases stock yearly accumulation may increase as much as the economy can facilitate and absorb, and thus stock per person thresholds may make more sense. These fundamental differences are summarized in Table 1.1. Thus, in the case of the stocked materials, both the inflows and the outflows of these materials are governed by the amount and quality of existing stock. In order to reduce environmental pressures caused by the flows of materials that accumulate in society as long-term stocks, the aspects of using materials longer and more efficiently, as well as the re-use of these materials through processes such as recycling and material recovery should be well examined.

Table 1.1 Comparison of fundamental differences between throughput materials and stocked materials

	Throughput materials	Stocked materials
Main function	energy	services
When Consumed	“disappear” from the economy	“appear” in the economy
When accumulated as stock	Provide no service	Provide service
Cause for inflow	Current demand	Maintenance and expansion of the existing stock
Threshold indicators	Consumption per person	Stock per person
Cause of Outflows	Current Consumption	Aging and depreciation
Recyclability potential	Low	High
Examples	Biomass, fossil energy carriers	Metals, construction minerals

The material stocks (MS) of nations, from large-scale construction to consumer goods, have numerous roles: they are suppliers of services such as accommodators of residence and work, transportation, and communication; repositories of capital and of resources; determiners of socio-economic metabolic dynamics and of material and energy consumption; indicators of wealth; and shapers of human settlements (Pauliuk and Müller 2014), and therefore are important objects of research.

1.1.3. Construction materials

Of the materials that become stocked, construction materials have two distinct characteristics: they compose by far the biggest group in mass, and they remain in society the longest (Tanikawa and Hashimoto 2009; Hashimoto et al. 2007). Construction materials in buildings and infrastructure are durable and immobile, and remain in society as in-use stocks for decades. These materials form the physical base of human society in the form of the buildings and infrastructure which provide the foundations of modern civilization. Economic development goes hand in hand with the physical accumulation of these materials, mainly in cities and the hinterlands that support them.

This group includes minerals such as sand, gravel, and bitumen; metals such as iron, aluminum, and copper; timber; and several other materials in less significant amounts such as plastics and ceramics. While these source materials might not be the most environmentally hazardous, scarce, or economically valuable, they require special attention. Construction materials are high volume, low value and low environmental impact per unit of use, and have relatively high recyclability. However, the sheer amount of construction minerals excavated globally is huge and fast growing. On the global scale, they are responsible for about 40% of the yearly consumption of raw materials (Krausmann et al. 2009), dominate the consumption accounts of rapidly developing giants such as China (Schandl and West 2012), and form a large proportion of advanced economies' material inflows - about 60%, but have very low yearly consumption-to-waste ratios even in developed economies (Hashimoto et al. 2007, 2009) of only 20-30% of its outflows (Adriaanse et al. 1997; Ministry of the Environment 2009). As such the net balance of in-use stock is positive: construction material stocks are growing, implying that the role of inflows is not only to satisfy demand for replacement of aged stock (which becomes an outflow), but that there is also a constant demand for new material stocks. Globally, almost 600 Gt (billion tonnes) of construction materials were added to physical stocks of buildings and transport infrastructure between 1970 and 2010.

The accumulated environmental effects are formidable, including rapid land use change through urbanization, excavation, and demolition waste sites and high energy and emissions related to the extraction, transport and manufacturing of these materials (Allwood et al. 2012). Because of their sheer magnitude their extraction from the environment, transport, and disposal impose direct environmental and economic concerns (Horvath 2004; Kennedy et al. 2007). The embodied energy and carbon in construction materials is high (Hammond and Jones 2008; Müller et al. 2013), and the quality and longevity of building and infrastructure stock determine the throughput of energy and resulting carbon emissions (IPCC 2014; Cai et al. 2015). There is also a substantial maintenance effort required as well as waste flows from decommissioning buildings and infrastructure (Lawson et al. 2001; Kohler and Yang 2007; Vieira and Horvath 2008; Hashimoto et al. 2007, 2009). The spatial characteristics of building and infrastructure stock alter the landscape (Douglas and Lawson 2000) and play a role in debates about "green" architecture (Humbert et al. 2007), city planning (Norman et al. 2006) and urban metabolism (Kennedy et al. 2011).

The efficient usage of these stocked materials to provide services to society is thus key to sustainability: long-lifespan stock reduces future raw material consumption (Müller 2006; Reyna and Chester 2014), high quality stock requires less refurbishment over its lifetime (Power 2008; Pincetl et al. 2014; Wiedenhofer et al. 2015), energy efficient stock requires less fossil fuel consumption (Pérez-Lombard et al. 2008; Chester et al. 2014), and so forth. On the opposite end, infrastructure and buildings that don't satisfy society's needs cause further demand for replacement and expansion, and inefficiencies in energy and water usage (Cai et al. 2015).

1.2. Problem statement

A certain level of stock is required to enable an economy to grow and to provide essential services to human society, which Bettencourt et al. (2007) claim display economies of scale, and certain material stocks may have an upper limit (Chen and Graedel 2015). As global extraction and consumption of construction materials is continuously increasing from year to year, several yet unanswered questions regarding national material stocks have great relevance for the international debate on sustainable resource management. The first is how to use the material stock efficiently? This question manifests in several ways: using the same mass of material in constructing more energy efficient buildings and infrastructure, planning more compact and user-friendly cities, increasing the usability of the stock in order to improve the quality of life and reduce inefficiencies caused by short-sighted planning and bad infrastructure such as traffic jams, high maintenance facilities, and vacant buildings, are a few examples. Therefore, improving the ratio of services-per-tonne of stock is crucial. A second issue is how much material stock is sufficient? In other words, is there an amount of material stock which is enough to support modern lifestyles without further increases? If such a saturation point exists and material stock ceases growing at a certain point of economic development and maturity, then flows would potentially fuel and maintain this level of stock preventing runaway throughput. Moreover, if this saturation can be reached using less materials thus improving the efficiency of the existing stock, it would culminate in less environmental strains and higher economic productivity- a win-win scenario. Finally, how to reduce new inflows and outflows of end-of-life material stock? Recycling and urban mining are crucial in this regards in order to reduce outflows, but not less important is improving the built-up stock by constructing long-lifespan, low-maintenance infrastructure and buildings in order to reduce demands for new materials. These three questions become important issues for countries such as China, Brazil, and India, whose material use at this point in time dominates global material use. Thus, even though construction minerals are considered less important in the analysis of economic demand for materials when compared to fossil fuels (energy) and metals, they exemplify best that materials form the physical basis of society and that rising per-capita use of materials and increasing use of mineral materials are fundamental to modernity. However, for various reasons our understanding of these material stocks and their flows, as well as their relations with the economy and society is still weak.

1.3. Research objectives

1.3.1. Research question and hypothesis

The research question is:

What are the trends of material stock in countries as they mature?

Hypothesis:

There exists an s-shaped growth curve for the accumulation of construction material stock in nations (Figure 1.1), and the growth of material stocks is driven by demands of population and economic activity, as the stocks are the means to support these two drivers. Specifically, at different phases of development, different drivers take the center stage and assume the role of main drivers. In a pre-industrial society, population acts as the main driver and correlates with material stock growth. Then, in an industrializing country, the demands of the economy, and especially of the secondary (manufacturing) sector, require faster increases to the material stock in the forms of infrastructure and buildings to serve industry. At the next stage, when a country is considered industrialized and reaches an amount of stock which suffices the demands of industry, the country transitions to a services-oriented economy and the tertiary sector becomes the major driver. As the services sector is less material-intense, and can use the material stock already built up in the previous phase, material stock growth would slow down. Finally, in post-industrial countries population again becomes the main driver for further increases to stock. Stock growth would be coupled to population growth, and if the population is stable no further additions to the stock are necessary, reaching a saturation.

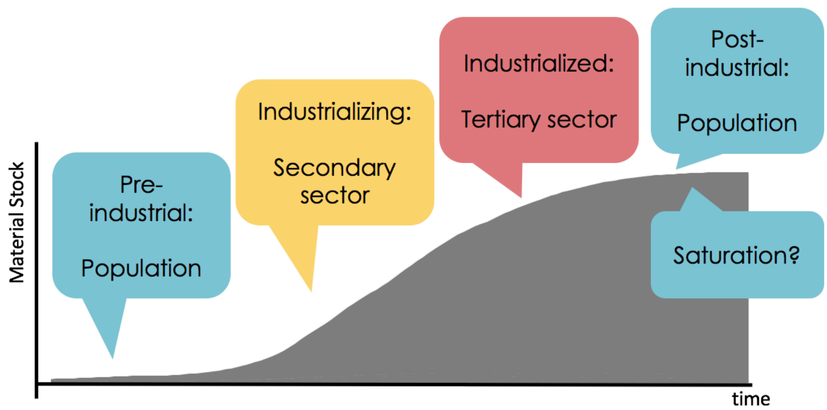

Figure 1.1 The hypothesis: different factors act as the major drivers to s-shaped material stock growth during a country's development.

1.3.2. Specific objectives

In order to test the hypothesis, the following four questions will be explored in this work:

1. What are the paths of accumulation of stocks of construction materials in countries during their development phases?
2. What are the relations of economic development and physical development?
3. Are there different drivers to material stock accumulation during different phases of development?
4. Do material stocks stabilize and reach a saturation when society reaches a certain stage of development and wealth?

1.4. Justification of the study

Despite the importance of material stocks to human society, research into the accumulation of these materials as stocks has been scarce, and the drivers of this accumulation even more so. Limited availability of data on the amounts on stocked materials, both contemporary and historically, and a lacuna in the understanding of the relations between economic development and physical development are obstructions to the analysis of material stock trends. There are no clear explanations to the relations of the trends of MS growth and other socio-economic indicators, nor have the drivers of MS growth been identified so far. Numerous open questions relate to material stocks: What drives these demands? Do material stocks fulfill their purposes efficiently? Do stocks reach saturation? What are the metabolic profiles of the stocks of societies in different stages of development? And are there more environmentally benign ways to produce, utilize, and dispose of these materials? In order to answer such questions, first accounting for society's stocks, and then quantifying their characteristics such as amounts, types, distributions, quality, and age are imperative. This research aims to fill these gaps by shifting the focus of previous social metabolism research from material flows to the material stocks that dictate those flows, which in turn requires to understand the drivers that dictate the accumulation of material stocks. This research would not only contribute to the body of knowledge of social metabolism and industrial ecology, but would hopefully be useful as a step towards environmental systems-oriented policy on national scales. By understanding the relations of socio-economic activities and material stocks, one could not only explain past economic and environmental impacts of material flows and stocks, but would also be able to project these relations to the future. An understanding of future inflow demands and outflow potentials caused by stocks would enable proper planning on how to handle these flows and work towards a sustainable steady-state economy for both mature and developing economies.

1.5. Scope and limitations

The scope of this research is the material stocks of nations and sub-national regions. The materials examined, end-uses, and spatial and temporal system boundaries are all defined in the methodological framework in section 3.1. The main limitation in material flow and stock studies in general, and hence in this study as well, is of data. This limitation can be differentiated into two issues: data availability and data quality. Data availability is one of the biggest challenges in this field, and is one of the motivations for the proliferation of studies in recent years. The work described in this volume is limited to specific case studies due to lack of further applicable data for other countries and regions. However, one of the main aims of chapter 4 is to describe methods to overcome the availability limitation by using existing statistics to produce material stock accounts, in the aim of formulating a methodology which can be replicable for further cases once basic data becomes available. The same goes for chapter 5 which describes analysis of the available data, and the novel methods presented here can be promptly used without much modification for new datasets.

The second limitation is of data reliability and precision. Growing awareness to this issue (Fischer-Kowalski et al. 2011) has made it into a topic of discourse in the field in recent times (Laner et al. 2014; Rechberger et al. 2014) and published studies are expected to include a discussion of data reliability in the forms of comparisons with previous results, sensitivity analysis, and production and analysis of statistical uncertainty ranges. Much work has been done to confirm the reliability of statistical data by the producers of the core raw data used in this study, as described in the published work related to it, and this issue is tackled in the new results of this study wherever applicable. Nevertheless, in dealing with national-scale and even global-scale data compiled from multiple sources and using various methods in the scale of billions of tonnes, accuracy remains an issue. In order to avoid overstatement of the precision of the results, figures are rounded throughout this work.

1.6. Structure of thesis

Following the introduction presented in the current chapter 1, chapter 2 presents the theories and principles on which this study is founded. It begins with an overview of the concepts guiding this work, gradually narrowing in from the general to the specific principles and conceptual frameworks which provide the foundations of this work. This is followed by a review of the state of the art focusing on the methods and literature of material flow and stock accounting and analysis. Chapter 3 presents the overarching general methodological framework in common to the entire body of work. Chapters 4 and 5 present the results, differentiating between accounting results and analysis results, respectively. Chapter 4 describes methods, results, and a discussion of the accounting-related work done in this study including compilation of new data and deterministic and stochastic future projections; while chapter 5 describes the methods, results, and discussion of analysis of the data. Chapter 6 offers a synthesis of the preceding two chapters, discussing the overall insights and conclusions reached in combining the findings, and closes with overall conclusions including a retrospective look into the aims and achievements of this study is presented.

2. Theories, principles, and state of the art

2.1. Theoretical Foundations

2.1.1. Sustainability and the steady state economy

The term "sustainability" has come to mean many things, making it nigh impossible to find a single universally agreed upon definition. In this work, sustainability is used in a specific, narrow meaning, rooted in the concepts put forward by Herman Daly (1974, 1991, 2005) and based on the measurable biophysical aspects of the interactions of human society with and as part of the natural environment The planet, as a nearly closed system, is confined by the laws of thermodynamics to a finite supply of matter, and any subsystem is therefore also bound to these limits. Human society and its economic system is, as a subsystem, is no exception. The planet has a limited ability to support human activity, and for the first time in the history, since the industrial revolution the human species is starting to reach the biophysical limits of the planet (Meadows et al. 1972; Rockstrom et al. 2009), and has become a major factor of influence on planetary conditions, on par with natural processes (Crutzen and Stoermer 2000). In this sense, a sustainable society or economy is one which operates well within the biophysical limits of the planet. In other words, economic development cannot continue infinitely as long as this development is based on constant increases of physical extraction of materials from the environment (Daly 2005).

In Daly's description, the current growth-oriented economic system is not only unsustainable, but its fixation on growth is leading to un-economic growth. It is a state in which "increases in production come at an expense of resources and well-being that is worth more than the items made" (Daly 2005), which could lead to a simultaneous collapse of the environment and the economy. In order to avoid such an event, a balance between the two should be achieved, culminating in a steady-state economy in which a dynamic equilibrium of resource use exists (Daly 1974). In this kind of sustainable economy, the growth of human well-being would be decoupled from materials and energy use, which would then cease to grow. Rather they would be reduced to a minimum in which energy and new material inflows are only meant for the maintenance of the existing stock, which would be extant in a quantity and quality which provides sufficient services to society. This is not to say that such a steady-state economy would be stagnant. It would have a dynamic equilibrium of material and energy, changing to fit the needs of society in parallel with maintaining a balance with the natural capacity of the environment to support it. Practical applications of the notions of the steady state economy are under formulation and debate to this very day (O'Neill 2015), yet it is clear that material stocks play a pivotal role in such an economy. Material stocks, as suppliers of services and determinants of the energy and material flows required to maintain them would have to reach a level of sufficiency in both quality and quantity.

2.1.2. Ecological Economics and Industrial Ecology

Ecological Economics and Industrial Ecology are the theoretical and empirical fields of study based on the premises of the biophysical limits described above. Ecological Economics has its foundations in insights and frameworks initiated by several pioneers. Nicholas Georgescu-Roegen (Georgescu-Roegen 1971; Cleveland and Ruth 1997; Mayumi 2002) described the thermodynamic base of the economy and its inherent entropic limitations, with which he aimed to disprove the possibility of unlimited economic growth. His fund-flow framework explains production as transformations of non-substitutable natural capital, paving the way to the realization that economic processes and the production of goods rely on the availability of natural capital, which is not boundless. In parallel, Kenneth Boulding (Boulding 1966) explained the consequences of the mass-balance principles on the environment, while Howard T. Odum (Odum 1971) shed light on the role of energy in the economic process and made headway in energy flow analysis. Their groundbreaking work set the principles of material and energy balances, paving the way to the concepts used in material flow accounting. The notions that the anthroposphere is a component of the global environmental system, and that certain biophysical planetary limits exist which human activity can appropriate only to a certain sustainable degree, are central to the notions of Ecological Economics and thus form a foundation to this work.

The field of industrial ecology focuses on the study of human activities and the environment from a systems point of view (Ayres and Ayres 1996), and analyzes processes of material and energy transformations between the natural environment and the anthroposphere as well as within it. Originating in the study of industrial processes, their inefficiencies, and environmental consequences, it aims to find pathways to simultaneously reduce economic costs and environmental burdens (Lifset and Graedel 2002). It offers practical tools to investigate these pathways, including lifecycle assessment, material criticality studies, eco-symbiosis, waste management and recycling, environmentally extended input-output analysis, and material flow and stock analysis under the premises of socio-economic metabolism (Weisz et al. 2015). The holistic, systems-thinking approaches of Industrial Ecology, as well as the implied notion of the existence of win-win scenarios for the economy and environment which are inherit in Industrial Ecological thought, form the second foundation to this work.

2.1.3. Socio-economic Metabolism

Based on these notions, the stocks and flows between the environment and the human economy which were described in the previous sections can be viewed and explored systematically. Borrowing the term metabolism from the life sciences, socio-economic metabolism (SEM) describes the human economy as a holistic whole, whose connection to the environment through inflows and outflows which can be traced, measured, and analyzed methodically (Fischer-Kowalski and Hüttler 1998; Eurostat 2001). As such, this framework formalizes the relations of material extraction both conceptually and mathematically. Socio-economic metabolism discourse is interested in the materials that society consumes, accumulates, and discharges, in several parallel dimensions:

1. The amounts of material (usually in mass). Using mass as the unit of measurement has several benefits. It enables to study both the stocks and the flows of materials using the same unit, it provides uniformity and comparability between different types of materials, different systems (natural environment, human society, different countries), and it can act as a proxy for comparative measurement of the services provided by materials and their efficiencies, such as the mass per capita, mass per unit of GDP, or mass per any other unit of service.
2. The types of materials. The most basic differentiation is into materials, air, and water. Air and water are commonly presented separately because of their different orders of magnitude (Fischer-Kowalski et al. 2011), and most focus is on materials. Disaggregation of materials may be done at different levels according to the data availability as well as the suitability to context. A common top-level disaggregation is to the four categories of biomass, fossil energy carriers, minerals, and metals, due to their distinct characteristics in both the natural environment and the anthroposphere.
3. The flows of materials from one stock (i.e. the environment) to another stock (i.e. the anthroposphere) and back.

4. The conversion of materials by the processes of extraction, production, usage, and discharge, and the energy required for these actions.
5. The sources of materials. Differentiation is made between domestically extracted materials and imports from other economies on the inflow side, as well as exports and domestic processed outputs.
6. Apparent vs. direct consumption, usually in two distinctions: Used and unused materials, and direct and indirect material flows. Used materials enter the economy with the aim of being used by human society, while indirect flows are materials that were disturbed from their natural state due to human activity but without the intention of being used, such as overburden or by-catch. Direct materials are those that actually enter an economy, while indirect ones are those required to the upstream production of a product before it enters an economic system.
7. The scale, efficiency, and intensity of usage as measured by unit per person or per unit of economic productivity.
8. The comparison of all the above over time and between countries.

Realizing that material flow and stock patterns in modern societies are dramatically becoming more intensive, SEM research has come to describe the historical pathways of material consumption as being composed of different eras of metabolic regimes and transitions between them (Krausmann et al. 2008, 2009). The metabolic regimes of industrialized developed economies are unsustainable, and in parallel to this, the transition of developing countries to similar metabolic patterns could prove disastrous to the planet.

2.2. Principles of material flow and stock accounting and analysis

2.2.1. The MFA framework

The methodologies and terminology of Material Flow accounting/Analysis (MFA) are central to socio-economic metabolism research. MFA is a holistic approach to accounting the movement of material inputs and outputs in a system, based on the laws of thermodynamics on the conservation of matter that state that physical materials can be always be accounted for in some chemical state as they do not disappear no matter the processes and changes they go through (Eurostat 2001). Simply put, what comes in must come out – or stay inside, which is the concept of material balance. This framework is advantageous because it enables to accurately and inclusively map all of the material flows in a process, which can reveal otherwise hidden inefficiencies, losses, and leverage points for improvement of the process. Comparison of the same process over time adds a further dimension to this analysis.

The key to the success of this accountancy is well-defined system boundaries, both spatial and temporal, which clearly demarcate what's "in", what's "out", and what are the entrance and exit points between the two. This approach was originally conceived and used as a system to account for material flows through industrial processes (Brunner and Rechberger 2004) such as a factory, where the system boundaries are physical and relatively simple to identify, such as pipes, loading bays, and smokestacks.

2.2.2. EW-MFA

The concepts of MFA have attractive advantages for larger-scaled economic systems from cities to nations to the entire planet, but the challenge of defining the system boundaries becomes much more difficult since the boundaries of the anthroposphere are not necessarily physical. Exemplary questions are: do mined materials enter the system the moment they were mined or when transported to a processing plant, or only when they are used to produce a commodity? How to treat the flow of water (e.g. a river flowing through a city, or rain runoff vs. sewage out of a city) and air? Which is part of the anthroposphere, cattle fodder, cattle, or processed beef? Many of these questions do not necessarily have a single "correct" answer, and so these and other such questions were resolved by a process of standardization of MFA for SEM research, entitled Economy-Wide Material Flow Accounting (EW-MFA) with standard accounting procedures under the auspices of the European Union Statistical Bureau (Eurostat 2001, 2009).

2.3. State of the art

Based on the theoretical foundations and principles described above, this section describes recent advancements and accomplishments of material flow and stock accounting and analysis. This review distinguishes two streams of research: accounting, which is the procurement, compilation, conformation, and arrangement of data; and analysis, the evaluation and scrutiny of the data in the aim of deduction of comprehensive understanding. Most studies in fact offer both new accounting results and analysis, but since the aims, methods, and type of typical results of accounting and analysis are widely divergent, this separation is used here.

2.3.1. Material Flow Accounting

Growing interest in socio-economic metabolism and the standardization of MFA for national accounts have motivated a proliferation of studies in recent years, and the major ones are listed in Table 2.1.

Table 2.1 Economy-wide MFA studies

Authors	Region	Time frame
(Adriaanse et al. 1997)	Germany, Japan, the Netherlands, USA	1975-1994
(Matthews et al. 2000)	Austria, Germany, Japan, the Netherlands, USA	1975-1996
(Schandl and Schulz 2002)	United Kingdom	1855-1997
(Krausmann et al. 2009)	Global	1900-2005
(Schandl and West 2010)	The Asia-Pacific region and its 6 sub-regions	1970-2005
(Krausmann et al. 2011)	Japan	1878-2005
(Kovanda and Hak 2011)	Czechoslovakia	1855-2007
(Gierlinger and Krausmann 2012)	USA	1870-2005
(Singh et al. 2012)	India	1961-2008
(Schandl and West 2012)	China, Australia, Japan	1970-2005
(West et al. 2013)	China	1970-2008
(Krausmann et al. 2014)	Iceland, Trinidad & Tobago	1961-2008
(West et al. 2014)	Former Soviet Union (12 countries)	1992-2008
(Schaffartzik et al. 2014)	Six global regions	1950-2010
(Infante-Amate et al. 2015)	Spain	1860-2010
(UNEP 2015)	All countries	1970-2010

While only few studies reached back beyond the 1950s, altogether previous research presents a data rich account of modern material extraction and consumption in every type of country.

This body of literature describes the growth in both absolute and per-capita material consumption of materials as well as their changing shares over time, supporting the metabolic regimes hypothesis.

However, economy-wide accounting research has focused almost exclusively on inputs. The other side of material flows, outputs, have been mostly neglected for reasons such as lack of data and a perception of less importance (Fischer-Kowalski et al. 2011). The mass-balance premises of MFA offer the ability to calculate additions to stock, defined as the difference between inputs and outputs in a given time frame (Eurostat 2001). This Net Additions to Stock (NAS) is perhaps sufficient as an indicator of input-output balance and resource efficiency, but its flow-focused approach treats the economy as a "black box" and only accounts net additions to stock as a balancing factor for inflows and outflows, and the lack of ability to measure the total stock makes EW-MFA insufficient on its own for stock-focused research. The material balance studies are listed in Table 2.2.

Table 2.2 Material Balance (Net Additions to Stock) studies: Input statistics minus output statistics

Authors	Region	Time frame
(Matthews et al. 2000)	Austria, Germany, Japan, The Netherlands, USA	1975-1996
(Kovanda et al. 2007)	Czech Republic	2000-2002
(Ministry of the Environment 2009)	Japan	2000-2006

These studies all point out that due to inflows being larger than outflows, net additions to the stocks are positive, signifying an overall increase in the materials stocked in society, and for the most part these net additions grow from year to year, meaning that the process of materialization is picking up speed.

2.3.2. Material Stock Accounting

Material stock accounting research has therefore resorted to alternative methods. Previous MS research examined various materials in diverse temporal and spatial scopes, in different levels of detail, and for numerous ends. Instead of focusing on any of those categories, there is an advantage in viewing the body of research through the lens of the methodological approaches employed. From an SEM centered point of view, the prominent methods can be described in four categories, which we term (1) bottom-up accounting, (2) top-down accounting, (3) demand-driven modeling, and (4) remote sensing approaches. Other terms have been in use for these methods and these are noted below. Further review of metal stock studies in MFA, not all necessarily SEM-centered, can be found in Müller et al. (2014).

2.3.2.1. Bottom up

The bottom-up method's starting point is an inventory of end-use objects in a defined area at a given point in time. Examples could include a region's roads, the buildings in a certain city block, or the television sets owned by a populace. The amounts of materials contained in these objects are calculated using material intensity coefficients – the amount of a specific material in a single unit of the examined object. This method thus enables one to convert stock inventories, which were compiled with unrelated measurements such as length, space, or monetary units, into comparable units of mass. Data sources for material intensities may vary in accuracy from exact amounts of materials used in the assembly of a specific consumer product to estimated or averaged amounts of materials used in the construction of a typical "model house". The results of a bottom-up account are "snapshots" of the MS in a single point in time and due to its independence from other time frames, this method is sometimes termed a "static analysis". It can provide quite a detailed account of the state of the stock, but only rough approximations of the age of the measured stock and related flows unless a temporally dense series of "snapshots" is compiled, from which changes over time can be discerned.

Table 2.3 Bottom-up material stock research

Authors	**Region & Time Frame**	**Material**	**distinctness**
(Lichtensteiger and Baccini 2008)	Switzerland 1900-2000	Gravel/sand, marl/clay, cement, timber, copper	Buildings only. Categorized by building types
(Gerst 2009)	Global 1990-2100	Copper	Divided by developing and industrialized regions, 4 scenarios

(Nagaoka et al. 2009)	Japan 1965-2005	Aggregate, cement concrete, mortar, ceramics, wood, glass, steel, aluminum, plastic, asphalt	Roads, buildings, and sewers only. Categorized by prefectures and by above ground or underground
(Tanikawa and Hashimoto 2009)	Salford Quays, Manchester, UK 1849-2004 Wakayama City Center, Japan 1855-2004	Aggregate, cement concrete, mortar, ceramics, wood, glass, steel, aluminum, brick, asphalt, others	GIS Inventory. Categorized end use and building types, and by above ground or underground.
(Han and Xiang 2013)	China 1978-2008	Steel, sand & gravel, cement, brick, wood, glass, lime, asphalt, plastic, ceramic	Residential buildings, railways, roads, and water pipelines. Divided by 8 regions.
(Zhang et al. 2014)	Shanghai 2012	Copper	By end-use
(Tanikawa et al. 2015)	Japan 1945-2010	Construction Materials	Combined GIS and statistical inventory. Categorized by end use. Divided by prefectures.
(Marcellus-Zamora et al. 2015)	Philadelphia 2004-2012	Construction materials	GIS Inventory.
(Wiedenhofer et al. 2015)	EU25 2004-2009	Concrete, other construction materials	Buildings, roads, and railways.
(Wang et al. 2015a)	China 2000-2010	Iron and steel	250 end-use categories

2.3.2.2. Top down: flow-driven

Methods (2) and (3) place priority on the life cycle of the flows and stocks of materials over time, and for both the term "dynamic analysis" has been in use, a potential source for confusion. Although both methods track a material from its entry into the economy through its time in-use by society and eventual outflow, these two approaches are distinct enough to deserve separate treatment and for the sake of clarity, they are distinguished as "flow-driven accounting" and "demand-driven modeling".

Early exploration of the top-down flow-driven method in the context of industrial ecology was conducted by Van der Voet et al. (2002), whose evaluation of lifespans and depreciation, and the levels of acceptable simplification in these regards, confirmed the usefulness of the method. Flow-driven accounting utilizes material inflow statistics to determine additions to stock in a series of time periods, referred to as cohorts. The material in a cohort gradually depreciates from stock to outflows. By summing the remaining material of all cohorts in a point in time, total MS is obtained. The level of detail of cohort modeling varies by study, from detailed life cycles to macro-scale aggregated statistical depreciation curves. This method allows for building time series of MS that reach back in time as far as inflow data is available and can model future stock accounts by postulating future inflows. Flows are inherent in these models, easing their integration with EW-MFA.

Table 2.4 Top down flow-driven material stock research

Authors	Region & Time Frame	Material	distinctness
(Elshkaki et al. 2005)	EU 1989-2030	Lead in CRT screens	
(Gordon et al. 2006)	USA 1900-2000	Copper	
(Müller et al. 2006)	USA 1900-2004	Iron	Categorized by end-use.
(Daigo et al. 2007)	Japan 1980-2000	Steel	Categorized by end-uses and by hibernating or in-use.
(Hashimoto et al. 2009)	Japan 1970-2000	Construction minerals	Categorized by end-use and by permanency or waste potential
(Hatayama et al. 2010)	42 countries 1980-2050	Steel	Categorized by end-use and divided to 8 world regions. 1980-2005: top-down account. 2006-2050: s-shaped curve fitting using population density and saturation estimations.

(Müller et al. 2011)	Australia, Canada, France, Japan, UK, USA 1900-2005	Iron	Includes a comparison to GDP growth, discuss saturation
(Lauk et al. 2012)	Global 1900-2008	CO2	categorized by 6 categories
(Pauliuk et al. 2013b)	Global 1900-2008	Steel	Divided by 197 countries
(Liu and Müller 2013)	Global 1900-2010	Aluminum	Divided by world regions. Includes a comparison to GDP growth

2.3.2.3. Top down: demand-driven

In place of historical material inflow statistics, the second dynamic modeling approach utilizes socio-economic indicators such as population and affluence to model the demand for specific types of objects over time, and thus the required materials for the manufacture or construction of said objects. Material intensity evaluations are used to measure the material stocked in those objects as in the bottom-up approach, and their lifespans and eventual depreciation towards becoming outflows are modeled in the same vein as the top-down calculation method. The integration of external socio-economic variables as drivers of MS offers varied simulation options for future stock and flow scenarios and goes a step beyond accounting into metabolic analysis of the relations of society and its material stocks. However, it requires separate indicators for each end-use category, such as dwelling space for the stock of houses or car ownership for the stock of vehicles. This could limit the scope of study if appropriate indicators are not obtainable.

Table 2.5 Top down demand-driven material stock research

Authors	Region & Time Frame	Material	Driver
(Müller 2006)	Netherlands 1900-2100	Concrete in dwellings	Population & floor area per capita
(Bergsdal et al. 2007)	Norway 1900-2100	Concrete and wood in dwellings	Population & floor area per capita

(Yang and Kohler 2008)	China 1978-2050		Buildings only. Categorized by urban/rural and residential/other
(Hu et al. 2010)	1900-2100	Steel in dwellings	Population & floor area per capita
(Pauliuk et al. 2012)	China 2000-2050	Cars	Population & car ownership
(Sandberg and Brattebø 2012)	Norway 2000-2050	Dwellings	Population & floor area per capita
(Huang et al. 2013)	China 1950-2050	Steel, Wood, Cement, Brick, Gravel, Sand, Asphalt, Lime, and Glass in Dwellings	Population & floor area per capita
(Wang et al. 2015b)	China 1950-2050	Concrete in dwellings	Population & floor area per capita

2.3.2.4. Remote sensing

Remote sensing utilizes satellite-based readings to identify the locations and intensities of human activity. In this approach, these readings are first correlated with known geographical distributions of stocks in a given area. This correlation can then be used to estimate the amount of MS in other areas captured by the same type of satellite readings. As the three other methods require a sound base of historical statistics, the remote sensing method is especially useful for estimation of the stock in statistics-poor locations. The spatial distribution of stock is inherent in this method, but details of the material composition, age, and quality of the stock are harder to obtain. In common with the bottom-up method, remote sensing is a static approach, in this case providing a *literal* snapshot of the stock in a given area.

Table 2.6 Remote sensing material stock research

Authors	Region & Year	Material	distinctness
(Rauch 2009)	World 2000	Aluminum, Copper, Iron, Zinc	High correlation of metal stocks with GDP by area
(Takahashi et al. 2009)	India, South Korea, Malaysia, Singapore, Taiwan, Thailand, Vietnam, Sri Lanka 1996/7	Copper	Calibrated with previous statistical studies
(Hsu et al. 2013)	61 countries 2006	Steel	Categorized by buildings and infrastructure. Calibrated according to world regions with (Hatayama et al. 2010)
(Liang et al. 2014)	China's provinces 2008	Steel	Differentiated by buildings and infrastructure

2.3.2.5. Hybrid accounting and miscellaneous methods

A handful of studies employed methods which are either hybrids of the previously described approaches or used other methods, such as Input-Output tables.

Table 2.7 Material stock research using miscellanous methods

Authors	Region & Time Frame	Material	Note
(Hashimoto et al. 2007)	Japan 1975-2030	Asphalt, cement, sand gravel & crushed stone	2 accounts: Categorized by end-use and IO tables-based calculation.
(Reyna and Chester 2014)	Los Angeles 1900-2008	Concrete, steel, wood	

2.3.2.6. Summary of previous material stock accounting research

This diaspora of methods, objects of study, scopes, and materials is both beneficial and detrimental to the SEM discourse. each of the four methodologies have their advantages and disadvantages but they in truth complement each other. For example, a series of bottom-up accounts of a region can contribute to more accurate depreciation functions for use in top-down models, which in turn can be used to calibrate the correlation calculations for remote sensing of material stocks of areas that lack statistics, as well as to project the relations of future MS and their driver-indicators in demand-driven models. Moreover, elements from the various methodologies can be used to supplement the main approach of a study, and studies of the same material or region with different methodologies can be used to compare results, increasing the robustness of research.

It is evident in this table that the top-down approach has been more prevalent than the other approaches. Regardless of method, there is a tendency to narrowly define at least one of the system's dimensions and borders to either single materials, single types of end-uses, smaller regions, or low disaggregation. These two characteristics are both related to issues of data: widening the scope of research is not a trivial task as data is limited, and the top-down approach is less data intensive as it only requires one stream of statistics.

All studies show that material stocks have been rapidly growing during the 20th and 21st centuries. Several trends are apparent in this body of knowledge. First, there is a pronounced focus on the stock of metals and on developed countries, followed by China. Second, top-down studies have been more prevalent than bottom-up studies, probably because of the intensive data collection required for bottom-up research. Demand driven-based studies have been using the same methodology introduced in (Müller 2006) for analyses of different regions and materials, with population as the driver. Different socio-economic indicators have not been used so far as drivers with this methodology. Remote sensing studies offer "snapshots" of spatial material distribution, but (Rauch 2009) is distinct in using the correlation of GDP and MS. Regardless of methodology, the aim of the majority of research was to estimate stocks in order to then estimate either waste flows or energy demands, not to explore the relations of stock with the socio-economy.

2.3.3. Material flow and stock analysis

Analysis of material flows and stocks is done with the objective of identifying patterns, coupling and decoupling trends, and the influence of socio-economic factors on material flows and stock dynamics. Foremost is the attempt to describe drivers of consumption and accumulation of materials in society, mainly focusing on population and economic activity as potential drivers. Analysis of the figures procured through accounting for material flows and stocks can be conducted in various ways. The main classes of analytical methods are described below.

2.3.3.1. Descriptive analysis

Descriptive analysis is fundamental and simple yet crucial, and has been the main tool of socio-economic metabolism since its beginnings. For comparison of metabolic profiles and regimes across time and between countries, descriptive observations of changes in the flows of material and the accumulation of stocks is a basic step, using raw numerical indicators, growth rates, and growth factors. Such indicators are presented in virtually all material flow and stock studies presented above. Compound indicators are included as well, which represent the metabolic scale or intensity of an economy (Fischer-Kowalski et al. 2011). Material flow studies usually present not only per-capita material flows but also material productivity (also termed material efficiency) figures, which presents units of GDP per ton of input- a simple method to observe the relations of material input and economic activity, most importantly looking at the question of de-coupling of these two indicators. For stocks, many of the studies presented per-capita stocks and showed that over the 20th century stocks have been growing faster that population in all scales. A slowdown in growth rates has been observed for developed countries, especially for metals and timber, hinting at possible saturation in the future. Comparisons with other growth indicators have been very scarce. Only two studies (Müller et al. 2011; Liu and Müller 2013) compared stock accumulation with GDP (material stock productivity). The first paper suggests a de-coupling of iron and economic activity as countries become more affluent, but no such relationship was found for aluminum in the second paper.

2.3.3.2. Decomposition analysis

Decomposition analysis allows to break down and quantify the relative impacts or effects of a series of factors on an examined variable (Hashimoto et al. 2008). The $I = P \times A \times T$ identity (Commoner et al. 1971; Ehrlich and Holdren 1971) has come to be a commonly used decomposition analysis framework for its simplicity and straightforwardness (York et al. 2003). Its starting point is to explain environmental impact (I) as the consequence of population (P), and affluence (A) as drivers. As a mathematical identity, by definition the two sides of the equation must be equal to each other; this is done in the IPAT identity by adding a balancing factor, termed technology (T). This identity and its variants and extensions have been in use for decomposition of energy use and carbon emissions (Kaya and Yokobori 1998; Waggoner and Ausubel 2002; Ausubel and Waggoner 2008) and in studies analyzing drivers of material flows (Steinberger and Krausmann 2011; Schandl and West 2012; West and Schandl 2013), but not yet in material stock research.

2.3.3.3. Stochastic analysis

Stochastic analysis utilizes statistical and econometric methods to analyze and identify the influence of independent variables on a variable of interest. This type of analysis comprises a plethora of statistics-based tools, including various regression methods and tests to identify and enumerate the statistical significance of the correlations of different factors. In the field of socio-economic metabolism early works include, for example, (Bringezu et al. 2004) which introduced several statistical regression analyses between inflow indicators and GDP for multiple countries. More recent studies use increasingly complex statistical analysis methods, such as multivariate regressions and panel regressions (Steinberger et al. 2010, 2013) to measure material and resource productivities among countries, autoregression (Wiedenhofer et al. 2013) to locate transitions in metabolic profiles, and equation fitting (Hatayama et al. 2010; Steinberger and Roberts 2010; Pauliuk et al. 2013a) to identify past and future material usage trends. Studies using this class of analytical tools have so far been mostly remained in the realm of material flows and their drivers, and much less so of stocks.

2.3.3.4. Other analysis methods

Rarely, other methods of analysis were used to analyze the trends of material flows and stocks and to identify their drivers. These include, for example, Lorentz curves and Gini coefficients to measure the distribution and inequality of resource use (Steinberger et al. 2010), and cluster analysis and decision trees (Steinberger et al. 2013; Gan et al. 2013) to identify country groupings based on similar traits.

3. Methodological framework

3.1. General framework

The general methodological framework of this work is the SEM/MFA framework, which was described in detail in section two. The fundamental premises of material balance are always maintained, and the basic unit of measurement is mass (tonnes). Material stocks are defined as depositories of material within a defined system boundary (measured simply in tonnes) and material flows measure the movement of material from one stock to another, and are measured in mass per unit of time (tonnes per year). For ease of readability, henceforth the term material stocks will refer to anthropological in-use construction material stocks. Further definitions will be given when applicable.

3.2. System boundaries (space & time, anthroposphere)

The examined system is the anthroposphere, and the "spatial" boundary of the examined anthroposphere is defined as the economies of countries, conforming with the standardized EW-MFA guidelines (Eurostat 2001, 2009, 2013). Materials are considered as input flows into the system when they are either extracted from the domestic natural environment or imported from outside the geographical borders of the country into the economy. Likewise, output flows from the system are defined as either discharge of material back to the environment (as waste and emissions) or export from the country to the rest of the world. In accordance with the data sources, the temporal boundary for this research is defined by the time unit of a year. A material that has both entered and exited the economy in less than a year will be considered throughput in the model, while material that remains in the system for longer than one year will be defined as stocked material.

3.3. Research flow

As done above in chapter 2 in the review of the state of the art, the research is also split into accounting and analysis, and each is further split into subparts with their own data sources and methodologies. The first part is an accounting of material stocks (described in chapter 4) and describes first the compilation of a deterministic historical model followed by deterministic future scenarios and stochastic forecasts. The second part (in chapter 5) is an analysis in several analytical approaches of the material stock accounts produced earlier and from external data sources, followed by a synthesis and conclusions of the findings in chapter 6. The research flow is presented in Figure 3.1. Blue highlights signify parts of the research and orange highlights are the main data sources used in each part. Detailed descriptions of the methods and data sources are provided in each chapter.

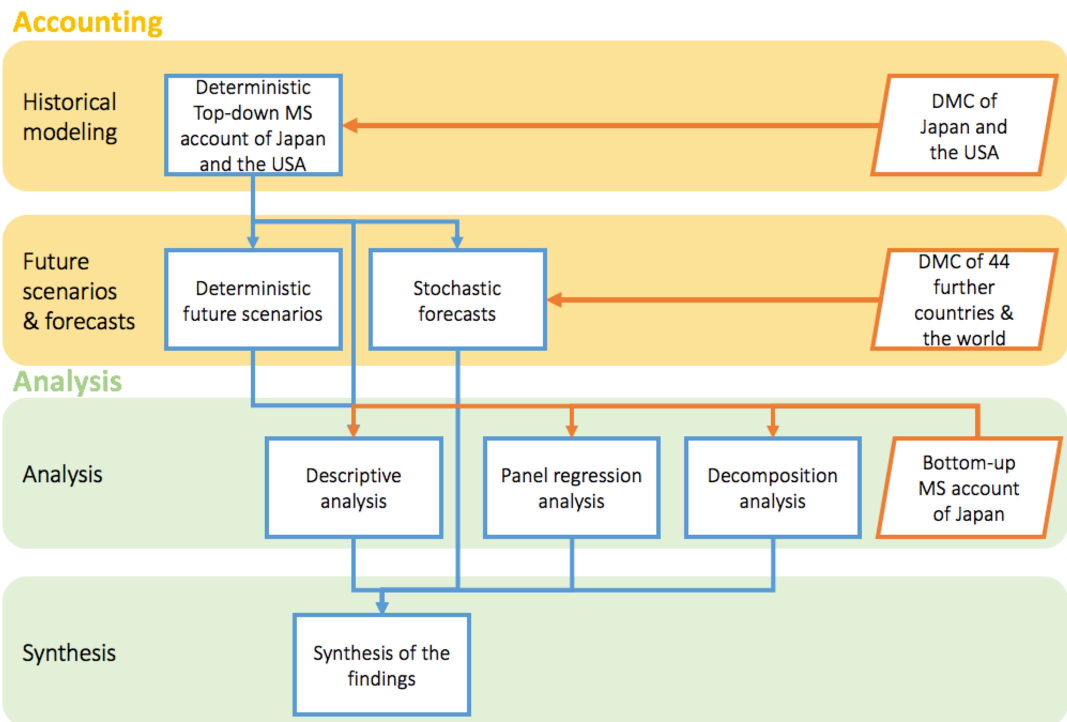

Figure 3.1 Diagram of the research flow.

4. Material stock accounting: modeling and forecasts

As mentioned in the previous chapters, a main challenge to the advancement of material stock research and policy has been the lack of data on material stocks on the national level. This chapter describes the accounting of material stocks through top-down modeling. It is split into two main sections based on the modeling approach used: deterministic modeling and stochastic modeling. The deterministic approach is used to first construct accounts of material stock accumulation for two countries with a novel method to model material stocks using consumption statistics and lifetime assumptions and then to investigate scenarios of future trajectories using the same model. In the second part of this chapter, modeling of future trajectories using a stochastic method is presented and comparisons of the approaches are made.

4.1. Deterministic modeling

This section presents a methodology for a top-down measurement of national material stocks and an application for two national economies, Japan and the United States. The aims are:

- To establish national material stock accounts from historical material flow accounts (proof of concept)
- To explore possible courses of material stock accumulation in the two countries using hypothetical future material flow scenarios
- To investigate whether there is a saturation of material stocks of nations when an economy has matured.

Two countries were chosen for examination in this research: Japan and the United States of America. Both are highly developed countries boasting some of the strongest economies in the world today. On the other hand, their historical developments as well as social, economic, and geographic characteristics are quite different, offering an interesting comparison of material usage and accumulation.

4.1.1. Methods and data

4.1.1.1. Data

This work employs long-term data compiled by Krausmann et al. (Krausmann et al. 2011) for the years 1878 to 2005 for the inflow of materials for Japan, and compiled by Gierlinger and Krausmann (Gierlinger and Krausmann 2012) for the years 1870 to 2005 for the United States. These datasets follow standard methods and definitions of material flow accounting (Eurostat 2009). They contain yearly material flow statistics for about 60 material groups separated into imports, exports, and domestic extraction, while unused domestic extraction and indirect flows associated to imports and exports are excluded, and in any case are not relevant as they don't enter the focal economy and hence can't become part of the material stock of that economy. In these datasets the direct material consumption (DMC) of the economy in a year is given by the following equation (Eurostat 2001):

$$DMC_{i,t} = DE_{i,t} + IM_{i,t} - EX_{i,t} \qquad (1)$$

where $DMC_{i,t}$ is the amount of domestic material consumption of material *i* in year *t*; $DE_{i,t}$ is the domestic extraction of material *i* in year *t*; $IM_{i,t}$ is the import of material *i* in year *t*; and $EX_{i,t}$ is the export of material *i* in year *t*.

For this study, material inflows related to the construction of buildings and civil infrastructure, the main portion of a national material stock in terms of mass, were extracted from the two data sources. Construction materials not only make up the vast majority of material stocks on the national scale, they also remain stocked in society for decades or longer, differently from other major material categories such as fossil energy carriers and biomass which are used and discharged usually within much shorter time frames (Eurostat 2001).

The construction-related materials were grouped into four categories *i*: (1) timber, (2) iron, (3) other metals, and (4) minerals to be used as inputs to the stock model. The other metals category includes metals other than iron which are used in construction such as copper, aluminum, and tin. The minerals category contains such non-metallic materials as stone, sand, limestone, gravel, and clay.

4.1.1.2. The top-down framework

Simply stated, the approach taken here is to employ the aforementioned long-term material flow datasets for establishing material stock accounts through a model of stock accumulation. The model framework is illustrated in Figure 4.1. The four material categories are maintained throughout the metabolic processes of input, stock, and output. Each yearly input is considered a new 'layer' of material added to the existing vintage stock from past years. Structures age and eventually get demolished and the quantity of material in each layer is reduced through a process of aging, estimated using the survival functions previously described in yearly calculation steps. Table 4.1 summarized the variables, classing them into exogenous variables sourced from existing data, and endogenously produced variables.

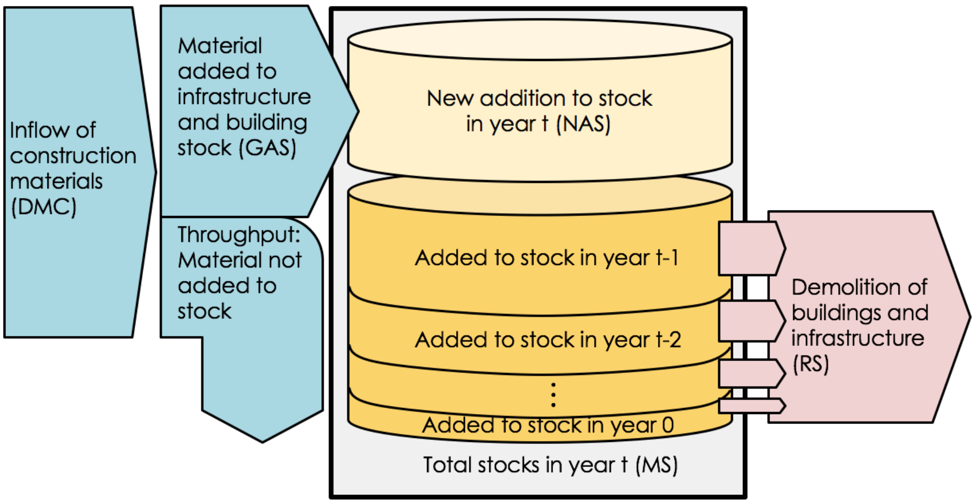

Figure 4.1 Framework of the model.

Table 4.1 Variables of the top-down model

Exogenous variables	
DMC	Direct Material Consumption
r	Rate of input into stock
µ	Mean lifetime of stocked material
σ	Standard deviation of the mean lifetime
Endogenous variables	
GAS	Gross Addition to Stock
MS	Material Stock
NAS	Net Addition to Stock
RS	Removal from Stock

For the future scenarios, population statistics and projections for Japan from 2006 to 2050 are from the United Nations (United Nations, Department of Economic and Social Affairs, Population Division 2013) and for the United States from the US Census Bureau (Population Division, US Census Bureau 2008).

4.1.1.3. Stocking rates and lifetime assumptions

The stocking rates (the fraction of the DMC of these materials that becomes stocked) vary for each material group: DMC values contain a mix of raw and processed materials, semi-manufactures, and final products, and the percentage of material that is used for construction and for other types of consumption varies between material categories. Moreover, some materials which are used in the construction process of buildings and infrastructure, such as scaffolding, are either reused or become on-site demolition wastes, but do not form a part of completed structures and should not be accounted towards stocks. The actual amount of input material that becomes stocked (gross addition to stock, or GAS) is calculated with the following formulae:

$$GAS_{i,t} = DMC_{i,t} \times r_i \quad (2a)$$

$$GAS_t = \sum_i GAS_{i,t} \quad (2b)$$

where $GAS_{i,t}$ is the gross addition to stock, the new 'layer' of addition to the total stock of material *i* in year *t*. r_i is the stocking rate of material *i* that is stocked as constructed structures in the anthroposphere, an aggregated percentage for which the assumed values are given in Table 4.2; and GAS_t is the total gross addition to stock in year t.

Table 4.2 Assumed rate of stock of materials and variables for estimating the probability of survival of material.

Material Group (i)	Rate of input into stock (r_i)	Mean lifespan (μ_i)	Standard Deviation (σ_i)
Timber	90%	40 years	13.3
Iron	20%	50 years	16.6
Other Metals	10%	50 years	16.6
Non-metallic minerals	90%	50 years	16.6

There is very little information available regarding the time construction materials spend as stocks in the anthroposphere. Lifespan probabilities of building and infrastructure lifespan in Japan (Cabinet Office of Japan, Socioeconomic Systems Survey Office 2007; Komatsu 2008) have been generalized and adapted for this research. This adaptation is based on the assumption that the lifespan of construction materials is similar to the lifespan of structures composed of them. The depreciation over time of materials that became stocked in a given year follows the s-shaped profile of the Normal Distribution's cumulative distribution function. For the objectives of the current study some further generalizations and simplifications were made: recycling processes are omitted as reliable long-term recycling data is not available, and stocking rates and depreciation rates for construction materials are kept constant over time. Moreover, building lifespans in the US are presumably longer than Japanese ones, because of historically lower building quality and fast material erosion of part of the Japanese housing stock, especially in single family homes. Thus, the results were compared to existing research to assure reliability. Furthermore, sensitivity analysis shows that different values for these variables have a relatively weak effect on the overall trends of material stock accumulation over the study period, and certainly no effect on the order of scales of the results. The statistical variables of stocking rates (r_i) and survivability probabilities (μ_i and σ_i) are provided in Table 4.2 above.

4.1.1.4. Estimation of material stock

The total stock of material in a given year is the sum of the material surviving (i.e. not yet demolished) from the layers of GAS from previous years, estimated with the following formulae:

$$MS_{i,t} = \sum_{\tau=t_0}^{t} \left[GAS_{i,t} \times \left(1 - \Phi\left(\frac{(t-\tau) - \mu_i}{\sigma_i} \right) \right) \right] \quad (3a)$$

$$MS_{i,t} = \sum_{i} MS_{i,t} \quad (3b)$$

where $MS_{i,t}$ is the stock of material *i* in year t; t_0 is the first year of DMC data (1878 for Japan and 1870 for the USA); τ is the index of summation from year t_0 to the current year *t*. In other words, it is the index of the layers of stocked material by year; Φ is the cumulative distribution function of the standard normal distribution, providing the percent of remaining material i stocked in year t after $(t - \tau)$ years have passed. μ_i is the mean lifespan of material i; σ_i is the standard deviation of material *i* (the values of μ_i and σ_i are given in table 1); and MS_t is the total material stock in year t. Historical material stock data do not exist for the periods preceding the material flow statistics (before 1870 and 1878 for the United States and Japan, respectively). The first year of the series until 1929 are used as a run-up buffer period for the accumulation of stock. It was found that only 0.1% of the stock in 1930 is composed of material stocked in the first year of the series, suggesting that material stocked before that is negligible. This facilitates the selection of 1930 as the base year for this study.

4.1.1.5. Net Additions to Stock and Removals from Stock

The term Net Additions to Stock (NAS) describe the change in total stock from one year to the next, fundamentally being the difference in MS from one year to the next.

$$NAS_{i,t} = MS_{i,t} - MS_{i,t-1} \quad (4a)$$

$$NAS_t = MS_t - MS_{t-1} = \sum_{i} NAS_{i,t} \quad (4b)$$

where $NAS_{i,t}$ is the Removal from Stock of material *i* in year *t* and NAS_t is the total material removed from stock in year t.

An alternative but equal depiction of net additions to stocks is the difference between the inflows (Gross Additions to Stock) and outflows (Removals from Stock, RS) in a single year. A simple rearrangement of reveals the material removed in a given year:

$$NAS_{i,t} = GAS_{i,t} - RS_{i,t}$$

$$RS_{i,t} = GAS_{i,t} - NAS_{i,t} \quad (5a)$$

$$RS_t = \sum_i RS_{i,t} \quad (5b)$$

where $RS_{i,t}$ is the Removal from Stock of material *i* in year *t* and RS_t is the total material removed from stock in year t.

4.1.1.6. Future scenarios

The historical data sets for both Japan and the United States end in the year 2005. In addition to the historical analysis offered by the available data, the model was extended until the year 2050 using material flow projections. The main purpose of these projections is to further explore the mechanics of the model and to present different scenarios of material usage and accumulation in the near future in search of the possibilities of reaching material saturation. As such these projections should be considered 'what-if' deterministic scenarios, not forecasts or predictions such as those made with stochastic methods.

The scenarios are driven by differing GAS rates to be used as inputs in the period 2006 to 2050. In other words, the scenarios in equations 6a-6d each substitute equation 2a, but equations 2b–5 remain unaffected. Three scenarios of future material stock accumulation with interesting profiles were selected for this analysis.

The first scenario is a "baseline" scenario. For every year from 2006 to 2050, material input (*GAS*) is kept at a steady rate based on the average of the material input of the final ten years of the dataset (1996–2005), with no further changes to the variables in Table 4.2:

$$GAS1_{i,t} = \frac{1}{10} \sum_{\tau=1996}^{2005} GAS_{i,\tau} \quad (6a)$$

$GAS1_{i,t}$ is the amount of gross addition to stock of material i in year $2006 \le t \le 2050$ in scenario 1, and τ is the index of the final ten years of the historical series.

The second scenario is a simple "population-driven" scenario. Changes to GAS are coupled to changes in population, based on exogenous population projections from the sources previously described:

$$GAS2_{i,t} = GAS_{i,2005} \times \frac{Pop_t}{Pop_{2005}} \quad (6b)$$

$GAS2_{i,t}$ is the amount of gross addition to stock of material i in year $2006 \le t \le 2050$ in scenario 2, $GAS_{i,2005}$ is the amount of gross addition to stock in the final year of the historical series, Pop_t is the estimated population in year t using projections sourced from the references mentioned above, and Pop_{2005} is the population in the final year of the historical series.

The third scenario is a "proactive environmental policy" scenario, postulating a yearly reduction of inflow by 0.5% compared with the previous year from 2006 to 2050, while also extending the lifetime of the newly built stock by 50%:

$$GAS3_{i,t} = GAS_{i,2005} \times 0.995^{t-2005} \quad (6c)$$

$$\mu 3_i = u_i \times 1.5 \quad (6d)$$

$GAS3_{i,t}$ is the amount of gross addition to stock of material i in year $2006 \le t \le 2050$ in scenario 3 and $\mu 3_i$ is the mean lifespan of material i in year $2006 \le t \le 2050$.

4.1.2. Results

4.1.2.1. Japan

The modeling results show for a period of 75 years (1930–2005) that the total stock of construction materials, *MS(t)* in Japan grew by a factor of 40, from about 920 million tonnes in 1930 to 38.7 billion tonnes in 2005 (Figure 4.2). The trend is characterized by slow growth in the pre-war period up to the 1950s, during which material stocks doubled. It should be noted that singularities of material stock loss such as the destruction of substantial amounts of Japanese infrastructure in World War 2 are unobservable due to the nature of the model. The post-war period is characterized by an immense increase in material stocks driven by rapid economic growth and the modernization and urbanization of Japan. By the early 1970s Gross Additions to Stock had reached about 1 billion tonnes per year, and they remained at that rate until the end of the 20th century. In recent years, fluctuating inflows and ongoing increases of outflows of material stocked in previous decades have led to an apparent slowdown in material stock growth. Since the beginning of the 1990s, every year had a smaller Net Additions to Stock (NAS) than its preceding year.

The future scenarios point towards visible slowdown in material stock growth. Assuming a future inflow of construction materials similar in quantity to the average of the last decade (scenario 1), overall stocks will continue to increase albeit at slower and slower rates, reaching 50 billion tonnes by 2050 and implying an s-shaped growth curve for material stocks, perhaps leading towards a saturation of total stocks at some point in the future. The second scenario is linked to Japan's population which is projected to decrease dramatically, in effect reducing the GAS to such low levels that it will become less than RS by 2031 and leading not only to a saturation of material stocks, but to dematerialization. Consequently, in 2031 MS will reach a peak of 46 billion tonnes and stocks will reduce afterwards, diminishing to only 43 billion tonnes in 2050. This is about 15% less than the MS of scenario 1 in 2050. The third scenario interestingly is almost identical to the second scenario despite its very different assumptions. It means that, given a proactive policy of reducing inflows by only 0.5% per year but with extension of lifetimes, the future stock necessary to accommodate Japan's reducing population can be maintained, albeit with a somewhat reduced consumption of materials. In this scenario, stocks seem to be approaching a stable level of around 44.5 billion tonnes in 2050.

It is notable that in the first two scenarios, the trend of Removal from Stock is constantly increasing, reaching almost 1 billion tonnes per year by 2050 and is hardly affected by the premises of the scenarios, as most of the removed material originated in the historical additions to stock. The third scenario is dramatically different, reaching a point of "peak wastes" in the late 2030s and then decreasing due to the longer lifespans of newer construction.

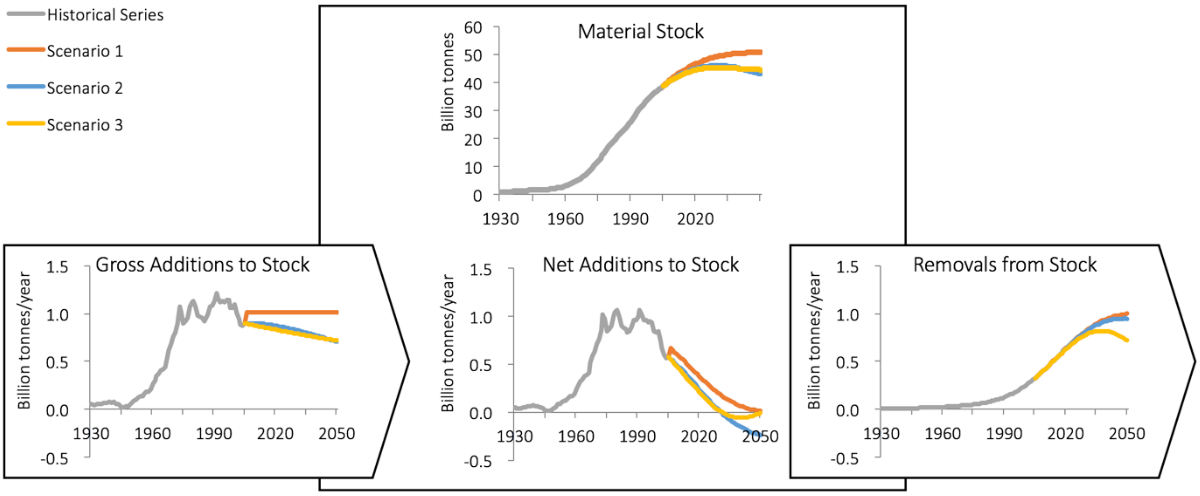

Figure 4.2 Stocks and Flows in Japan, 1930–2050: (a) Material Stock (MS), (b) Gross Additions to Stock (GAS), Net Additions to Stock (NAS), and Removals from Stock (RS).

Figure 4.3 shows the four stock categories, which have evolved differently, mirroring the changes in preferred construction materials and technologies over the 20th century in Japan. Iron, other metals, and minerals stocks have been rapidly increasing since the beginning of the 1960s in conjunction with Japan's economic growth phase. Iron stocks in 2005 were 791 million tonnes, 109 times the stock quantities of 1930, showing the largest relative increase of the four examined categories. Construction minerals stock has grown by a factor of 66 from 703 million tonnes in 1930 to 36 billion tonnes in 2005 while the stock of other metals has only grown about 12-fold, from almost 8 million tonnes in 1930 to more than 92 million in 2005.

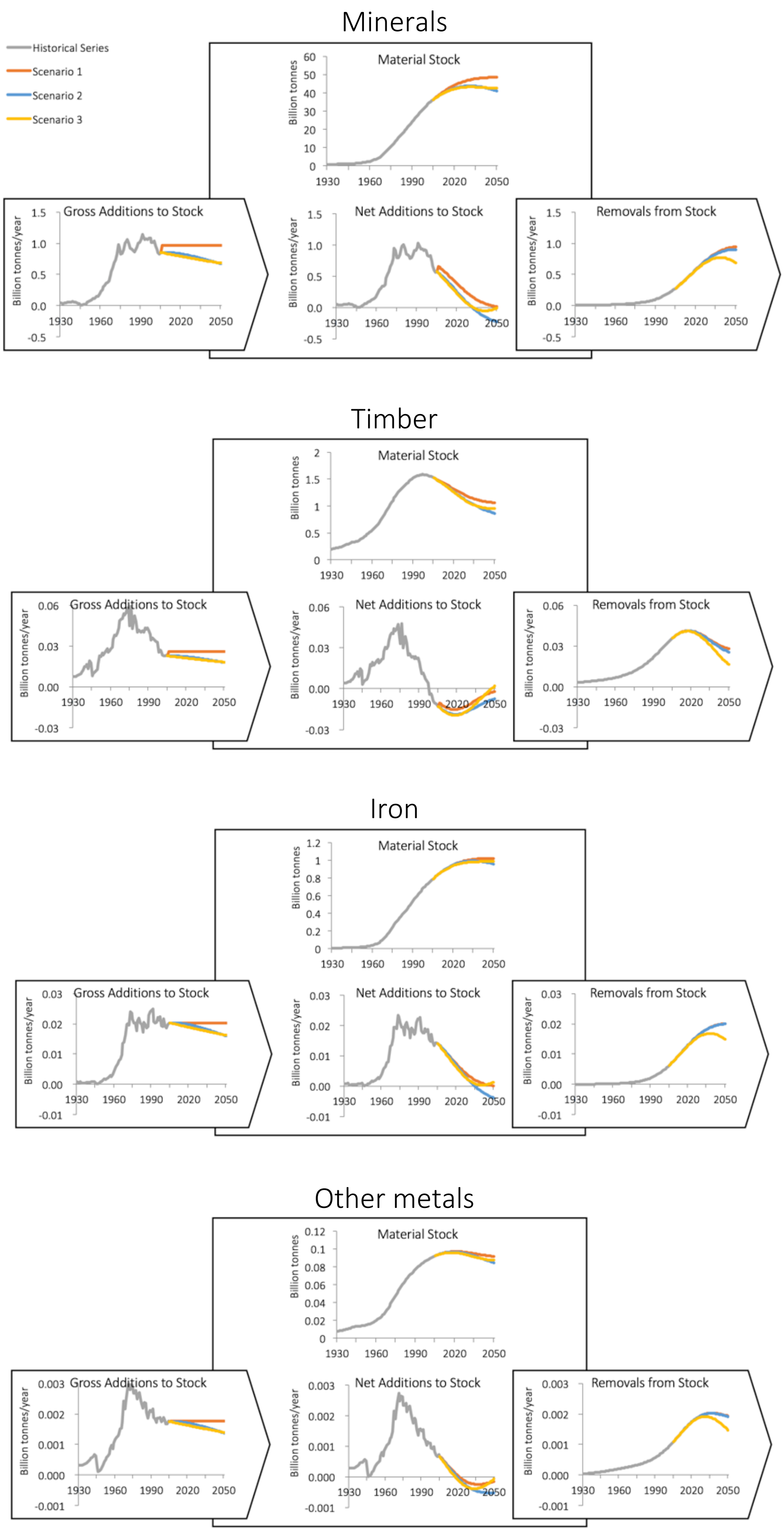

Figure 4.3 Individual stocks trends of materials in Japan, 1930–2050: (a) timber, (b) minerals, (c) iron, (d) other metals. Note the different scales.

Construction minerals and iron and steel stocks are continuing to grow, albeit at slower rates. The stock of other metals shows saturation during the next couple of decades and timber stocks peaked around 1995 at 1.3 billion tonnes and have since been in decline.

The scenarios project further decreases to timber, and other metals are projected to peak in the 2020s. Minerals and iron stocks would stabilize in the first and third scenarios (at different rates) but peak and then decline in the second one.

Throughout the study period the major constituent group of Japan's material stock was minerals. Their share rose from 76% in 1930 to 95% in 2005 and is expected to rise to 96% by 2030. In comparison, timber made up 22% of Japan's material stock in 1930 but declined to around 3% in 2005. It is interesting to note that in the immediate post-war period, timber regained in importance to a share of 18%, but since then has constantly declined, and is projected to reach 2% by 2050. The share of other metal stock including materials such as copper and aluminum was small during the entire study period. Iron had increased from 1% to 2% by 1964, and has remained at that rate since. In all future scenarios these shares do not change significantly until 2050.

4.1.2.2. USA

Figure 4.4 shows that stocks of construction materials in the USA were higher than in Japan during the entire study period, reflecting a larger and more populous economy and a higher level of wealth. Total stocks grew from 11 billion tonnes in 1930 to 107.5 billion in 2005, a 9-fold increase. The growth trend was characterized by steadily increasing amounts of yearly additions to stock throughout, despite some fluctuations in the 1970s. Removals from stock have been slowly increasing as well, at lower levels than inflows. As a result, material stocks in the US continued to increase until 2005. This results in somewhat stabilized yearly net additions to stocks since the 1970s. This model suggests that in the first scenario the rate of accumulation of material stock will decrease and material stock will reach 155 billion, but the second scenario points toward continuously increasing stocks caused by the projected further growth of population in the USA until 2050. In the United States, this scenario behaves in an opposite way from the Japanese case. Removals from stock reach almost 3 billion tonnes per year in 2050 in both scenarios. In this country, the third scenario of lifetime extension and reductions in consumption more closely resembles scenario 1 of constant consumption. As with

Japan, removals from stock peak in the late 2030s and then gradually reduce due to extended lifetimes.

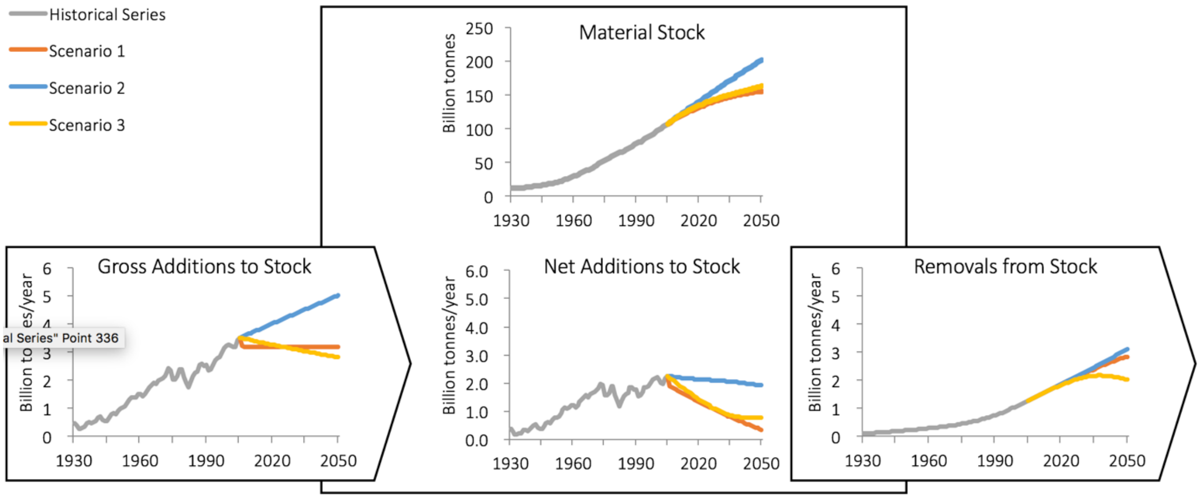

Figure 4.4 Stocks and Flows in the United States, 1930–2050: Material Stock (MS), Gross Additions to Stock (GAS), Net Additions to Stock (NAS), and Removals from Stock (RS).

The trends of each material category are shown in Figure 4.5. Construction mineral stock was 6.5 billion tonnes in 1930 and 96 billion in 2005, a 15-fold increase that was characterized by a moderate growth until the beginning of the 1950s, after which a sustained rapid growth is ongoing. Timber has followed a similar growth curve but much more restrained, almost doubling from 4.5 billion tonnes in 1930 to 8.2 billion in 2005. Iron stock increased from 366 million tonnes in 1930 to 950 million in 1979, and since then its growth has almost halted, reaching about 970 million tonnes in 2005. Other metals show no similar slowdown. This category's stock grew from 346 million tonnes to 1.6 billion in 2005. Timber and Mineral stocks are expected to continue growing in all scenarios, while the growth of iron and other metals stocks seems to come to an end in the three cases. Similar to Japan, the major component of material stock is non-metallic minerals. These materials had a share of 55% of total stock in 1930 and increased to 90% in 2005. Concrete gradually replaced timber as a major construction material and timber lost in share from 39% in 1930 to less than 10% by the 1980s. At the end of the 1960s the succession of timber by construction minerals was complete and the composition of stock has not changed significantly since. Both iron stocks and other metal stocks had only a small and decreasing share of total stocks in the United States, from 3% to 1% each, despite growth in real numbers.

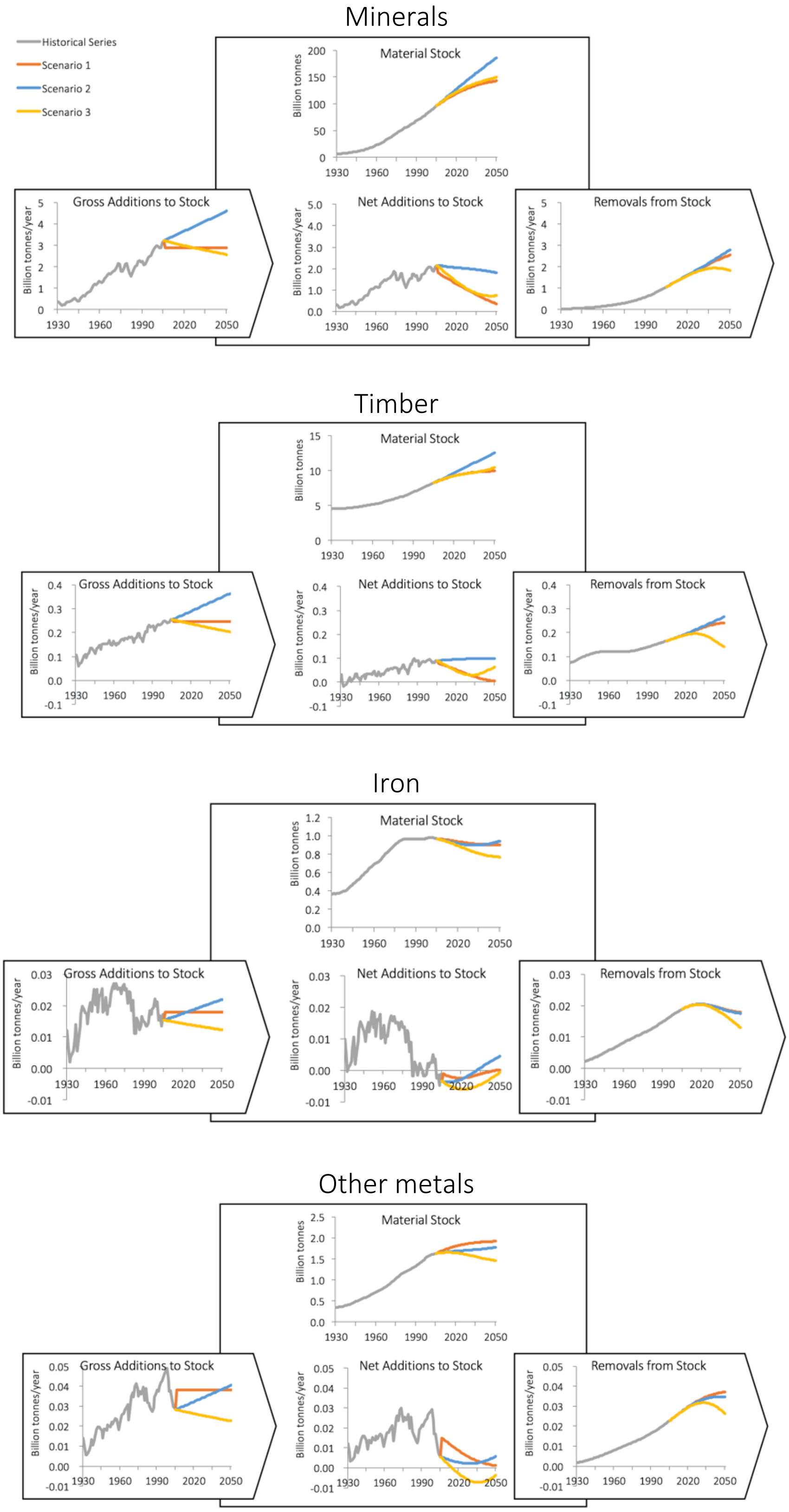

Figure 4.5 Individual stocks trends of materials in the United States, 1930–2050: (a) timber, (b) minerals, (c) iron, (d) other metals. Note the different scales.

The results show that by 2005 material stocks in both Japan and the United States continued to increase and are not saturated yet. On the contrary, total stocks in both countries, fueled mainly by minerals accumulation in buildings and infrastructure, have not shown any significant slowdown. However, future scenarios of Japan offer projections of total stock saturation and even dematerialization. In the United States, even though no scenario presents such a trend, scenarios 1 and 3 do present a slowdown of material stock growth, suggesting that at some point in the future stabilization of stocks could occur there as well.

4.1.3. Sensitivity analysis and validity

Sensitivity analysis was conducted on the model to understand the effects of changes in stocking rates and lifespan assumptions. Because the stock account is derived from a model, sensitivity analysis is a straightforward task. By definition of the model, increasing or decreasing stocking rates changes the resulting stock account by the exact same proportion. Lifespan variables have a weak effect on overall stock. A 10% change in mean lifespan results in a 2% change in the stock account on average. These variables have relatively weak effects because the aggregation of the dozens of layers of stocks has a dampening effect on changes in lifespans. The modeling approach, in contrast to a bottom-up analysis, also allows for testing assumptions about future trends in stock, amounts of input required and amount of materials that will be discarded. This may well become policy relevant information if economic planning would focus on extending the durability and lifetime of buildings and infrastructure to allow a shift from a throughput metabolic pattern to a focus on stocks and services derived from the stock.

A previous study (Hashimoto et al. 2007) calculated the construction-related material stock growth of Japan for the years 1976 to 2005 using a bottom-up method of stocking rates of materials per unit of floor space for several types of buildings and material intensities for different infrastructure, and provided a projection of growth until 2030. The materials examined in the research were limited to asphalt, cement, sand, gravel, and crushed stone, which correspond with materials in the category of construction minerals in this research. Another study, Tanikawa et al. (Tanikawa et al. 2015), employed a bottom-up method of material intensities per unit of construction and focused on the materials found in buildings, roads, railways, airports, dams, and sewerage systems for the period 1960 to 2015.

Due to a more limited scope of these previous studies (fewer materials in Hashimoto et al. 2007 and fewer construction types in Tanikawa et al. 2015) we would expect the new results to be higher than those presented in previous studies. A year by year comparison (Figure 4.6) shows that the figures for Japan's material stock of Tanikawa et al. (2015) are on average less than

40% of the new estimate because some of the most material-intensive infrastructure projects such as ports, harbors, agriculture, and landslide/flood control had not been accounted for in that research. The aggregate numbers of Hashimoto et al. 2007 are very similar to the new estimates but about 20% lower, mainly due to a more limited scope of material categories. The low variance in the year by year difference between the new results and the previous studies shows very similar growth trends of all three studies.

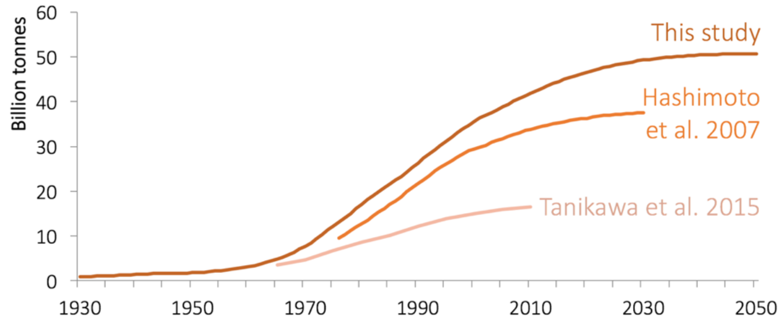

Figure 4.6 Comparison between construction material stock estimations for Japan: The studies published by Hashimoto et al. (2007) for 1976–2030, Tanikawa et al. (2015) for 1960–2010, and this study, scenario 1, for 1930–2050.

Although there are no material stock studies of the United States for comparison, Figure 4.7 shows that the values and trends of change in net additions to stocks obtained by the World Resources Institute (WRI) (Matthews et al. 2000) for both the United States and Japan are very close to the results of the current research, despite the different methodologies employed. The scope of Matthews contains materials not related to construction which are not included in this study and only have small contributions to the total anthropogenic stock. Accounting for these materials in the previous study explains their slightly larger results.

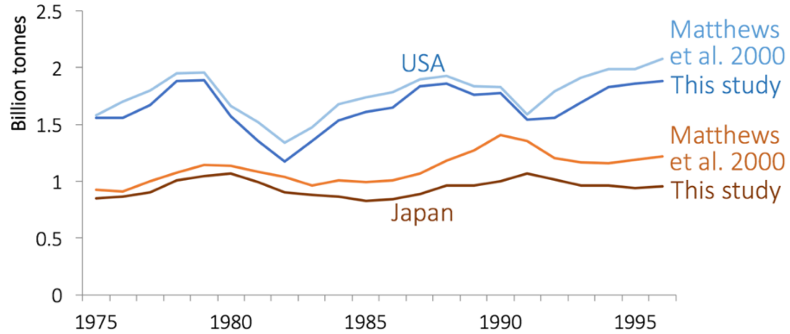

Figure 4.7 A comparison between Net Additions to Stocks (NAS) estimations for Japan and the USA, 1975–1996: The study published by WRI (Matthews et al. 2000) and this research.

The comparison with previous studies shows a high coincidence in both level and evolution of national material stock and provides confidence about the validity of this analytical approach.

4.2. Stochastic modeling

Deterministic methods have in common a reliance on external factors to explain historical and future stock levels. This causes some inherent limitations:

- External factors are subject to their own uncertainties which permeate into stock projections;
- Results are influenced by presuppositions and choices in the selection of factors – and some factors which have a direct influence on the amount of stocked construction material such as geography and distances have yet to be taken into account;
- Relations with external factors and stocks must be definable and stated mathematically. This is especially challenging with qualitative factors such as cultural preferences and fashions or political decisions;
- Changes to stock are assumed to be explained by changes in external variables over the same time period, ignoring lagged influence;
- The focus on external factors overlooks the endogenous effects of the existing stock on its own future state.

In light of these limitations, in this section a different approach is undertaken. Rather than trying to explain and forecast material stock accumulation trends through external factors, the time-related characteristics of material stock accumulation itself is exploited by stochastically analyzing historical trends for 46 countries and the entire world.

4.2.1. Methods and data

4.2.1.1. Framework – differences and integrals

This analysis revolves around the examination of the amount (level) of material stocked in society simultaneously with its speed and acceleration of accumulation. These three terms of level, speed, and acceleration of material stock have been in use, sometimes interchangeably, in previous studies and have yet to be formalized in the context of material stock. Borrowing from classical mechanics, the mathematical relations of these three analytical measurements of stock accumulation are hereby formalized as differentials and integrations of each other. Conforming to practices established in the material flows and stocks research discourse, time steps of one year are used throughout the analysis and Table 4.3 details the relations of the layers in discrete one-year time steps as differences and summations, accordingly. Figure 4.8 shows an example of the differential relations of levels and speed for ease of understanding.

Table 4.3 The mathematical relations of level, speed, and acceleration of material stocks.

Name	Notation	Description	Unit	Alternative notation	Notes
Level of material stock	MS_t	Total societal material stocks at year *t*	Mass (tonnes)	$MS_\tau + \sum_{i=\tau}^{t} NAS_i$	τ is a base year with a certain level of existing material stock and $\sum_{i=\tau}^{t} NAS_i$ is the sum of all net additions from base year τ to current year *t*.
Speed of material stock accumulation	ΔMS_t	The change in material stock between two consecutive years	Mass per year (t/y)	NAS_t	*NAS* is the Net Addition to Stock = Inflows – Outflows in year *t* (Eurostat 2001).
Acceleration of material stock accumulation	$\Delta^2 MS_t$	The change in speed between two consecutive years, or the second order of difference of the level of material stock	Mass per year, per year (t/y^2)	ΔNAS_t	

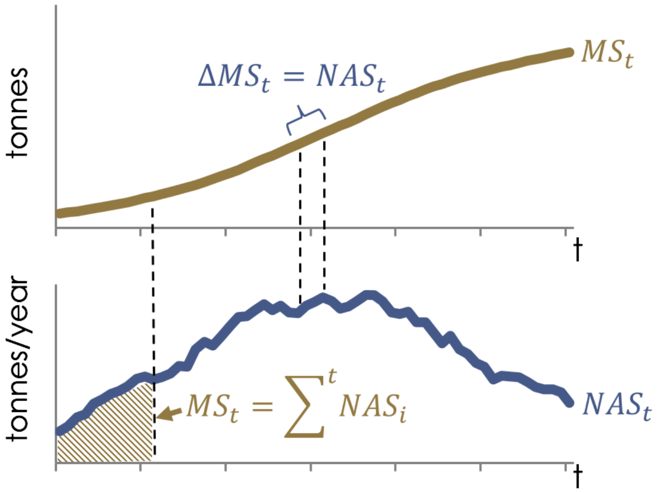

Figure 4.8 Graphical representation of the differential relations of material stock level (top) and speed (bottom)

4.2.1.2. ARIMA

Previous studies have focused on either the levels or the speed of accumulation (consumption), offering a one-dimensional analysis, and moreover have not looked at time series characteristics, nor at how the past affects current stock trends. Here the level, speed, and acceleration are concurrently analyzed using the ARIMA (Auto-Regressive Integrated Moving Average) methodology, a stochastic approach commonly used in business and economics analysis to inspect and forecast time series (Becketti 2013).

An ARIMA (Auto-Regressive Integrated Moving-Average) model is classified as ARIMA(p,d,q)+c where:
p is the number of autoregressive (AR) terms.
d is the number of orders of difference.
q is the number of moving average (MA) terms.
c is a constant.

The general ARIMA equation is:

$$(1 - \phi_1 B - \cdots - \phi_p B^p)(1 - B)^d y_t = c + (1 + \theta_1 B + \cdots + \theta_q B^q) e_t$$

Where y_t is the value of the time series at time *t*, e_t is random white noise (random, in this sense, means external to the model and thus unpredictable), *c* is a constant, *p*,*d*, and *q* are as above, ϕ_i is the AR coefficient of lag *i*, θ_i is the MA coefficient of lag *i*, and *B* is the backshift operator, defined as:

$$By_t = y_{t-1}$$
$$B^d y_t = y_{t-d}$$

Using the backshift operator, order of difference *d* can be written as:

$$(1 - B)^d y_t$$

For example, if country S's *speed* of material stock accumulation is found to be explained by an ARIMA(1,0,0) model (i.e. a model with a single AR term) with an AR(1) coefficient of 0.674 and a constant with the value of 45139172, its ARIMA equation is:

$$\left(1 - 0.674B\ \right)(1 - B)^0 y_t = 45139172 + e_t$$

Which can be rearranged and rewritten as:

$$y_t - 0.674By_t = 45139172 + e_t$$
$$y_t = 45139172 + 0.674y_{t-1} + e_t$$

This is interpreted as: the speed y_t is a constant of 45,139,172 tonnes/year affected by the speed of one-year prior (a "lag-1 Auto-Regressive term") with a coefficient of 0.674, and random white noise.

A central notion in the ARIMA method is the requirement to employ it on a stationary time series, i.e. on data which is time-independent. In cases of non-stationarity, sufficient orders of differencing are applied to achieve a stationary series (Becketti 2013; Hyndman and Athanasopoulos 2014), the forecast is conducted on the differenced stationary series and the results, including the associated uncertainties, are re-integrated into the original series. This trait of ARIMA is beneficial to the aims of this work since these differentiation and integration mechanics of the ARIMA method offer a gateway to understanding the underlying dynamics of speed and acceleration that brought about historical levels of material stock by recognizing and analyzing the time-dependence or lack thereof for all three layers of level, speed, and acceleration. It enables the production of stochastic, endogenous one-period-ahead forecasts of future development and the establishment of uncertainty ranges based on the behavior of historical time series, which can thus be termed business-as-usual or baseline scenarios.

In another example, the model for country T's *level* of material stocks is found to be an ARIMA(0,3,2) model, then:

$$(1-B)^3 y_t = (1 - 0.1682B - 0.6475B^2)e_t$$

$$\vdots$$

$$(1-B)^3 y_t = e_t - 0.1682e_{t-1} - 0.6475e_{t-2}$$

The level of stock at time t is a re-integrated (undifferenced) third order of difference of y_t affected by the previous year's random error (a "lag-1 Moving-Average term") with a coefficient of -0.1682 and the random error of two periods ago (a "lag-2 Moving-Average term") with a coefficient of -0.6475, and random white noise.

For each country an ARIMA model was selected using the Box-Jenkins approach with the R statistics package through the following steps (Hyndman and Khandakar 2008; Hyndman and Athanasopoulos 2014):

(1) The order of integration / order of differences for stationarity was identified using two independent unit root tests: the Augmented Dickey-Fuller test and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test, accompanied by a visual confirmation of the differenced series. In cases where the differenced series was clearly not mean-reverting, a further level of differencing was done and stationarity was then confirmed with the above statistical tests to the further differenced series.

(2) The number of Autoregression or Moving Average terms and their coefficients, and the inclusion of a constant, (i.e. the 'best fit' model) were chosen by minimizing the Corrected Akaike's Information Criteria.

(3) Diagnosis for the absence of residual time series correlations was confirmed by the Ljung-Box Portmanteau test and autoregression and partial autoregression correlograms.

The countries were then partitioned into three groups by the criteria of the order of integration (0, 1, or 2), and additionally the third group were split into two groups by these countries' distinctly different curves in all orders of differentiation and integration.

4.2.1.3. Data

Data for the material stock of Japan and the United States is based on the top-down modeling described in section 4.1, which established historical material stock accumulation for the United States and Japan. In this section, only the stock figures from the post-war era (1950) until 2010 are used, since the pre-war and war periods had distinctly different growth patterns than the modern ones. Only the time series of construction minerals is used in this analysis, since it could be extended until 2010 using newly available data on the speed of material stock accumulation (DMC) from (UNEP 2015), which also provides the DMC data for each of the countries and at the global level for 1970-2010. The countries with populations of over 10 million in 1970 were selected for analysis, using population figures from (World Bank 2015). Four countries (Russia, Ukraine, Uzbekistan and Kazakhstan) were omitted despite suiting these criteria due to lack of country-level DMC statistics before the split of the Soviet Union. In total, the analyzed countries together account for over 80% of global population.

4.2.2. The USA and Japan

The framework is demonstrated by an analysis of the level, speed, and acceleration of stock accumulation of the United States and Japan. In both cases lagged variables were found to have correlation with those of the following periods and were used for forecasting future trends.

4.2.2.1. Results

The ARIMA analyses for the USA and Japan was conducted on the material stock levels series, and the values of the selected 'best fit' models for both countries are presented in Table 4.4.

Table 4.4 ARIMA models for the USA and Japan

	The United States ARIMA(3,2,0)			Japan ARIMA(0,3,2)	
	AR(1)	AR(2)	AR(3)	MA(1)	MA(2)
Coefficient	0.5436	-0.1846	-0.3595	-0.1682	-0.6475
Standard Error	0.124	0.1545	0.1425	0.1066	0.1048

Due to the nature of the ARIMA framework, the coefficients' values would remain the same for all "layers" of integration or differentiation. For example, if the ARIMA procedure is conducted for the USA on the speed (the difference in levels from one year to the next) rather than the levels series, the model would be an ARIMA(3,1,0), but the number of AR terms and their coefficients remain the same.

The forecasts produced by the ARIMA models for the USA and Japan are shown in Figure 4.9. The level of material stock of the United States in 1950 was about 19 Gt and by 2010 total construction material stock in the United States had reached about 114 Gt. At the layer of the total level of material stock (top panel), this growth seems linear with constant additions to the stock, however the middle panel shows that physical stock growth was in fact achieved through fluctuating yearly additions – the United States experienced long periods of gradually increasing accumulation speed interrupted by slowdowns of a temporary nature, and growth reverted to pre-crisis rates for each occasion after only a few years. Although these trends visually appear somewhat cyclical, they do not follow a predictable periodic pattern and slowdowns occurred in the 1970s, the early 1980s, and again in 2008–09, years which marked important global economic events. This can best be seen at the layer of acceleration (bottom panel): in the 60 years examined the United States experienced fairly stable positive acceleration. Most years with positive acceleration levels were followed by years with similar trends, but occasionally external shocks with strong negative acceleration "dips" (i.e. deceleration) coincided with economic downturn events. The acceleration series seems to be following a long-term trend of reversion to a mean, and these shock-induced dips behave somewhat as regulators that keep the mean level of acceleration at or just slightly above zero. The 2nd order of difference is a stationary series and therefore the forecasts are generated at this order of differencing, under the modeling assumption that this series will again revert to its mean. The manifestation of this reversion in terms of speed is that the slowdown following the recent crisis will again be short and the speed – the net yearly addition – will reach about 1.4 Gt per year, culminating in a level of 143 Gt of material stock by 2030. The low, slowly diverging uncertainties of the stationary acceleration series are re-integrated to produce uncertainty ranges for speed and levels, which result in a relatively low uncertainty range of 128 Gt to 157 Gt at the 95% confidence level in 2030. The United States hence presents an example of an advanced and wealthy economy that has not slowed its demand for physical stock accumulation at any time over the past four decades and will see further growth occurring until 2030.

In comparison, the historical evolution of construction material stock in Japan has followed a remarkably different pattern. Starting from a low level of about 1.4 Gt in the years after World War II, material stocks had increased to 38 Gt by 2010. Speed has been positive throughout the historical time period, explaining the ongoing accumulation of in-use stock levels. However, the historical speed profile shows three distinct phases: accumulation picked up speed until the beginning of the 1970s, followed by a regulated and more or less constant speed until the 1990s. Since then there has been an ongoing slowdown, and the speed of accumulation in 2010 decreased to what it was in 1960. Unlike the case of the United States, the time trend of acceleration has not been stationary. It was positive and growing until the early 1970s, then reverted to above or below a near-zero mean for the next two decades, and most years since the early 1990s have experienced negative acceleration, a clear deceleration of stock growth. The length of each period varies, and the change from one acceleration episode to the next coincided with external shocks – the 1970s oil crisis and burst of the Japanese economic bubble in the 1990s. Since the acceleration time series of Japan is time-dependent and does not revert to a global mean, the third order of differencing was found to be stationary, as required for ARIMA modeling for this country. This third order of differencing measures the level of jolts, or surges, that the material stock has undergone. The forecast for Japan is therefore not based on an overarching long-term acceleration trend but instead the most recent trend is extended into the future for the length of the forecast horizon under the assumption of "business-as-usual" – no other assumption can be made in these circumstances, since the timing of and reaction to any random future shock cannot be predicted. Material stock levels are forecast to peak at nearly 40 Gt around the year 2020 before the accumulation speed drops below zero, i.e. negative yearly net additions to the stock – a dematerialization. However, the erratic year-on-year behavior, unpredictability of the response to external shocks, and re-integration of three orders of difference manifest as wide and rapidly diverging uncertainty ranges in all three series. This is illustrated most interestingly in the top confidence bands of the levels series which even at the 80% level show a possibility of a return to stock growth.

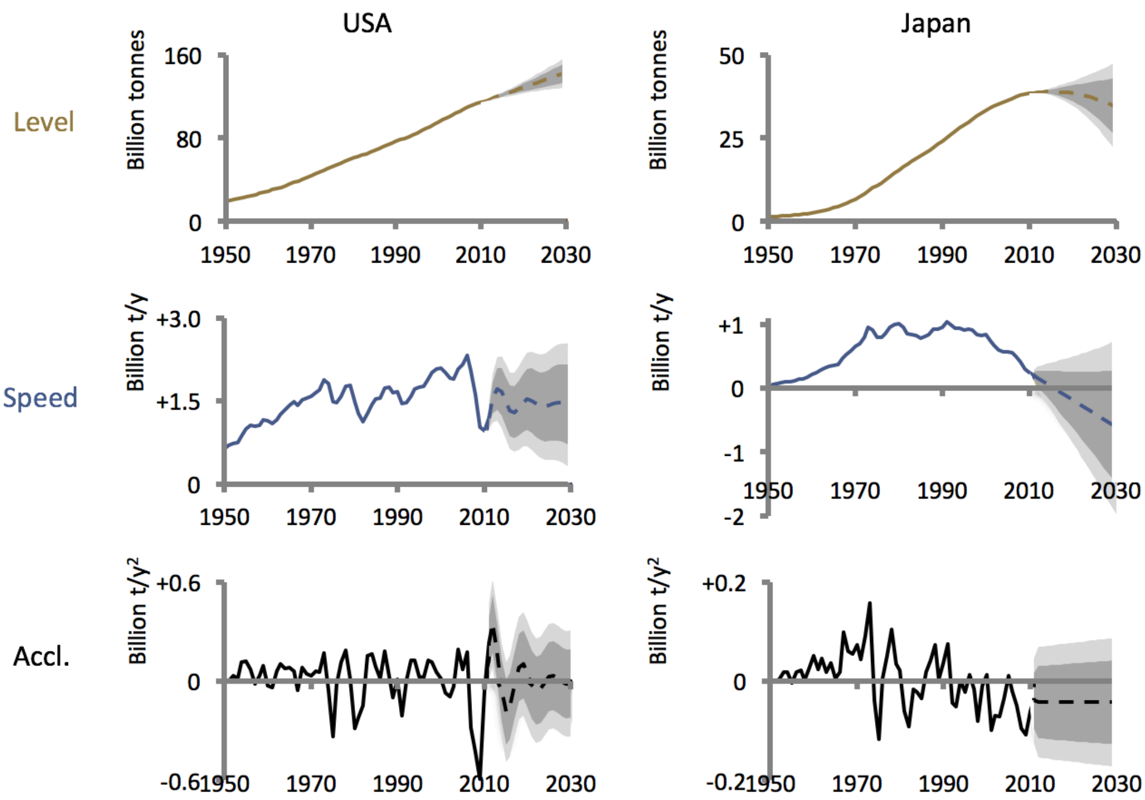

Figure 4.9 The accumulation of material stock in the USA (left) and Japan (right), 1950–2030, with forecast intervals of 80% and 95%. Top panels: total stock levels. Middle panels: speed of accumulation. Bottom panels: acceleration of accumulation speed.

4.2.2.2. Comparison with the deterministic forecasts

A comparison with the deterministic scenarios of the previous section show some interesting findings (Figure 4.10). In the USA, the "baseline" scenario of constant inflows (scenario 1) and the "proactive environmental policy" scenario of 0.5% reductions to inflow and 50% extensions to lifespans (scenario 3) are within the 80% probability intervals of the ARIMA forecast and quite close the point forecasts. The scenario of inflow rates changing with population (Scenario 2) is outside the top 95% margin, suggesting that the probability of that scenario to occur are lower. This finding is remarkable, as the stochastic ARIMA method doesn't assume prior assumptions regarding the material stock accumulation process on which the scenarios are based, and yet provides similar results.

However, in Japan the three scenarios offshoot the ARIMA forecast which predicts a much faster dematerialization trajectory. While scenarios 2 and 3 eventually return to within the top 80%-95% intervals in the mid 2020s, scenario 1 remains outside the forecast margins. Nonetheless, it should be noted that the scenarios start in 2005 while the ARIMA forecast starts in 2010 and the scenarios in fact overshoot Japan's real world figures of 2006-2010 too. The ARIMA model of Japan is especially sensitive to trends of the most recent years and if this model was run only on the data until 2005, it would suggest a forecast that more closely resembles the trajectories of the three deterministic scenarios. This finding suggests that in dynamic cases such as the dynamically decelerating Japan, both deterministic and stochastic models require yearly updates with the most recent data in order to remain practical- a finding that also hints that long-term forecasts for these countries may have less reliability, even though in this case two scenarios return to within the ARIMA forecast intervals.

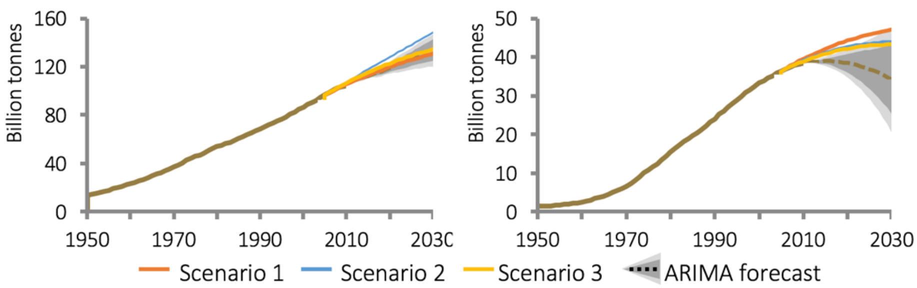

Figure 4.10 A comparison of the deterministic scenarios and stochastic forecasts for the USA and Japan until 2030.

4.2.3. 44 further countries and the World

Of the countries analyzed, historical data on the levels of material stock exist for Japan and the United States for 1950 to 2010 and so their results are the most complete. For the rest of the countries the analyzed data is the yearly speed of consumption since 1970, which closely approximates the yearly speed of accumulation. Without data for the base level of stock in 1970 only total accumulated additions to stock in the years since 1970 can be calculated. In other words, in the alternative notation for the levels given in Table 4.3 above, ($MS_\tau + \sum_{i=\tau}^{t} NAS_i$), $\sum_{i=1970}^{t} NAS_i$ can be calculated but MS_{1970} remains an unknown figure.

4.2.3.1. Stock accumulation trajectory profiles and archetypes

The results show that all of the 46 nations (including Japan and the United States) and the world fit into one of only four archetypal stock accumulation profiles. The partitioning trait is the layer which exhibits a time-invariant behavior of reversion to a mean (i.e. stationarity), and stylized figures of the four profiles are presented in Figure 4.11, using computer generated random values of accumulation to emphasize the acceleration trends, which culminate in the various speed and level growth shapes. The profiles are: (I) countries whose speed of stock accumulation is stationary, (II) countries whose speed changes over time but whose acceleration is stationary, (III) countries with non-stationary acceleration which has a general increasing trend throughout time, and (IV) countries with non-stationary acceleration which exhibits varying phases.

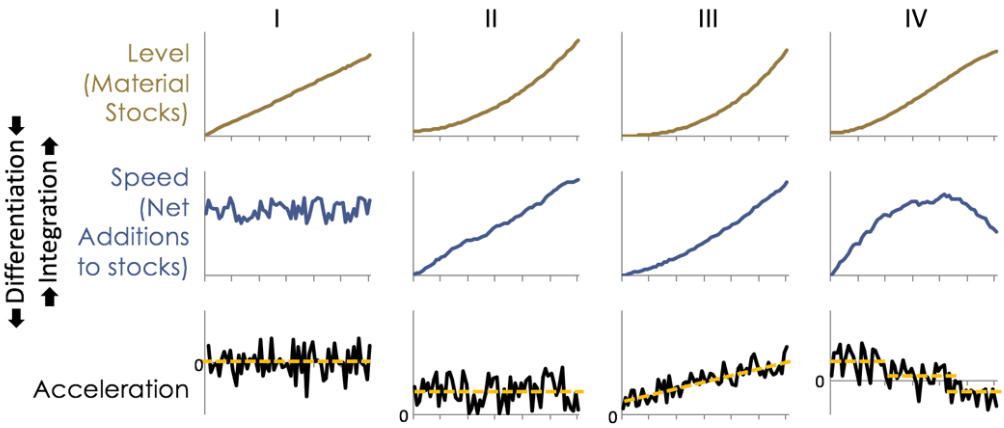

Figure 4.11 Stylized representations of the four archetypes of material stock accumulation profiles over time.

4.2.3.2. Results

Table 4.5 presents the allocation of the analyzed countries into the four archetypal accumulation profiles. The groups are described below, with figures for exemplary cases. The details of the ARIMA models and accompanying figures for all countries may be found in the appendices.

Table 4.5 Country groups based on their accumulation profiles.

(I)	Stationary speed The Netherlands
(II)	Stationary acceleration Argentina, Australia, Bangladesh, Colombia, Indonesia, Malaysia, Mexico, Morocco, Myanmar, Nepal, Nigeria, Philippines, Romania, South Africa, Spain, Sri Lanka, Thailand, Turkey, Venezuela, USA
(III)	Overall increasing acceleration Afghanistan, Algeria, Brazil, China, DR Congo, Ethiopia, India, Iran, Kenya, Pakistan, Peru, Poland, Sudan, Tanzania, Vietnam, *World*
(IV)	Varying phases of acceleration Canada, France, Germany, Italy, Japan, N. Korea, S. Korea, UK

The first group includes a single country, the Netherlands, which exhibited a unique material accumulation profile from 1970 to 2010. Its historical speed of stock accumulation appears to undergo aperiodic cycles around a mean of about 44 million tonnes of additional stock per year, which culminated in a total increase to stock of over 1.8 Gt in the last 40 years, equivalent to the area below the speed trend in Figure 4.12, panel I. The model found an auto-regressive relation between past years and the current time period, and based on this and the stationary trend, the forecast is of a slow reversion to the mean of the historical series, totaling in a further addition of almost a billion tonnes to stocked construction material in the next 20 years. The confidence interval bands are wide due to historical fluctuations, and grow due to the accumulation of uncertainties from year to year in this one-period-ahead forecast.

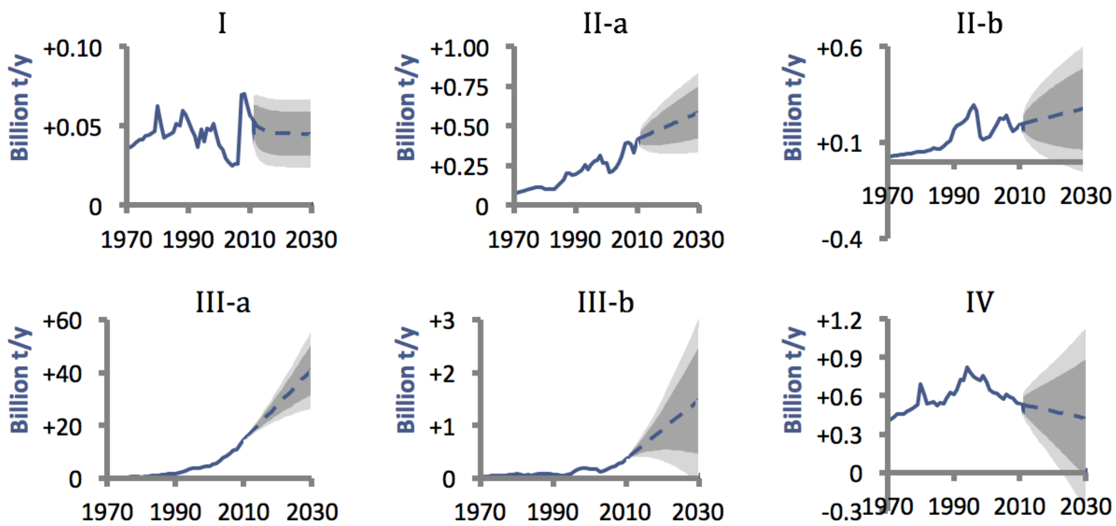

Figure 4.12 The speed of accumulation of material stock, 1970–2030 with forecast intervals of 80% and 95%, in (I) The Netherlands, (II-a) Turkey, (II-b) Thailand, (III-a) China, (III-b) Brazil, (IV) Germany. Note the different vertical scales.

Unlike the first group, the speed of material stock accumulation of the countries in the second group changes over time. However, common to these 20 countries is that their rates of acceleration revert to a mean with a positive value independent of time. This constant and positive acceleration means that material stock accumulation picks up speed year-on-year at a linear rate, forecast to continue into the future with confidence bands that are characterized by sideways-parabolic shapes. For example, Turkey's addition to its stock in 1970 was about 75 million tonnes but accelerated at an average yearly rate of 8.5 additional million tonnes, and by 2010 stock growth had sped up to more than 400 million tonnes per year totaling to an increase of over 8 Gt in 40 years. If these rates continue, the speed of growth will reach over

580 million tonnes per year in 2030, totaling an addition of a further 10 Gt of stock (Figure 4.12, panel II-a).

The third group and fourth group include those countries for which, like Japan, acceleration was not stable or mean-reverting throughout 1970 to 2010. They thus all share several characteristics: as there is no overarching global mean acceleration trend to which they revert, their forecasts are based on trends from recent years and their uncertainty levels rapidly expand with funnel-shaped confidence bands. However, the two groups' trends are remarkably different. The third group includes 15 developing economies whose material stock accumulation has been accelerating year on year. Unlike the countries in category II, which follow a steady acceleration trend that causes a linear increase in speed, here speed is increasing faster and faster due to acceleration surging from year to year. China is the most pronounced example. In the 1970s, its range of acceleration – the difference in accumulation speed – was in the magnitude of tens of thousands of tonnes/y from year to year. By the 1980s it grew to hundreds of millions of tonnes per year and most years since 2003 have had acceleration of over a billion tonnes per year. This surging acceleration is apparent in the total accumulated stock. From 1970 to 2010 China increased its construction mineral stock by over 146 Gt, of which over 50% were added in the last few years, from 2004 to 2010. The 14.5 Gt added to the stock in 2010 are equivalent to the total addition to stock from 1970 to 1988. Although not as massive as China's case, the rest of the countries in this group all experienced similar surging growth, and their forecasts are therefore for further acceleration. However, the forecast profiles of these countries differ in their unique uncertainties: some countries, like China, had more assured acceleration (Figure 4.12, panel III-a) resulting in narrower levels of uncertainty, but others such as Brazil (Figure 4.12, panel III-b) experienced more setbacks in their recent growth, manifesting as higher uncertainties in their forecasts and therefore wider and diverging confidence bands.

The fourth group is of countries whose recent trends, and thus their forecasts, are of steady speed or deceleration. It includes Japan and seven other advanced economies plus North Korea. The advanced economies all underwent phases of acceleration, stable speed, and deceleration in recent years, but vary in the timing, length, and strength of each of these phases, and in some cases entire phases were skipped. For instance, Germany (Figure 4.12, panel IV) had a prolonged acceleration phase that came to an abrupt end in the mid-1990s and has been decelerating since then, never going through a stable speed of material stock accumulation in this 40-year period. Japan and Italy are both forecast to enter an era of dematerialization before 2030, but even the other four advanced economies' 95% confidence intervals mark some probability of negative speeds by 2030. North Korea, whose material consumption and economic history are markedly different than advanced economies, also belongs to this group for having varying phases of acceleration, although its case is of acceleration-deceleration-stabilization.

4.2.4. Discussion

In comparison with country clusters presented in previous research (Steinberger et al. 2013), the advantage of the groupings presented here is in the ability to identify common pathways of material accumulation that go beyond mere observations of the values of material consumption at different points in time, and which can look at the total material consumption and stock accumulation of nations without resorting to per-capita rates, which may hide the total environmental burden of material stock and which also inherently assume a certain relation to the population at a designated year, hiding any lagged effects.

The ARIMA time series analysis distinguishes between intrinsic growth trends and exogenous shocks. Trends may be driven by any of a wide range of conceivable processes such as population growth, economic growth, and government policy. Shocks may also manifest in a multitude of ways: economic surges or downturns, international crises, political decisions, changes in technology and design standards, changes in prices, or any other reason. The advantage of the ARIMA framework is the ability to form forecasts even without clear identification of the causes of such trends and shocks. Forecasts are based on the intrinsic trends and influence of lagged terms found by the ARIMA analysis, which together with historical variance and historical response to shocks contribute to the model's forecast uncertainty ranges.

It is remarkable that only four archetypal profiles of material accumulation pathways were found, despite the huge diversity of socio-economic and geographical properties and scales of the 46 examined countries. These profiles show how different countries respond to external shocks to their material accumulation trends. The Netherlands was found to have the most indifferent inflow trend of construction material. The actual inflow of a single year may be higher or lower than that of previous years and may have a lagged effect into the next few years, but the long-term trend was found to be stable and to fluctuate within a fixed amount over time. Given the Netherlands' characteristics as a wealthy, mature economy, with very low population growth and already quite dense infrastructure, it may well be that inflows are used merely to maintain existing stock. This is corroborated by the very low amounts of materials used yearly.

In comparison, a big group of countries are characterized by stable acceleration rates, in which their long-term speed of accumulation grows by a certain fixed amount per year. Except for the United States, these countries respond to shocks – either sudden drops or surges – by rapid reversion to their previous trends of acceleration. In effect, this means that external shocks have only a small long-term effect on the accumulation of material stocks in these countries, and they seem to be locked into a certain growth trend. However, these countries differ by the nature of the shocks they have experienced: some, like Turkey and notably many Latin American countries (Argentina, Colombia, Mexico and Venezuela), were mostly subjected to intermittent drops in their otherwise constant increase of speed of accumulation, showing resilience to economic downturns and other shocks, which hints that the socio-economic structure of these countries can withstand temporary setbacks and that there is ongoing demand for further stock increases. This observation may also relate to policy settings that have enabled anticyclical investment into construction activities to counterbalance years with slow economic growth. In sharp contrast, some countries had undergone "shocks" of short periods of surges of positive acceleration, after which they returned to their linear trend, as seen in the case of Thailand in Figure 4.12, panel II-b which had two such surge periods, in the 1990s and again in the early 2000s. Some other Southeast Asian countries (the Philippines and Malaysia) had similar patterns, as well as European late developers Spain and Romania, whose recent growth spurt and crash are remarkable in their scale and rapidity. It would seem that all these countries attempted to hasten their growth but could not withstand long-term stresses and eventually were pulled back to their previous slow linear growth trends. Other countries like Indonesia, Nigeria, and South Africa have experienced a mix of both positive and negative surges since the 1970s, and in any case rapidly returned to their intrinsic growth trends. The United States is unique in this category, as even though it has a stationary acceleration trend, its response mechanism to external shocks is quite different from the previously described ones – it does not quickly return to the pre-shock speeds, but instead slowly starts to increase its speed of accumulation from the new minimum. This seems to mean that the socio-economic structure of the United States causes its stock growth pattern to be characterized by cycles of slow growth that overshoot actual demand and culminate in external shocks that pull growth rates down to undersupplied levels. One reason for this may be the role the housing sector plays in the United States to bolster domestic demand in years where growth driven by export industries has slumped. Either way, the finding of stationary acceleration for these countries is significant as it means that shocks, whether positive or negative, might seem dramatic when looking at the time series graph of speed, but have only a minor effect on long-term growth and may be compensated for by bigger growth in later years.

This is even more pronounced in the 15 countries that were found to have sustained accelerating phases, including Brazil, India, and China. Their archetypal stock accumulation profile superficially resembles category II yet rates are much faster. It would seem that their economic structures provide a sufficient base from which to sustain ongoing demands for more and more material stock increases from year to year.

From the viewpoint of sustainability, these results are the most alarming. Due to domination in recent years by highly populated countries like China and India and the aggregation of all countries – which tends to smooth out any "bumps" in the time series – the speed of accumulation of the world in total is accelerating at expanding rates and is forecast to continue to increase (Figure 4.13).

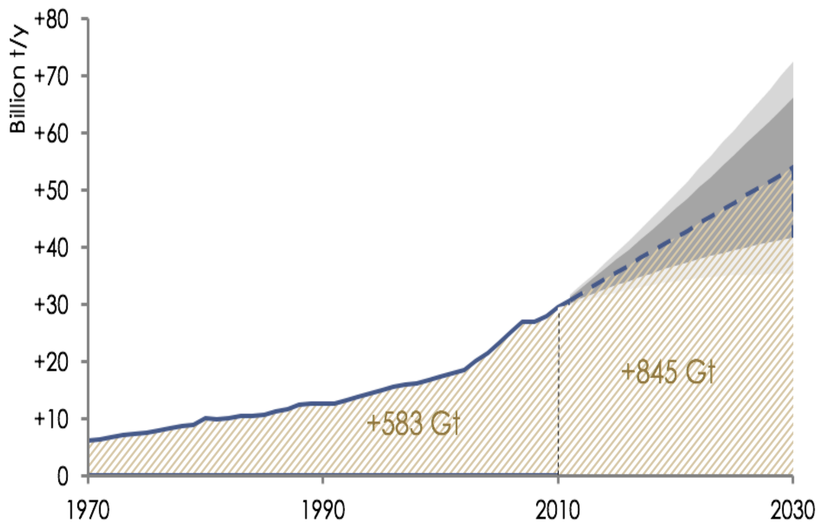

Figure 4.13 The global speed of accumulation of material stock, 1970–2030, with forecast intervals of 80% and 95%. The areas below the trend line are the total accumulated material 1970–2010 and the forecasted total accumulation 2010–2030.

Almost 600 Gt were accumulated from 1970 to 2010, of which more than half were added in the last 13 years. Under this model's assumption that historical trends will persist year-on-year into the future, a further 800 Gt will be added to stock by 2030. The question is then, whether such increases can realistically continue unhampered into the future, or whether this accelerating growth will slow down or even stop due to either endogenous or exogenous reasons. The forecasts are produced based on the historical paths countries have undergone. To rephrase the question, can countries change their paths?

The answer may lie with the seven developed countries which are already undergoing deceleration that could lead to stable stocks or dematerialization. Of the stock growth archetypes, only s-shaped growth describes a change in path between acceleration and deceleration at an inflection point which appears as a peak in the graphs of the speed of growth. The Japanese and South Korean cases are the most straightforward examples. Their early material stock accumulation profiles (Japan until the early 1970s and South Korea until the end of the 1990s) indeed resemble the surging acceleration seen in the third country group, and this acceleration period ended in clearly identifiable external shocks – the 1973 and 1979 oil crises in Japan and the Southeast Asian crisis of 1997 in South Korea. Japan changed its accumulation profile a second time in 1991 to coincide with another exogenous shock, the economic bubble. It would thus seem that the countries which exhibit no long-term stationary acceleration trend change their accumulation behavior due to external shocks. However, identification of the external shocks that triggered the other five countries to change their course is more difficult. The UK's change from acceleration to deceleration occurred in 1989 and Germany's speed peaked in 1994, while Canada, Italy, and France changed from acceleration to stable or slowly decreasing speeds in 1980, 1983, and 1991 respectively. Unlike for Japan and South Korea, no prominent economic shocks occurred in these years. The trigger for the inflection in trends in these countries may thus be a "soft" reason such as a change in policies, and it could also be that these countries reached saturation in their material stocks. Such saturation is probably not purely a physical, spatial limit, but rather a combination of physical and socio-economic conditions under which material stocks reach a level of sufficiency to meet the demands of society and the economy, and further expansion is constrained. However, to explore this hypothesis, examining the net additions to stock (NAS) or domestic material consumption (DMC) per person or per unit of economic output as done in previous studies is weakly helpful at best since speed is only a symptom, not the end-point.

5. Material stock analysis: Drivers of accumulation

The aim of this chapter is to characterize the relationships between socio-economic drivers and stock accumulation, and specifically to identify which driver is most important, and how the importance of drivers has changed over time. To this end, the focus of this chapter is on comparing the change in material stock to the changes in the different drivers throughout time. The influence of social geography is also touched upon to analyze the influence of the location and degree of urbanization through an investigation of Japan's prefectures. Three analytical methods are employed in this chapter. The first is a descriptive analysis of the growth of material stock compared to the growth of population and economic activity. Two further approaches, decomposition and panel analyses, are then used to unpack what has determined stock accumulation in Japan's prefectures during the past five decades.

While international country-level comparisons remain limited to Japan and the United States, the recent compilation of a highly detailed database of the material stock of Japan in the 20th and 21st centuries (Tanikawa et al. 2015) enables in this study to examine Japan's stock accumulation at national and subnational level applying the analytical tools previously used exclusively in material flow research. The stock accounts modeled in section 4.1 and the Tanikawa et al. database are used to investigate the extent to which trends in population and economic activity have acted as drivers of material stock accumulation in Japan. Japan's 47 subnational constituents, named prefectures (Figure 5.1), are characterized by different trends in population and economic activity, and different geography. Analysis is conducted to check whether the relationship between population, economy and stock accumulation found at the national level is reproduced at the subnational level in a uniform way, and whether building stock and transport infrastructure stock are influenced by population and economy in different ways.

Figure 5.1 schematic of the prefectures of Japan (Excluding Okinawa). The Tokyo-Nagoya-Osaka urban strip is marked in color.

5.1. Data

As mentioned above, material stock data for this section was sourced from two sources. For subsections 5.2.1 and 5.2.2, the analysis is done using the top-down stock models and scenarios of the United States and Japan described in section 4.1. For the rest of this chapter, the data is from a comprehensive and highly disaggregated material stock database for Japan and its prefectures (Tanikawa et al. 2015) which offers a higher resolution of the spatial distribution and the end-uses of the stock. It was compiled bottom-up using detailed GIS (Geographic Information Systems) and statistics-sourced inventories of Japan's buildings and infrastructure. The database contains information about the anthropogenic stock of construction materials in Japan at a spatial resolution of 1 km^2 for the time period 1945 to 2010 in yearly time steps, measured in tonnes. The data can be spliced by material type (for example minerals, metals, or timber) and by function or end-use (for example residential buildings, commercial buildings,

roads, or railways). For the aims of this study, a subset of the database is employed with focus on buildings and transport infrastructure, which have very close links to economic activity and material standards of living. Other elements of the database such as, for example, dams and sewer pipes, are not used. The period 1965 to 2010 for which full data coverage exists is analyzed. Okinawa prefecture was omitted from this study, leaving 46 prefectures to examine, because it was only returned to Japan in 1975 when the US occupation ended and data for Okinawa is therefore incomplete. The data is aggregated to the prefecture level and includes the materials cement, aggregate, asphalt, timber, and iron, as well as an "others" category of materials which are minor in sheer mass and includes glass, copper, aluminum, and plastics.
Data for population and Gross Domestic Product (GDP) was used to determine per capita material stock and material efficiencies. These statistics for Japan and the United States until 2005 were taken from Maddison (Maddison 2008). Population and Gross Prefectural Product (GPP) for every prefecture were sourced from the Statistics Bureau of Japan (2014). The GPP figures were converted from local currency to 1990 International Dollars by applying currency conversion factors from Maddison (2008) and OECD (2014).

5.2. Descriptive analysis

In the next two subsections, a descriptive analytical investigation of the growth of stocks in Japan and the United States is conducted using the stock data and scenarios modeled in section 4.1. In the third subsection, a more detailed descriptive analysis is made for the stock of buildings and transport infrastructure only in Japan, using the bottom-up database described above.

5.2.1. MS per capita

Figure 5.2 compares the level and evolution of per capita material stock in Japan and the United States. The US started at a much higher level of material stock of about 100 tonnes per capita in 1930 reflecting its higher level of industrialization and wealth. Material stock in Japan was only a fifth of that in the US at that time. Japan has since shown a much higher dynamic of material stock growth, increasing 20-fold while material stock in the US grew fourfold. Despite much faster growth in Japan, the US was still ahead of Japan in per capita material stock in 2005, with 375 tonnes per capita compared to 310 tonnes per capita in Japan. It appears that despite the different historical developments and social and economic differences, a certain level of material stocks per person are to be expected in developed countries with mature economies (Rubli and Jungbluth 2005) quantified material stocks for Switzerland at 311 t/cap which appears to be in line with the results. However, Japan's population projections are negative and the United States projections are positive. The per person stocks in these countries are projected to change in quite different ways in each of the future scenarios. In scenario 1, by 2050 stocks in Japan will increase to about 470 tonnes per capita while the United States' per person stocks will peak at 392 tonnes per capita and then decline to 370 tonnes. Japan's per capita material stock levels will surpass the United States by 2023.

On the other hand, the dynamics of scenario 2 offer another course in which the stock per person in the United States remains higher than in Japan. In this scenario, stocks in the United States continue to grow to 480 tonnes per person in 2050, while in Japan stocks per person will stabilize at about 395 tonnes per person by 2042.

The third scenario is remarkable in the fact that for Japan, a policy of constant reductions of consumption together with extension of lifespans comes to resemble the scenario of consumption coupled with population trends (scenario 1), while in the USA this third scenario resembles the first scenario, of constant figures of consumption.

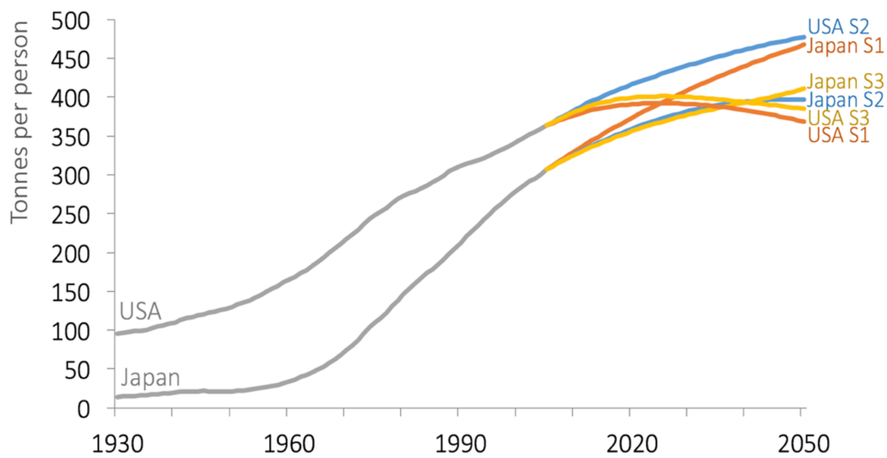

Figure 5.2 Material Stocks per Person in the United States and Japan, 1930–2050.

Steady or decreasing per capita stock could be termed per capita material saturation. In the case of the US this can be achieved using policies that reflect scenario 1 - or better yet, scenario 3 in which inflows and outflows are also reduced - and in fact lead to per capita dematerialization. However, in Japan scenario 1 has opposite results – the materials per person will continue to increase despite reaching towards saturation in absolute terms, and scenario 3 points towards the most material stock per capita in Japan of all three scenarios. From these it can be understood that pursuing policies of a certain scenario in one country would not necessarily provide the same results in another.

5.2.2. Growth rates and material efficiency

One important measure for the success of sustainable resource management at national economy level is material efficiency – the amount of economic output per unit of material use. Most studies show that economic material efficiency increases as economies mature (Schandl and West 2010) which is caused by a growing share of minerals and fossil fuels and declining share of biomass and the different income elasticities of those different materials (Steinberger and Krausmann 2011). These previous studies discuss only material throughput, and the model presented here allows a long-term comparison with stock efficiency as well. Since stocks provide services to society, more effective usage of existing stocks is of benefit to both the economy and the environment. Nevertheless, material flow efficiency is an indicator of the flows and economic activity of a certain year, while material stock efficiency measures the efficiency of the accumulation of materials over time. Therefore, an appropriate comparison between these two indicators is to look at the trends over time, and not a year by year comparison.

In the US, there seemed to be a trend until about 1975 with all three individual indicators (DMC, MS and GDP) growing in concert (Figure 5.3, top panel). Delinking started from 1974 when GDP growth rates outpaced growth in both material stocks and flows. This increased efficiency is visualized in the bottom panel, which shows both material efficiency trends of the USA. The material efficiency measures were moving in concert from World War 2 until 1974, and since then material flow efficiency measured as GDP/DMC is increasing, slowly being trailed by improvements in material stock efficiency when measured as GDP/MS.

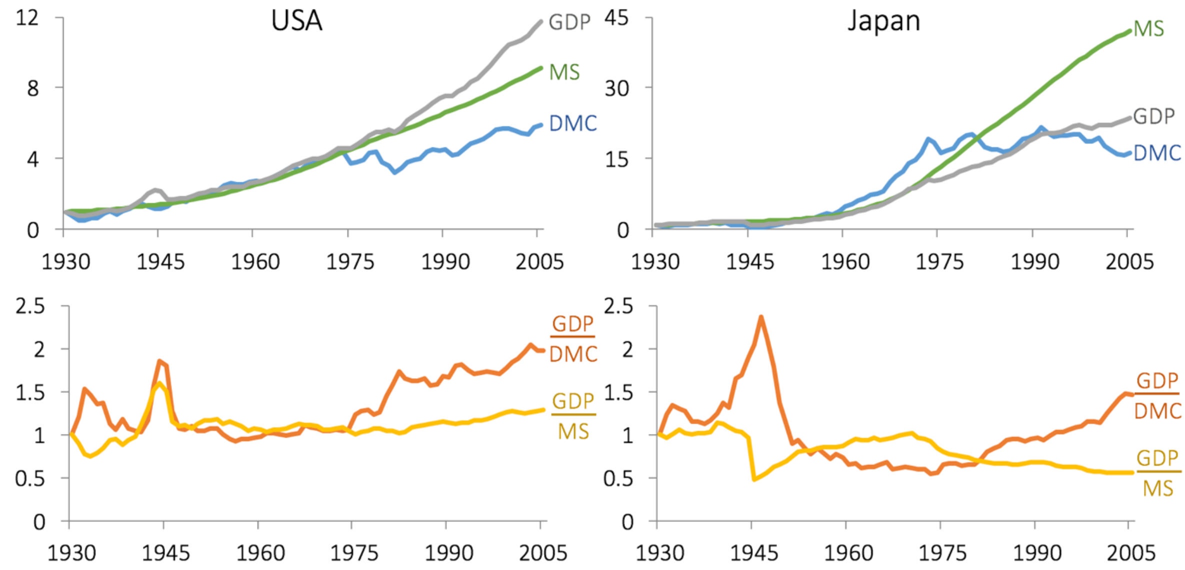

Figure 5.3 Comparison of the growth rates in the United States (left) and Japan (right), 1930–2005. Values normalized to 1930=1. Top panels: Direct Material Consumption (DMC), Material Stock (MS), and Gross Domestic Production (GDP). Bottom panels: material productivity of material input (GDP/DMC) and material productivity of material stock (GDP/MS).

The right hand of the figure shows growth rates for DMC, GDP and material stock for Japan. All three indicators evolved on a similar trajectory from the 1930s until 1975. Since 1975 DMC has stabilized and material stocks have grown much faster than GDP. Measuring material efficiency of the Japanese economy based on both material indicators (DMC and MS) shows an inverse trend for the two. As mentioned in the results above, singularities such as the effects of World War 2 on Japanese material stocks are omitted in this type of model and deserve more detailed study. This is obvious during the 1940s where extreme divergent trends for the two efficiency measures are visible. From the early 1950s until about 1972 the material efficiency of stock (GDP/MS) was increasing while the material efficiency of throughput (GDP/DMC) was decreasing. This was a period of fast growing material input to fuel the economic growth period of Japan. Following that, a new trend has been triggered, probably by increasing oil prices and a genuine slowdown in the Japanese economy, which has meant a turning point for material efficiency. Flow efficiency has increased since then, making Japan the most material efficient economy globally (Schandl and West 2012). Because stock has continued to grow beyond GDP growth rates a material efficiency measure based on material stock shows declining or stagnant productivity. The amount of material stock needed for economic activity has not declined at all despite a long period of de-investment in Japan since the 1990s (Randers 2012). This raises the question of the reasons for the ongoing increases in material stocks and several answers are possible. First, Japanese building standards are periodically updated to enforce increasingly more intensive construction to withstand Japan's susceptibility to natural disasters such as earthquakes (Tanikawa and Hashimoto 2009), requiring more material per unit in each new or replaced structure. A second reason is the growing affluence of Japanese society, creating demand for bigger and higher quality construction. Third, nationwide infrastructure projects such as high speed rail, dams, and national highways have been constantly expanding through government policy. Japan's rugged mountainous terrain necessitates vast numbers of bridges, tunnels, and other material-intensive civil engineering structures to support these kinds of projects which contribute to the increase in stocks. A fourth reason could be that some of the stock included in this calculation is actually dissipated stock such as disused buildings and infrastructure, which still 'hibernate' in the anthroposphere but make no meaningful contribution to the economy (Hashimoto et al. 2009). Unfortunately, the lack of data on abandoned infrastructure for Japan or any other country hinders answering this question at this time. In any case, the trends of material efficiency in Japan and the United States would warrant additional analysis. In a comparison of the conjoint behavior of flow efficiency and stock efficiency in the two countries, some correspondence becomes visible. For example, flow efficiency increased and stock efficiency decreased during both countries' economic recessions: the United States' great depression (1930s) and Japan's 'lost decade' (1990s). Whether these, and other such similarities, are coincidental or characteristic of material-economic dynamics should also be subject to further study.

5.2.3. Descriptive analysis for Japan's prefectures

The construction materials stocked in buildings and transportation infrastructure in Japan increased from 3.3 billion tonnes in 1965 to 15.4 billion tonnes in 2010 (Tanikawa et al. 2015). Growth rates of material stock have been slowing over time. The average yearly growth rate was over 10% (varying from 4% to 20% by prefecture) from 1965 until 1971, when it dropped to about 5%, and it has been declining slowly since then. Yearly growth was as low as 2% in the early 1990s and has been below 1% since 2006. In the final two years of the time series, about half of the prefectures experienced a decline in material stock of about 0.5% per year, caused by less new construction of buildings compared to the demolition of aged stock and reduced additions to the stock of infrastructure.

As seen in Figure 5.4 panel a, GDP and material stock have grown in concert and much faster than population signifying that the amount of accumulated stock per capita has risen tremendously over the last five decades. Until 1985, GDP and material stock grew almost simultaneously. Then, for a period of several years economic activity decoupled from stock growth suggesting that the rate of additional stock to service economic activity has been declining, but as GDP growth slowed down, stocks have begun to catch up.

Figure 5.4 panels b–d show the growth of population, GDP, and material stock for Japan. Nine prefectures that constitute a roughly continous urban strip are marked, composed of the Tokyo, Nagoya (Aichi Prefecture), and Osaka metropolitan areas along the Pacific coast (Figure 5.1), and compared to the rest of the country. This strip is only slightly more than 10% of Japan's land mass but overtook the rest of Japan in terms of population around 2005 and has been ahead in terms of economic activity since the 1970s, with the gap increasing. Despite hosting more than 50% of Japan's population and economic activity, this area has a smaller share of the total material stock of the country, appearing be more efficient in using the services of buildings and infrastructure in supporting the same number of people and producing far greater economic output, which is investigated in the next sections.

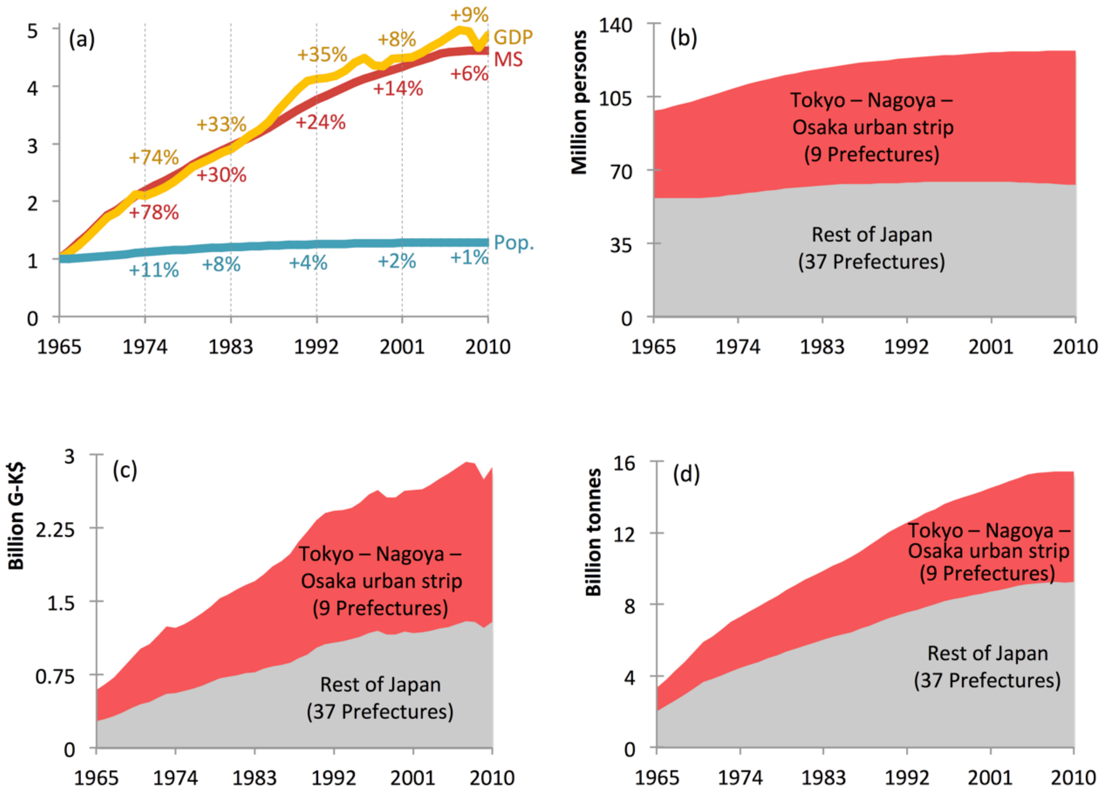

Figure 5.4 Socio-economic indicators for Japan 1965-2010 (Excluding Okinawa): (a) Growth rates of material stock, population, and GDP, 1965 = 1. Figures in percent show the growth of the indicator at the end of each 9-year period; (b) The population of Japan; (c) Socio-economic indicators for Japan 1965-2010 (Excluding Okinawa): (a) Growth rates of material stock, population, and GDP, 1965 = 1. Figures in percent show the growth of the indicator at the end of each 9-year period; (b) The population of Japan; (c) The GDP of Japan (note: G-K$ is Geary-Khamis Dollars); (d) The material stock of Japan.

5.3. Decomposition analysis

Here the IPAT identity is applied to the analysis of determinants of material stock growth. The evolution of material stock (I) is explained by three drivers: population (P), affluence measured as GPP per capita (A), and technology (T) which in this study is defined as material stock per unit of GPP, i.e. "material stock intensity", forming the basic identity $\mathrm{MS} = \mathrm{POP} \times \frac{\mathrm{GPP}}{\mathrm{POP}} \times \frac{\mathrm{MS}}{\mathrm{GPP}}$. In this case the interpretation of T is quite straightforward. Since we consider the mass of MS as an indicator of these stocks' provision of services to society, this indicator – material stock intensity – measures the productivity of the current material stock. A reduction in the value of T denotes improvements in efficiency, indicating that the services provided by MS are sufficient to support the demands of socio-economic activities at this point in time, while growth of T indicates a loss of efficiency. A decrease in efficiency hints at further demands for MS in the future and thus for additional extraction of construction materials leading to additional environmental impacts.

5.3.1. Methods

The relative strength of influence of the three parameters – population, wealth and the stock intensity of GDP – aren't static over time and we are interested in capturing these changes. To do so, we split the 45 year time period into five periods of equal duration: 1965 to 1974, 1974 to 1983, 1983 to 1992, 1992 to 2001, and 2001 to 2010. This periodization offers a good base for a balanced temporal comparison, and also coincides with several major macro-economic events which affected the nature of the four indicators that constitute IPAT, especially in Japan: the 1973–74 oil crisis and the 1992 bursting of Japan's economic bubble. We thus compare the difference (Δ) in the natural logarithm of every indicator from the beginning of each period to its end, through which the values become comparable, unitless percent changes (Herendeen 1998), as otherwise the strength of the drivers' influence relative to each other is difficult to ascertain since the units of measurement for each indicator are different. The log-transformations also change the nature of the IPAT identity to a more intuitive additive formula:

$$\Delta \log(MS) = \Delta \log(POP) + \Delta \log\left(\frac{GDP}{POP}\right) + \Delta \log\left(\frac{MS}{GDP}\right)$$

$$\cong$$

$$\Delta\% MS = \Delta\% POP + \Delta\%\frac{GDP}{POP} + \Delta\%\frac{MS}{GDP}$$

where MS is the material stock (I in the IPAT identity), POP is the population (P in the IPAT identity), GDP/POP is the Gross Domestic Product per capita (A in the IPAT identity), and MS/GDP is the Material Stock Intensity (T in the IPAT identity).

5.3.2. Results

5.3.2.1. USA

Material stock growth rates have consistently slowed down from one 9-year period to the next (Figure 5.5). Stocks grew 35% between 1965 and 1974, but this growth decreased to only 16% between 2001 and 2010. Population growth, however, was fairly consistent throughout, at 8% to 10% in each of the five periods. Population thus forms a baseline driver for stock growth in the United States, and changes in affluence and technology growth rates explain the variances in stock growth. In the first examined period, the 35% growth of stock is explained by a 21% increase in affluence plus a 5% increase in material intensity, and these two drivers reduce in scale in the next period of 1974 to 1983, which witnessed slower economic growth. In the next two periods of 1983-1992 and 1992-2001, economic growth returned to its previous rates of 20-21%. However, this time around material stock growth has not been as fast as before. In fact, the growth rates of affluence and stock were the same, signifying a coupled growth of the two indicators. Nevertheless, as the population continued to grow in both periods, the overall stock increases were slower than the combined effects of population and affluence. This manifested as improvements to material stock intensities, which were negative with values of -9% and -10%, compensating for the ongoing growth of population and affluence. This seems to imply that the stock already available in these two periods was mostly meeting the demands of population and economic activity, and less new stock was required. However, in the most recent period of 2001-2001, with steady increases to the population, affluence has seen the slowest growth yet (mostly due to the economic events of 2007-2008), and the technological improvements of the previous periods have not persisted- new material stock has accumulated despite the economic slowdowns.

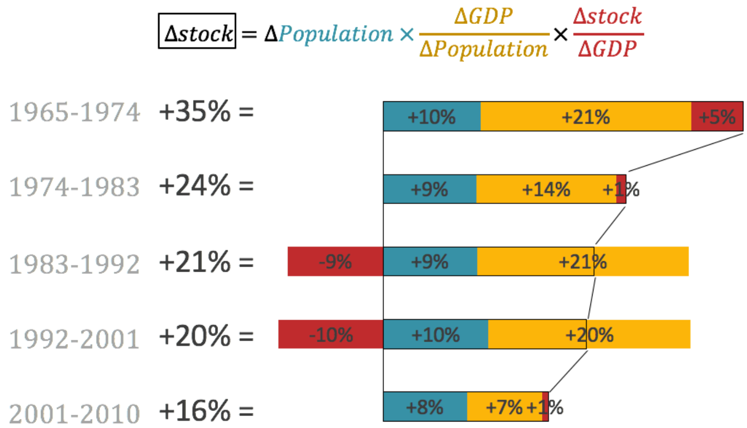

Figure 5.5 IPAT analysis of 5 equal periods in the USA. The percents are logarithmic percent changes. Note that for each period the bold-lined bar (%ΔI) is equal in space to the three colored bars of the drivers (%ΔP, %ΔA, and %ΔT).

5.3.2.2. Japan

Figure 5.6 shows the relative influence of the three driving forces of material stock accumulation based on the IPAT identity for Japan. The five nine-year periods are presented below each other with the same scales for ease of comparison and the diminishing scale of activity from the earliest period (1965–1974) to the latest (2001–2010) is very visible.

For the whole of Japan, the major driver of MS accumulation was affluence, measured as GPP/cap, while population had a smaller positive effect, especially as population growth has been in decline in Japan. Material intensity displays a fluctuating pattern. The first period had the biggest boost in MS with a 78% growth rate over nine years, which is explained by increasing demand from the 63% growth rate of affluence, while population growth rate (11%) had a much smaller effect and also material intensity had a growth rate of 4%.

The 1974 oil crisis had a significant dampening effect on the growth trajectory of the Japanese economy and on material stock accumulation. During the years 1974 to 1983 affluence growth rate was 25%, and population growth rate was around 8%. At the same time the growth rate of MS was 30%, and the difference is explained by a −3% figure for material intensity. This negative figure indicates that the capacity of the accumulated material stock to provide services to society was increasing.

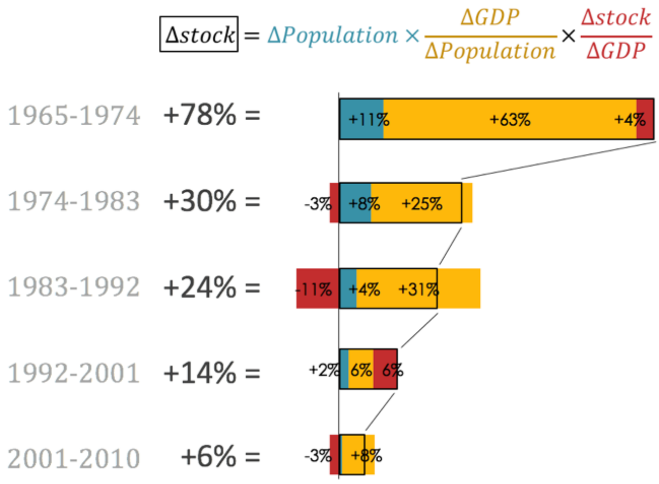

Figure 5.6 IPAT analysis of 5 equal periods in Japan. The percents are logarithmic percent changes. Note that for each period the bold-lined bar (%ΔI) is equal in space to the three colored bars of the drivers (%ΔP, %ΔA, and %ΔT).

This trend was even more accentuated in the next period until 1992, in which the change in material intensity was −11% and acted as a moderating factor against continuing growth rates of affluence (31%) and population (4%). In this period the growth rate of MS was 24%, but these trends came to a dramatic halt caused by the burst of Japan's economic bubble in the early 1990s. The bubble was characterized by an overheated economy, and fast and large rises in asset prices, money supply and credit, which ended with a rapid drop in asset prices and a prolonged recession (Okina et al. 2001). Japan's economic recovery was slow, and the following years are sometimes referred to as the "lost decade" as is visible from the trend from 1992 to 2001 in which, concurrent with the ongoing sluggish growth rate of population (2%), affluence grew only slightly more than 6%. During this period, the Japanese government actively promoted infrastructure projects in an attempt to boost economic activity trough Keynesian interventions, resulting in a 14% growth rate of MS in this period. As a result, the productivity gains of MS of the previous period have been mostly consumed as demonstrated by a 6% increase in material intensity.

Trends in the latest period from 2001 to 2010 are again quite different. The gradual recovery of the Japanese economy is manifested in an 8% growth rate of affluence, still very low compared to the periods that preceded the economic bubble. However, population growth has virtually come to a halt with only a 0.5% growth rate. Material intensity has returned to mitigate growth in material stock (−2.5%), conceivably influenced by the previous period's induced construction sufficing current demands. Overall, MS had the smallest growth rate (6%) of all five periods and this was the only period in which MS growth rates were smaller than affluence, perhaps signaling a beginning of a dematerialization trend in Japan with respect to overall material stock.

5.3.2.3. Japan's Prefectures

Spatial disaggregation of the IPAT analysis (Figure 5.7) shows that the national trends have not been repeated in all prefectures, and some prefectures have followed quite different trajectories, demonstrating the effect of geography on the economy and material stock. While Tokyo (in bold text in Figure 5.7), as Japan's political and economic capital as well as the most populous prefecture, mostly resembled the national trend until 1992, it has since departed from it. In the 1992 to 2001 period Tokyo's affluence continued to increase and material stock intensity continued to decrease as in previous periods, in stark difference to neighboring prefectures. Despite its high share in Japan's total, the trend observed in Tokyo was not enough to counter the combined effect of the economic bubble and slow economic recovery in the rest of Japan. However, the most recent period is perhaps the most intriguing in Tokyo: the main driver of MS accumulation has become the growth of its population, while affluence in Tokyo has been decreasing. This was caused by strong migration to the capital from other prefectures, bringing new people looking for economic opportunities and jobs from economically disadvantaged rural regions to Tokyo. Although the total GPP of Tokyo has also increased, this population influx has been more influential, signified by a decrease in the indicator of GPP per capita.

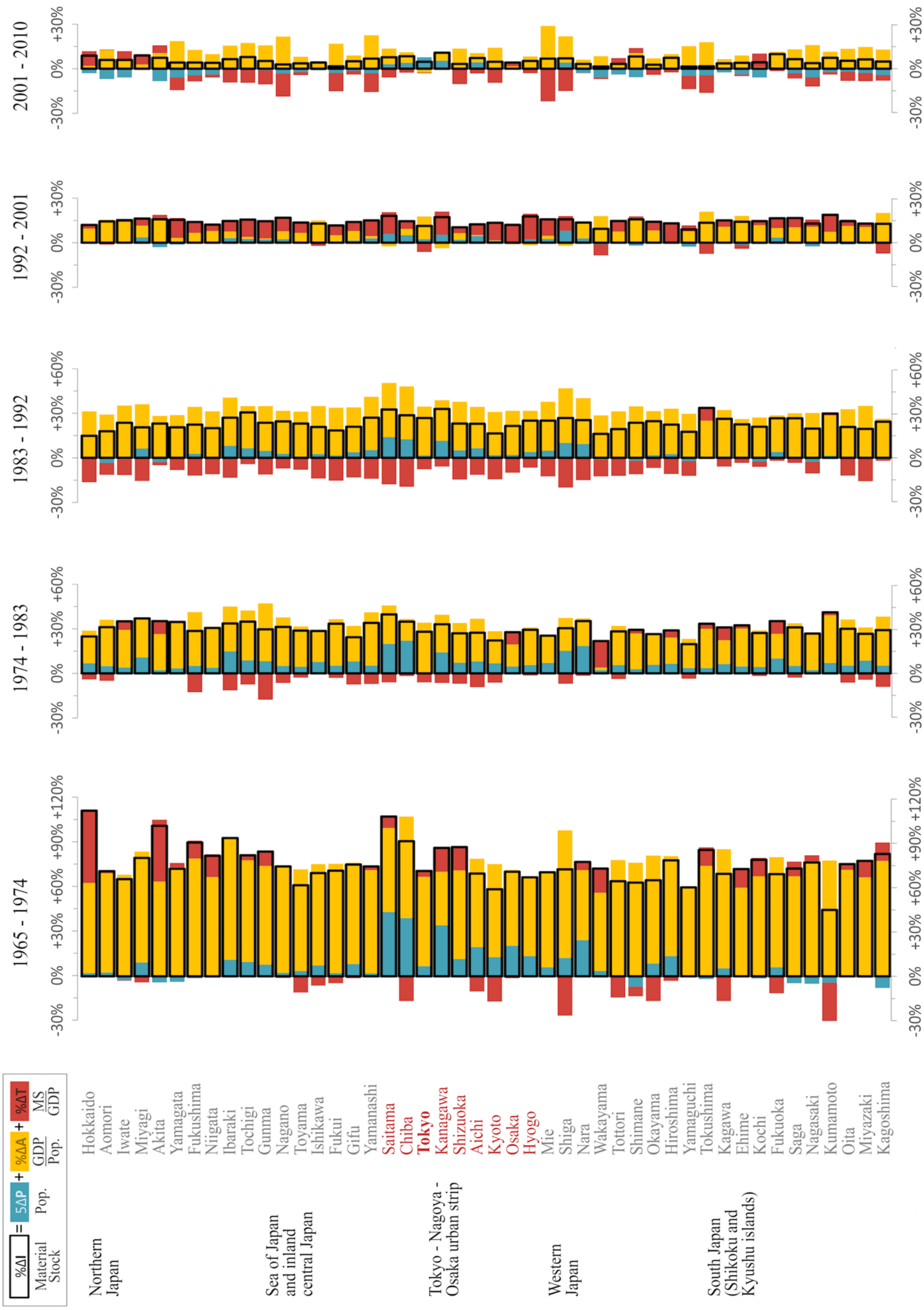

Figure 5.7 IPAT identities of Japan's 46 prefectures (except Okinawa) for 5 equal periods. The prefectures are ordered roughly from north to south, refer to Figure 5.1 for the exact locations. The percent values are logarithmic percent changes. Note that for each period the bold-lined bar (%ΔI) is equal in space to the three colored bars of the drivers (%ΔP, %ΔA, and %ΔT). The horizontal axis is scaled equally for all 5 periods.

There has been much variance in the trends observed in other prefectures. Material stock in the 1965 to 1974 period grew at high rates. All but two prefectures had 60% growth rates in their material stock. The smallest was in Kumamoto (46%) while in three prefectures, Hokkaido, Akita, and Saitama, the amount of MS more than doubled in this nine-year period. While affluence was the main driver of MS growth in all prefectures, its contribution ranged from 36% (Kanagawa Prefecture) to 86% (Shiga Prefecture). In the case of population, regional trends are noticeable. Remarkable growth occurred in the population of the prefectures surrounding Tokyo (Saitama, Chiba, and Kanagawa), caused by Tokyo metropolitan area's overflow outside of Tokyo prefecture proper. Population was also a major driver, albeit to a lesser extent, in the stretch of prefectures spanning Shizuoka to Nara, whose centers are Osaka and Aichi (Nagoya city), which are the second and third major manufacturing and commerce centers of Japan. Together these compose the urban strip described above and a few neighboring prefectures. Concurrently, a depopulation trend in the more remote southern prefectures acted to moderate material stock accumulation there.

Although twenty of the 46 prefectures underwent improvements to their material stock productivity, signified by decreasing material intensities, it is not visible on the national scale since their overall contribution to the MS and GDP of Japan was not enough to counter trends in the rest of the prefectures. Only in the following period, 1974 to 1983, when about two thirds of Japan's prefectures underwent material intensity reductions, did it affect the national trend. The 1974 oil crisis reduced the rates of growth of affluence in all prefectures to some extent and in one prefecture, Chiba (a neighbor of Tokyo), population became the dominant driver. Indeed, population in all prefectures except Tokyo increased in this period, contributing to the growth rate of MS which increased between 20% and 42% among the prefectures.

The period preceding the economic bubble (1983–1992) was unique in the uniformity of trends in all prefectures. MS grew in the range of 15% to 34%, driven mostly by affluence which grew at rates of 25% to 37%. This driver was somewhat balanced by high efficiency gains, visible as material intensity reductions in all prefectures except one (Tokushima). Population lost much of its contribution in the more rural regions, including the most of the northern prefectures, as well as the Japan Sea facing, inland, western, and southern prefectures, eleven of which experienced slight depopulation trends. The other prefectures also showed weak population growth trends of less than 10%, except for Tokyo's three neighbors which had growth rates of 12% to 14%.

The burst of the economic bubble in 1992 was, not surprisingly, very observable at the prefectural level. While the range of MS accumulation was quite uniform (only 9% to 19%), in most prefectures the growth of affluence came to a halt and it even decreased in five prefectures. Most of the MS growth was driven by increasing material intensities, possibly triggered by government funded construction activities, visible in Figure 5.7 from in many of the more central prefectures of the urban strip and surrounding areas. However, affluence remained the main driver in geographically more distant prefectures in the north, west, and south of Japan, suggesting that the downturn following the economic bubble affected prefectures in these rural regions much less than the eastern and central prefectures where most of Japan's population and economic activity is located (colored in Figure 5.1). Since population growth in this period was very close to zero in the vast majority of prefectures, not only was its effect as a driver quite weak but it also shows that the various changes in affluence in this period were caused mainly by the behavior of the economy.

In the 21st century, population trends have become either stable or negative in Japan's prefectures. The only prefectures in which population is still growing and thus a driver of MS are Tokyo and its three neighbors, as well as Aichi, Osaka, and Fukuoka, which are the urban and commercial centers of their regions; and Shiga, a small rural prefecture close to the Osaka-Kyoto urban conglomeration. In general, Japan is on the way to a belated economic recovery, as positive growth of affluence has regained its position as the major driver of MS growth, except in Tokyo as described above. However, at the same time material intensity has been decreasing in many prefectures and the existing MS is now sufficient for the needs of these prefectures and acting as a strong counter-effect against affluence growth. This is manifest in the low level of MS growth rates (1%–11%) in this period. Apart from Kanagawa and Fukuoka prefectures, all prefectures experienced only a single digit growth rate of MS. This is most pronounced in some rural prefectures across the country such as Wakayama, Fukui, Yamaguchi, and Tokushima, where the combination of depopulation and reduced material intensities has been powerful enough to almost completely counterbalance increases in affluence, and as a result MS growth was less than 2%. Also unique to this period is that the highest growth rates of MS have been in the prefectures of northern Japan, driven by affluence overcoming depopulation and mixed material intensity changes, which signify that these prefectures, considered the "remote north", are only now catching up with the rest of Japan in terms of infrastructure.

5.4. Panel analysis

In the next step, an econometric panel analysis of the data is conducted in order to uncover the nature of the long-term relationships of the evolution of population and economic activity. Since the objective is to analyze the effects of the growth or decline of population independently from economic activity, the per capita figures for MS and GPP are not examined as that approach inherently assumes a constant scale effect of population complementary to GPP. The effect of changes in population and economic activity on the ratio of change of material stock is the main interest. To this end, the natural logarithms of MS, population, and GPP are examined. In the equations below, the logarithm operator (log(x)) is not presented for ease of reading, but should be implicitly incorporated for all variables.

5.4.1. Methods & models

The basic model is a multivariable panel regression:

$$MS_{it} = a + b\ POP_{it} + c\ GPP_{it} \quad (1a)$$

where *MS* is the material stocked in buildings and transport infrastructure, *POP* is the population, and *GPP* is the gross prefectural product of prefecture *i* in year *t*.

The coefficients *b* and *c* are the coupling elasticities of MS with population and GPP, respectively. Since the rates of growth of the indicators vary, a comparison of the values of the *b* and *c* coefficients provides little information. Instead the focus is on the magnitude and range of the coefficients and their decoupling implications, ceteris paribus. A value of 1 describes a coupled growth trend – a 1% growth in population or in GPP is correlated with an equivalent 1% growth in MS. A positive value below 1 indicates relative decoupling. For instance, if b = 0.7, when population grows by 1%, MS only grows by 0.7%. Values close to zero indicate weak effects on material stock. As an example, if c = 0, it could mean that despite economic growth, material stock doesn't change. A value of *b* below zero denotes absolute decoupling, indicating that the trends of the two factors are adverse to each other.

The analysis is extended by disaggregating the variables into more detailed components. In order to examine the effects of cities compared to the countryside, population is partitioned into urban and rural populations for every prefecture with model 2a:

$$MS_{it} = a + b_1\,POPU_{it} + b_2\,POPR_{it} + c\,GPP_{it} \tag{2a}$$

where POPU is urban population and POPR is the rural population of prefecture *i* in year *t*. Likewise, GPP can be disaggregated into the three major sectors of the economy, providing model 3a:

$$MS_{it} = a + b\,POP_{it} + c_1\,GPP1_{it} + c_2\,GPP2_{it} + c_3\,GPP3_{it} \tag{3a}$$

where *GPP1* is the contribution of the primary sector, *GPP2* is the contribution of the secondary sector, and *GPP3* is the contribution of the tertiary sector to the GPP of prefecture *i* in year *t*. The fourth model combines the split explanatory variables of both model 2a and model 3a:

$$MS_{it} = a + b_1\,POPU_{it} + b_2\,POPR_{it} + c_1\,GPP1_{it} + c_2\,GPP2_{it} + c_3\,GPP3_{it} \tag{4a}$$

Furthermore, the material stocks of buildings and the material stocks of transport infrastructure have evolved in different ways, and may have different correlations with the explanatory variables. The trends on building material stocks separately from infrastructure material stocks are examined by adding two additional sets of models 1 to 4, in which the dependent variable of total material stock *MS* is replaced with its two constituents:

$$MSB_{it} = a + b\,POP_{it} + c\,GPP_{it} \tag{1b}$$
$$MSB_{it} = a + b_1\,POPU_{it} + b_2\,POPR_{it} + c\,GPP_{it} \tag{2b}$$
$$MSB_{it} = a + b\,POP_{it} + c_1\,GPP1_{it} + c_2\,GPP2_{it} + c_3\,GPP3_{it} \tag{3b}$$
$$MSB_{it} = a + b_1\,POPU_{it} + b_2\,POPR_{it} + c_1\,GPP1_{it} + c_2\,GPP2_{it} + c_3\,GPP3_{it} \tag{4b}$$
$$MSI_{it} = a + b\,POP_{it} + c\,GPP_{it} \tag{1c}$$
$$MSI_{it} = a + b_1\,POPU_{it} + b_2\,POPR_{it} + c\,GPP_{it} \tag{2c}$$
$$MSI_{it} = a + b\,POP_{it} + c_1\,GPP1_{it} + c_2\,GPP2_{it} + c_3\,GPP3_{it} \tag{3c}$$
$$MSI_{it} = a + b_1\,POPU_{it} + b_2\,POPR_{it} + c_1\,GPP1_{it} + c_2\,GPP2_{it} + c_3\,GPP3_{it} \tag{4c}$$

where *MSB* and *MSI* are the materials stocked in buildings and transport infrastructure, respectively.

This provides three sets of four models each, a total of twelve models. Since the dataset consists of the prefectures of a single country, the panel data displays several statistical features which should be taken into account. Time dependency, in which the trends of previous time periods have a certain correlation with the next period, are probable in this type of time series. The change in MS in a given year can be reasonably assumed to be affected not only by contemporary economic activity and population but also by the past performance of these drivers, as well as the quality and quantity of existing material stock. Moreover, it can be expected that the trends of each individual prefecture are not independent of each other – the trends and performance of neighboring prefectures affect one another and all prefectures are subject to nationwide trends and external events and therefore cross-sectional correlation is likely. Unobserved factors such as technological lock-ins and advancements, geographic features, and government policies are considered and statistical tests were conducted to check for the two types of dependence as well as for heteroskedasticity. The modified Bhargava et al. Durbin–Watson statistic (Bhargava et al. 1982) and the Wooldridge test (Drukker 2003) signaled time dependence in the data, while the Pesaran test (De Hoyos and Sarafidis 2006) found strong indication of cross-sectional dependence, and likelihood ratio tests indicated heteroskedasticity across the panels. Ignoring these correlations in a panel regression would lead to inconsistent coefficients and biased standard errors and so in order to account for these characteristics the Feasible Generalized Least Squares (F-GLS) estimator with an AR(1) autoregressive term (Baltagi 2011; Davidson and MacKinnon 2004) was chosen. The models that look at total prefectural population as a single indicator (models 1 and 3) cover the years 1965 to 2010, although models 2 and 4 begin in 1975 because of data availability for urban and rural population figures.

5.4.2. Results

The results of the panel regressions are presented in Table 5.1. Relative decoupling of MS accumulation from economic growth is apparent in model 1a: a GPP increase of 10% is correlated with a 7.5% MS increase. The coefficient of population is very close to zero. As described earlier, there is fairly large variation in population trends between prefectures as well as in each prefecture over time. This doesn't necessarily mean that population has no effect on MS, rather that any such effect is not captured by the specifications of this model, as suggested by the lower statistical significance of the coefficient b of population. Population is further examined in greater detail in model 2a, where it is differentiated into urban and rural populations. This model has better explanatory power than the model using total population. The coefficient of urban population is 0.22 – a 1% growth in the number of city dwellers is correlated with a 0.22% increase in material stocks, a strong relative decoupling trend suggesting that as cities' populations expand, less new material stock is required for each additional person. Similar to GPP and urban population, the coefficient of rural population is also positive (0.14). However, rural population has been decreasing in the vast majority of prefectures and so the interpretation of this figure is that, ceteris paribus, stocks would decrease at a rate of about 0.14% for each 1% decrease in rural population. In practical terms considering the simultaneous dynamics of the other factors, this indicates that the shrinkage of rural population in Japan has a moderating and stabilizing effect on the growth of MS.

Table 5.1 Coefficients obtained from the results of the feasible GLS panel regressions. Numbers in parentheses are the standard errors. Confidence levels: * p<0.05, ** p<0.01, *** p<0.001.

Model		Pop. *b*	Urban Pop. b_1	Rural Pop. b_2	GPP *c*	Primary Sec. GPP c_1	Secondary Sec. GPP c_2	Tertiary Sec. GPP c_3	Constant *a*	AR(1)
Stock *MS*	1a	0.04 * (0.017)			0.76 *** (0.009)				0.17 (0.184)	0.95
	2a		0.22 *** (0.012)	0.14 *** (0.015)	0.47 *** (0.012)				2.94 *** (0.248)	0.95
	3a	0.03 * (0.013)				0.04 *** (0.005)	0.08 *** (0.007)	0.67 *** (0.009)	0.25 (0.159)	0.93
	4a		0.10 *** (0.009)	0.28 *** (0.013)		-0.02 *** (0.004)	0.02 *** (0.005)	0.54 *** (0.009)	1.21 *** (0.194)	0.94
Bldg. Stock *MSB*	1b	0.27 *** (0.010)			0.67 *** (0.007)				-1.48 *** (0.107)	0.89
	2b		0.25 *** (0.010)	0.07 *** (0.010)	0.58 *** (0.011)				0.09 (0.193)	0.91
	3b	0.36 *** (0.009)				-0.02 *** (0.004)	0.06 *** (0.006)	0.55 *** (0.007)	-0.36 *** (0.117)	0.89
	4b		0.24 *** (0.008)	0.17 *** (0.010)		-0.03 *** (0.004)	0.04 *** (0.005)	0.53 *** (0.008)	0.06 (0.164)	0.92
Infr. Stock *MSI*	1c	-0.52 *** (0.026)			1.07 *** (0.016)				-0.002 (0.275)	0.91
	2c		0.20 *** (0.019)	0.16 *** (0.027)	0.32 *** (0.014)				5.62 *** (0.378)	0.98
	3c	-0.59 *** (0.026)				0.19 *** (0.012)	0.12 *** (0.015)	0.91 *** (0.018)	-1.56 *** (0.330)	0.91
	4c		-0.05 ** (0.016)	0.45 *** (0.023)		-0.02 ** (0.005)	0.01 (0.006)	0.47 *** (0.012)	1.76 *** (0.317)	0.96

If instead the components of GPP into three sectors are differentiated while keeping population as a single indicator (model 3a), the vast majority of MS growth is found to be caused by growth in the tertiary sector (0.67) and the coefficients of the primary and secondary sectors are close to zero (0.04 and 0.08, respectively). As the tertiary sector has been expanding, it has created further demand for buildings and infrastructure albeit at slow rates. The very low coefficients of the primary and secondary sectors could mean that demand from these sectors for infrastructure and buildings has been mostly satisfied during or perhaps even before the examined time period, and thus any change in these sectors (including shrinkage of the primary sector) has little effect on MS. As in model 1a, the statistical significance of population is quite weak. Model 4 disaggregates both population and GPP, showing that overall the tertiary sector's economic activity explains most of the growth of MS. The coefficient of the primary sector is now negative but since it is still very close to zero it would be cautious not to interpret this as absolute decoupling.

To this point the combined growth trends of the material stock of both buildings and transport infrastructure were explored. On average, buildings comprise about 60% of total material stock, and growth rates have been slowing down since the 1990s, coming to a halt in the most recent years of this data series. The buildings category includes residential, commercial, industrial, and public buildings. Using the same four model specifications as described previously next the MS of buildings is examined. In comparison with the first set of models, the regressions on building MS in general show more emphasis on the effects of population change. The coefficient of population in model 1b is remarkably bigger and more significant than its counterpart, model 1a. This larger coefficient is also evident in model 3b in which population is kept aggregated and GPP is disaggregated. In the case of models 2b and 4b, which separate population into urban and rural populations, the coefficients of urban population are bigger than their total MS counterparts and the coefficients of rural population are smaller. This data seems to indicate that the main demand of population, specifically urban population, for construction material stock is in the form of dwellings and other buildings. The small values of the coefficients of rural population could corroborate claims that as the rural population is decreasing, many buildings in the countryside do not get demolished but instead remain abandoned as hibernating material stock (Hashimoto and Tanikawa, 2007, 2009). In all four models, GPP and its breakdown into three sectors display quite analogous trends to the total stock regression set, with the only exception in model 3b, where the coefficient of the primary sector is now negative and close to zero as in models 4a and 4b.

In similar fashion to buildings' MS, transport infrastructure MS as the dependent variable is also analyzed. The material stock of infrastructure in Japan has grown on average 4% per year to become about 6.5 times bigger in 2010 compared to 1965. Growth rates were higher in the early years of the series, but unlike building MS a slowdown has not occurred in recent years. Therefore, different results can be expected from the four models in this case. Model 1c is indeed very different from models 1a and 1b. Coefficient b of population has a value of −0.52, the first substantial instance of absolute decoupling encountered in this study. A 1% population increase is correlated with a 0.52% decrease in infrastructure stocks. This observation has to be put in perspective, however. Since population has been in decline in recent years and even for several decades in some prefectures, this decoupling might not be the type usually looked for, but rather "inverse" decoupling: infrastructure MS could be growing by 0.52% for every 1% decrease in population. The coefficient *c* of GPP is also notable for being larger than 1, suggesting that the MS in infrastructure increases at faster rates than GPP. However, model 2c, which distinguishes urban and rural populations, does not present negative coefficients for population nor a coefficient bigger than 1 for GPP, rather the coefficients are similar to those of models 2a and 2b. Model 3c again presents a sizable negative coefficient for population (−0.59) but the disaggregation of GPP into three sectors does not show a coefficient higher than one for any economic sector. Nevertheless, these coefficients are higher than their counterparts in the total stock model (3a) and building stock model (3b), suggesting that economic activity indeed has a stronger effect on the growth of infrastructure MS than on building MS. The fourth model's disaggregation of both population and GPP suggests that rural decline has a relatively high (0.45) moderating effect on the accumulation of infrastructure MS while urban population has only a weak statistical effect on it, which might explain the negative coefficients of aggregated population in models 1c and 3c. As before, the tertiary sector seems to be the main driver of stock accumulation in this model.

5.5. Discussion

The stock dynamics explored for Japan and its constituent prefectures between 1965 and 2010 reveal the contribution of the underlying drivers to construction material stock accumulation at different stages of economic development. In a situation of rapid economic growth with yearly growth rates close to 10%, such as was the case in Japan until the 1970s, wealth is the most important driver of growth in buildings and transport infrastructure. Because of the transition to modern technologies and designs in the building and transport sectors the ability of stock intensity to offset the growth dynamic is very limited or non-existent. This national trend is also quite uniformly represented at the prefectural level, which is testament of a government led effort to link-up the country to enhance the economic potential across all prefectures. This attempt to service the economy with infrastructure through government is most notably seen in the northernmost prefectures, which had a substantial need to increase available infrastructure to keep in step with national economic development. Despite the uniform trend across provinces, the urban strip between Tokyo and Osaka experienced the highest population growth and commensurate stock accumulation during the late 1960s and early 1970s.

The high growth period in Japan was completed by 1974 and coincided with the first oil price shock. The negative values for stock intensity across many prefectures in the following two decades mean that enough buildings and transport infrastructure were available to satisfy economic growth during that time. This does not mean that stock has not continued to grow but rather it has done so at a much slower speed. The decade until the turn of the century shows a new period of extending government investment into stock accumulation in an effort to stimulate economic growth, but with little success. The decade until 2010 shows a decline in national population numbers and intra-migration out of rural areas into the urban centers of Tokyo, Yokohama (Kanagawa prefecture), Nagoya (Aichi prefecture), Osaka, and their immediate neighbors. In some parts of Japan an overcapitalization of building stock and transport networks has resulted, which is demonstrated by the large number of uninhabited houses and underutilized roads in many rural areas. While there may be stock saturation of buildings in Japan today the maintenance cost of existing stock is growing over proportionally at a time when investment has plummeted in favor of consumption.

Panel analysis allows further investigation of the patterns found through the IPAT approach. The general finding is that more people leads to more stock and more economic activity leads to the same result but as population and economic growth slow stock accumulation does as well, and relative decoupling is present. An analysis of sectoral GPP shows that there are enough farm houses and factories but not enough office buildings, with continuing construction activity of high rise buildings very visible in the urban landscape of Japan. A disaggregation into buildings and transport infrastructure is very useful as they have different relationships to economic growth and population trends. While population growth has a positive relationship with building stock the amount of transport infrastructure needed declines with rising population density, which demonstrates economies of scale, corroborating Bettencourt et al. (2007). The panel analysis confirms the negligible effect of infrastructure investment through government programs in what could be called a failed Keynesian effort of the Japanese government during the 1990s. It appears that in a situation of stock saturation investing into additional built capital does not yield any additional positive effects on economic growth. In many ways Japan presents a case study for the stock implications of socio-economic development leading, after a period of fast growth, to saturation. It would be interesting to apply the learnings from this study to other countries, such as Korea and China, which have experienced or are undergoing rapid industrialization, to assess the dynamics and saturation points of physical stock in these economies. Material stock is a good indicator for doing exactly that as it does not share the dependency of other material flow indicators, such as DMC, on trends found in the global economy and presented through trade of raw materials.

6. Conclusions

6.1. Summary and discussion of the findings

Even though for the most part the accounting and analysis of material stocks were segregated in the above chapters, it is only a didactic choice of presentation. As mentioned in the review of the state of the art, most studies of material flows and stocks include both, as in truth one cannot exist without the other.

The accounting of material stocks was tackled from three different angles. First, a novel method was developed for a top-down account of material stocks of national economies based on historical material flow studies and applied the approach for two national economies, the United States and Japan. It was proven that the approach delivers credible results and has merits in comparison to bottom-up approaches for stock accounts which are usually very time consuming and costly. The evolution of national material stock was compared for the two case studies and showed that by 2005 both economies reached comparable levels of per capita material stock of about 310 tonnes per person in Japan and 375 tonnes per person in the USA. These results show that material saturation has not been reached in neither of these countries as the growth of material stock, both per capita and in absolute numbers, has been continuous until 2005. Nevertheless, as this approach is input-driven, it is unable to show mass output of construction material stock events such as the destruction of assets that occurred during World War 2, Japan's 2011 Tsunami or the USA's 2005 Hurricane Katrina.

Next, three deterministic scenarios until 2050 were presented which suggest possibilities of reaching saturation in the future, and even dematerialization of total stocks in Japan and dematerialization of per capita stocks in the USA. Despite the relatively simplified scenarios assumptions, the scenarios may be useful for policy making, and for the management of future material requirements for stock maintenance and the expected amounts of demolition waste.

Finally, using analytical techniques and stochastic modeling borrowed from business studies and economics time series patterns in physical stock accumulation were investigated in the global economy and for 46 countries, and future pathways of physical stock accumulation and specified uncertainty ranges were inferred.

Four archetypes of countries were identified which display important differences in the speed and acceleration of stock accumulation which coincide with their economic development stages and have important implications for the global sustainability of construction materials management. Of most concern for global sustainability are countries which show overall increasing acceleration of stock accumulation, which is the case for China, India and Brazil among other countries (type II). The time these countries will need to establish sufficient levels of stock of buildings and transport infrastructure for their growing population and economies and their growing cities to adapt a new pattern of stock saturation (found for type I and type IV countries) will be a determining factor for global sustainability.

This calls for comparison of the stock per person and per unit of GDP in various countries and analysis of whether the stock stabilized at any period near the inflection points identified here. This kind of investigation requires data not only on the speed of accumulation or the additions to the stock, but on actual levels of stock in as many countries as possible beyond the USA and Japan to further inspect this question, data that does not currently exist at the country level. Rather, the relationships between stock accumulation, population and economic growth in the USA and in Japan and its prefectures were investigated, and trends were identified in how different phases of development impact on physical stock levels. This has enabled to draw conclusions for generalized patterns of how physical stocks underpin economic development across a national geography. The trends of material efficiency of throughput were compared to material efficiency of stock finding that in the United States both efficiencies have improved since the 1970s, albeit the efficiency of stock much less so. In Japan it was found that the improving material efficiency of throughput that goes hand in hand with declining efficiency of material stock. This trend in Japan is further exacerbated by the fact that the share of throughput that goes to stock is much larger than in the United States, which employs a throughput metabolic pattern (Matthews et al. 2000).

The IPAT and panel regression methods employed in this study prove to be practical tools in the analysis of anthropogenic material stock buildup and would be useful on larger scales for country comparisons once international stock data becomes available. The relationships that have been unveiled may facilitate scenario building for assessing the future stock requirements of the Japanese economy or other economies, providing valuable insights into the physical underpinnings of modern economies. The indicators and relationships presented in this study may become useful to inform policies that enhance the quality and longevity of buildings and transport infrastructure to contribute to a sustainable and low throughput economic model.

6.2. Overall achievement of the research objectives

These findings all combine to explain the dynamics of material stock accumulation over time in different countries and regions, and the socio-economic drivers of these activities. They help to fill the gap in SEM research, which has historically mostly focused on the flows of materials and failed in explaining material stocks, by attempting to use approaches fitting for throughput materials rather than stocked materials. These findings can be summarized by revisiting the research question. The research question (What are the trends of material stock in countries as they mature?) was resolved by reaching conclusions to the four specific objectives:

1. What are the paths of accumulation of stocks of construction materials in countries during their development phases?

   It was found that four archetypal growth patterns exist for the countries of the world, and that countries may be "locked-in" to their pattern. The growth of material stocks in some countries follows a stable growth trajectory, but many countries undergoing rapid development seem to have an explosive growth path. Most mature economies were found to have decreasing speeds of additions to their material stocks and may even reach negative net additions in upcoming years.

2. What are the relations of economic development and physical development?

   Different patterns of coupling and decoupling were found in the examination of the USA, Japan, and Japan's prefectures. The USA seems to follow a somewhat decoupled development path, in which economic activity grows faster than the physical stock. Nevertheless, economic activity dictates the yearly fluctuations and long-term trends of stock accumulation. In Japan, material stock growth was found to be correlated with economic growth, especially with tertiary sector activity, until the early 1990s, following which physical development continued despite economic slowdown. Specifically, however, Japan's prefectures have differing relations with economic activity depending on their urbanization.

3. Are there different drivers to material stock accumulation during different phases of development?

Population was found to be a driver for material stock accumulation throughout the different development phases examined, and seems to be a major stable driver in the United States. However, in both Japan and the USA it is usually shadowed by economic activity, which is the main driver of physical stock accumulation especially during phases of high growth. Nevertheless, the continued growth of material stocks in Japan after 1990 hint that under certain conditions, other unmeasured drivers may play an even bigger role- such as government policies and activities.

4. Do material stocks stabilize and reach a saturation when society reaches a certain stage of development and wealth?

   The material stock of Japan and most of its prefectures was found to be reaching towards stabilization, and its growth is forecast to further stabilize or even start a dematerialization process. Several other developed countries (category IV) may be following similar paths to stock stabilization and saturation. However, the population and economic centers of Japan seem to be experiencing sustained growth due to intra-national migration which is overflowing to neighboring prefectures, and so while the whole country is on a pathway to saturation, internally it is an active system, hinting that saturation at the national level is in fact a state of dynamic equilibrium.

6.3. Implications of the findings

In order to increase the validity of research results for policy and planning, physical economy research has to include stock accumulation and the relationship of stock to other factors such as population and economic activity. Research on physical stocks is still in its infancy and hence little is known about what drives stock accumulation. In this research, in contrast to previous studies that only focused on flows, new information was established on a topical subject for sustainable materials management, namely the boundless growth of construction materials extraction and stock accumulation in the global economy which has caused tremendous impacts on the environment and will, according to this analysis, may continue to accelerate causing runaway impacts for climate, land use change, resource exploitation and waste flows.

The findings of this research can contribute to the larger debate around economic development and its metabolic causes and consequences. This new information on national material stocks may become very useful in an economic context that refocuses on the services delivered by quality buildings and infrastructure, based on a new focus of lowering throughput of materials and achieving a steady state. With the growing interest of governments and international organizations in material consumption, the understanding of material stocks, their drivers and dynamics are crucial, and this study offers a sound, systematic base of understanding and a toolbox of analytical methods for use in this discourse.

6.4. Limitations of the research

The limitations to the research presented in section 1.5, of data availability and precision, were overcome. Limits to the results of this work are thus not centered on data attributes, but rather on several inherent assumptions that may influence the analysis. First, it was assumed that all of the material stock accounted for is in fact in use. That is, this stock is actively providing services to society. However, some parts of the stock may be derelict, hibernating, lost, or dissipated (Hashimoto et al. 2007, 2009; Tanikawa et al. 2014; Daigo et al. 2015), in which case it has no productive role and does not support the growth of population or of the economy. If these types of stock take a high portion of the overall accounted stock, the results would be distorted. While it is extremely difficult to accurately quantify these unused or underused stocks, the use of cautious lifetime assumptions for the compilation of the top-down accounts, and the reliance on bottom-up accounts (which is at much smaller risk due to its in-use data sources) for many parts of the analysis, together reduce the risk of miscalculations.

A second limitation is the reliance on DMC figures of the ARIMA analysis of the 44 further countries and the World rather than on total material stocks or at least on NAS, which both limits the results to accumulated additions to stock and may also distort the analysis. As seen in the results of the deterministic models of Japan and the USA, as time progresses DMC and NAS diverge from each other. However, this divergence is a complex function of dynamic reductions from stocks which cannot be simply approximated as a function of time (Van der Voet et al. 2002; Elshkaki et al. 2005). While more accurate point forecasts will be enabled by improved NAS data, the fundamental findings such as the country trajectory profiles, the relative sizes of uncertainties, and country groupings will not change, due to DMC and NAS sharing the same higher-level differentiation characteristics.

Third, the assumption that drivers of material stock accumulation consist of only population and economic activity may be a limitation. From some of the results it becomes clear that the actions of government policy also play a part as a driver of material stock accumulation. The IPAT and panel regressions employed allowed to indirectly detect its effects, such as the otherwise weakly explained MS growth, especially of infrastructure, in the 1990s. It would be interesting to add government as an explicit factor, although enumerating a proper indicator that encompasses all types of government intervention might prove to be challenging. There are several other factors that have remained underexplored in this study, which can be termed the "spatial endowments" of countries and prefectures such as physical geography – mountains and coastlines for example, as well as human geography – the evenness of distribution of the population across the landscape and the size and the shape of prefectures and the country as a whole, more often than not defined by artificial borders. While these might be somewhat implicit in parts of the analysis, different methodological approaches are required to further examine the effect these have on building and infrastructure demands.

In summary, although improving on these limitations may improve the accuracy of the results and analysis, none of them are crucial to the fundamental conclusions reached by the work presented here.

6.5. Areas for future research

The accounting methods and analytical tools presented in this work can be used for further case studies of other sub-national regions, countries, global regions, and the entire world. It remains to be seen whether Japan and the USA, on which most of the work was focused, are characteristic models or unique cases.

Both the IPAT framework and the panel analysis can be extended with further explanatory variables which may shed light on further drivers of material stock accumulation. Likewise, the ARIMA framework for time series analysis is but one in a family of stochastic forecasting methods, some of which also include external explanatory variables, offering in a way a merger of time series and panel analysis, and may produce novel results.

A characteristic which is absent in the current discussion is the geo-social aspect of material stocks. Many of the roles of stocks, such as accommodators of residence, work, and transportation, and shapers of human settlements, are spatial in nature. Whether stocks fulfill their roles to society is not only a question of amount and quality but also of location. Buildings and infrastructure are by their nature fixed assets, taking up physical space on land and altering its shape. The total area taken up by material stocks, the spatial distribution of material stock, and the available land for potential construction, all affect material stock accumulation values and trends. Countries have unique land areas, land use, building densities, and other geo-social differences. The saturation of material in both absolute terms and per person were examined, but further country comparisons and material saturation could be potentially examined through the lens of geography in addition to the economic and population perspectives presented so far. To these ends, an integrated approach, utilizing the different methodologies to supplant each other, is indeed the future of material stock research in socio-economic metabolism.

Notes

Portions of this thesis were peer-reviewed and published (Fishman et al. 2014, 2015; Tanikawa et al. 2015; Fishman et al. Under review) as part of the PhD requirements.

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List of figures

List of tables

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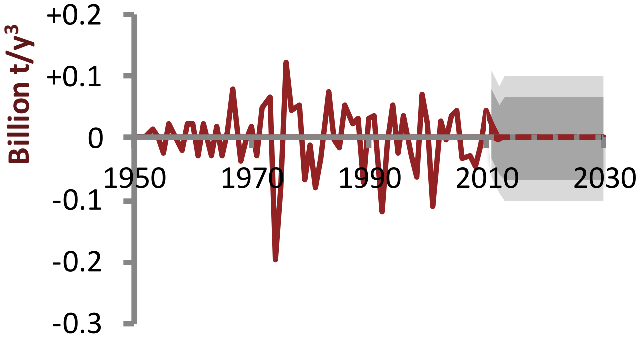
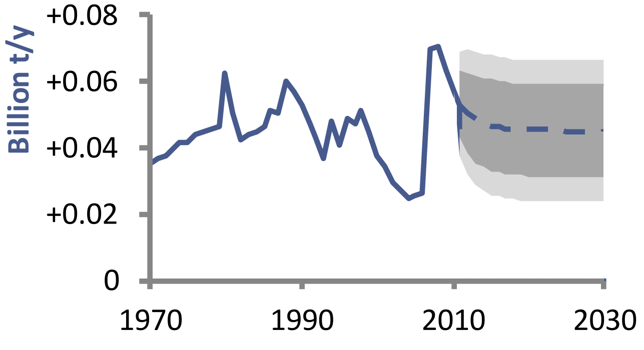
1. 3rd order of difference for Japan, measuring the change in acceleration, or "surge" in material stock accumulation, 1970-2030, with forecast intervals of 80% and 95%.



2. ARIMA models of the speed of accumulation of material stock, 1970-2030, with forecast intervals of 80% and 95%, for all countries.

2.a. Category I – stationary speed (one country)

I.1 The Netherlands

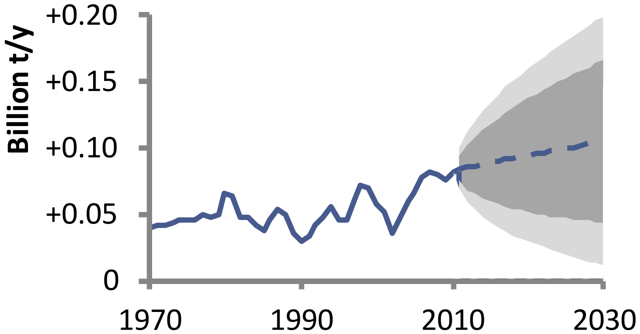


ARIMA(1,0,0) with non-zero mean

	AR(1)	Intercept
Coefficient	0.674	45139172
Standard Error	0.1145	3666545

2.b. Category II – stationary acceleration (20 countries)

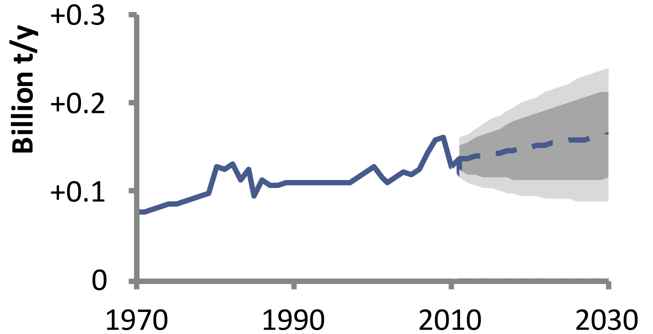
II.1 Argentina



ARIMA(0,1,1) with drift

	MA(1)	Drift
Coefficient	0.4394	1093932
Standard Error	0.1542	1699479

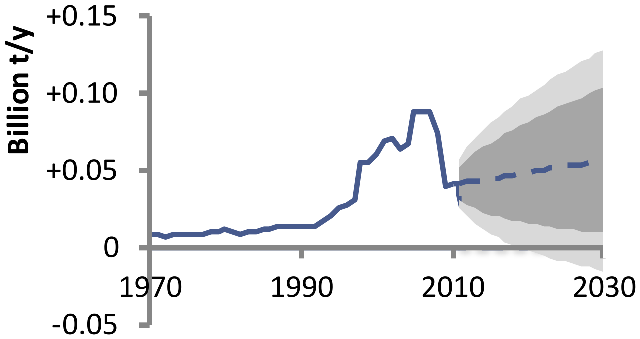
II.2 Australia



ARIMA(1,1,0) with drift

	AR(1)	Drift
Coefficient	-0.2889	1474016
Standard Error	0.1755	1361527

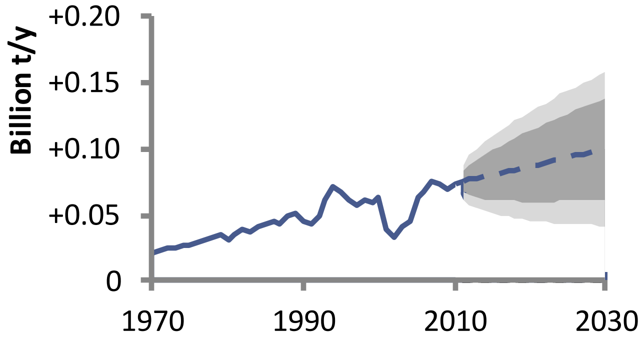
II.3 Bangladesh



ARIMA(0,1,0) with drift

	Drift
Coefficient	789150
Standard Error	1289089

II.4 Colombia

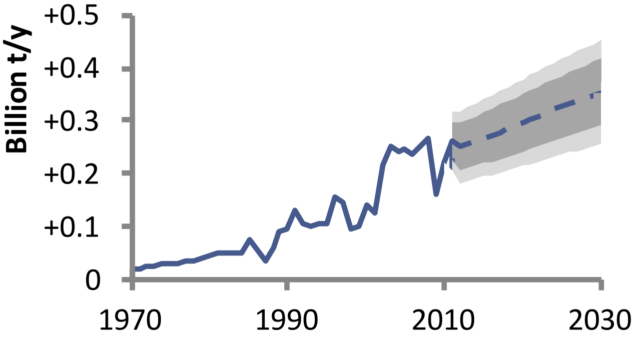


ARIMA(0,1,0) with drift

	Drift
Coefficient	1311650
Standard Error	1046415

2.b. Category II – stationary acceleration (20 countries), continued

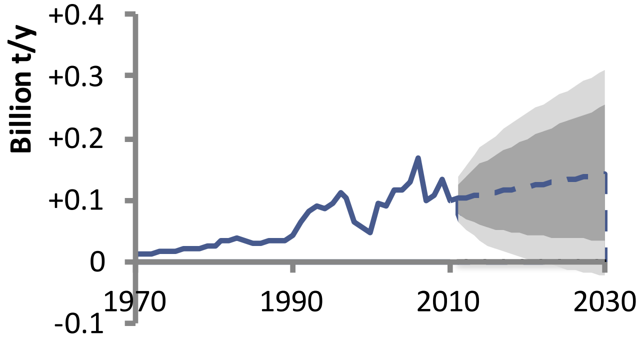
II.5 Indonesia



ARIMA(0,1,2) with drift

	MA(1)	MA(2)	Drift
Coefficient	-0.2649	-0.4322	5790536
Standard Error	0.1742	0.1993	1503771

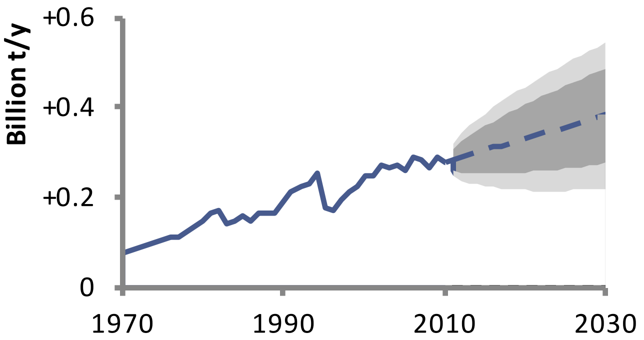
II.6 Malaysia



ARIMA(0,1,0) with drift

	Drift
Coefficient	2225500
Standard Error	3009882

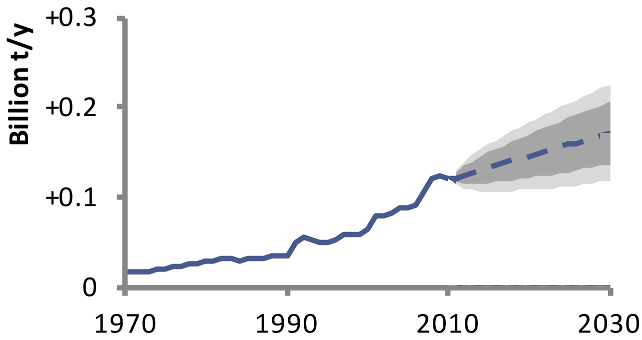
II.7 Mexico



ARIMA(0,1,0) with drift

	Drift
Coefficient	5062125
Standard Error	2908469

II.8 Morocco

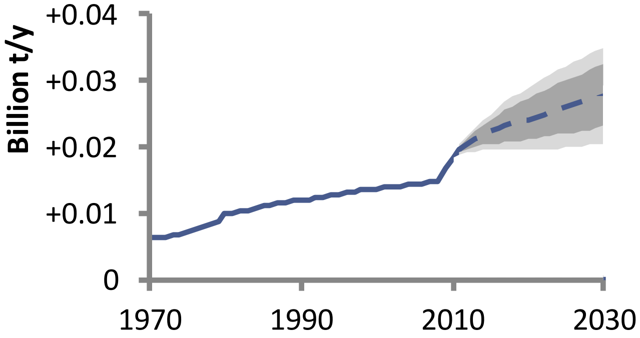


ARIMA(0,1,1) with drift

	MA(1)	Drift
Coefficient	0.4618	2564557
Standard Error	0.1497	964276

2.b. Category II – stationary acceleration (20 countries), continued

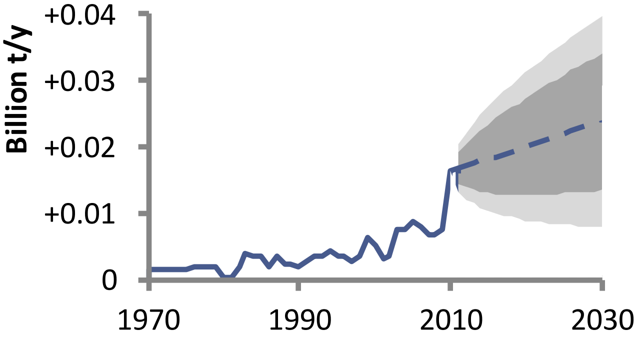
II.9 Myanmar



ARIMA(1,1,0) with drift

	AR(1)	Drift
Coefficient	0.6352	354093
Standard Error	0.1579	139369

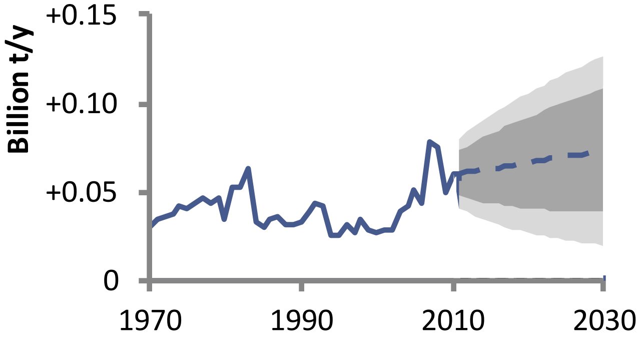
II.10 Nepal



ARIMA(0,1,0) with drift

	Drift
Coefficient	370850
Standard Error	284508

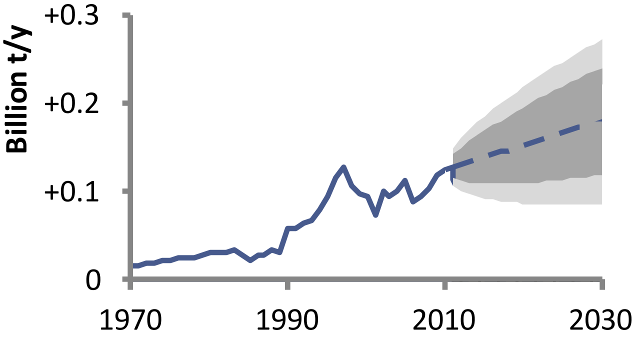
II.11 Nigeria



ARIMA(0,1,1) with drift

	MA(1)	Drift
Coefficient	-0.4125	684738
Standard Error	0.1683	938341

II.12 The Philippines

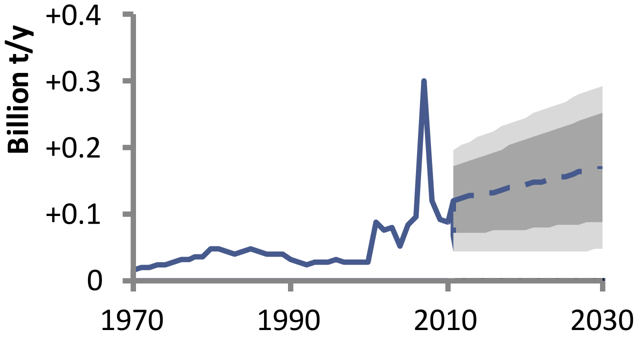


ARIMA(0,1,0) with drift

	Drift
Coefficient	2714900
Standard Error	1679422

2.b. Category II – stationary acceleration (20 countries), continued

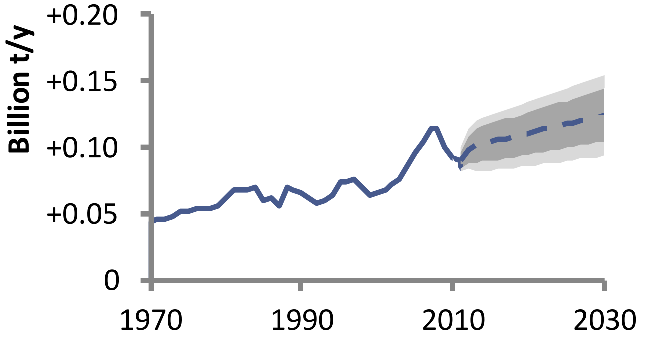
II.13 Romania



ARIMA(0,1,1) with drift

	MA(1)	Drift
Coefficient	-0.7133	2591781
Standard Error	0.1248	1912162

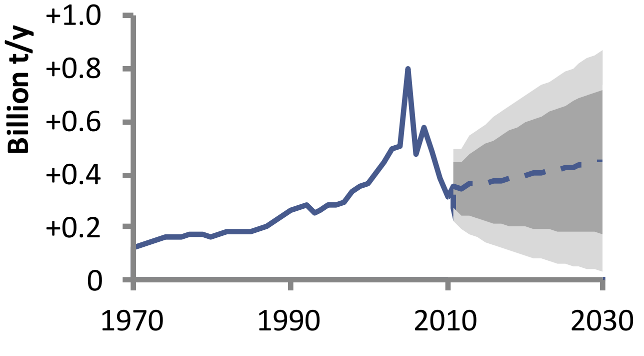
II.14 South Africa



ARIMA(0,1,3) with drift

	MA(1)	MA(2)	MA(3)	Drift
Coefficient	0.2676	0.1076	-0.7782	1331001
S.E.	0.2217	0.2457	0.3713	490330

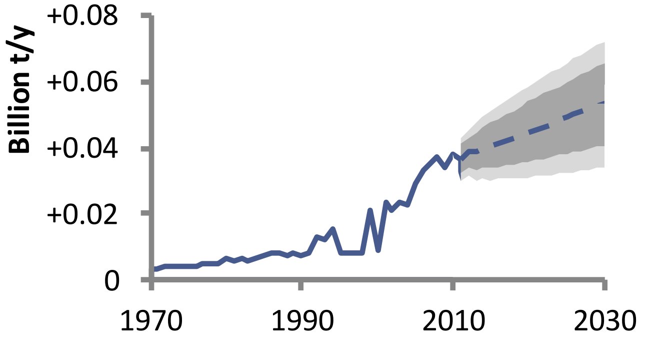
II.15 Spain



ARIMA(1,1,0) with drift

	AR(1)	Drift
Coefficient	-0.4761	5432756
Standard Error	0.1393	7458879

II.16 Sri Lanka

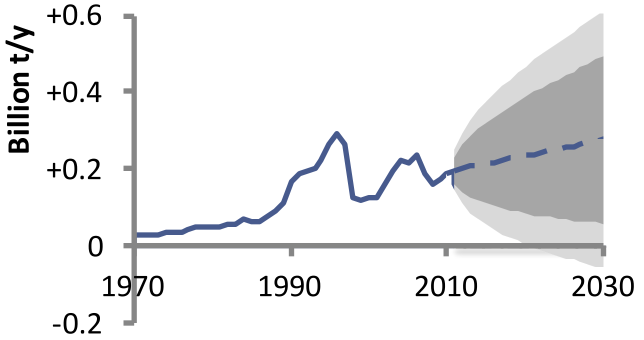


ARIMA(1,1,0) with drift

	AR(1)	Drift
Coefficient	-0.5935	826856
Standard Error	0.1257	332334

2.b. Category II – stationary acceleration (20 countries), continued

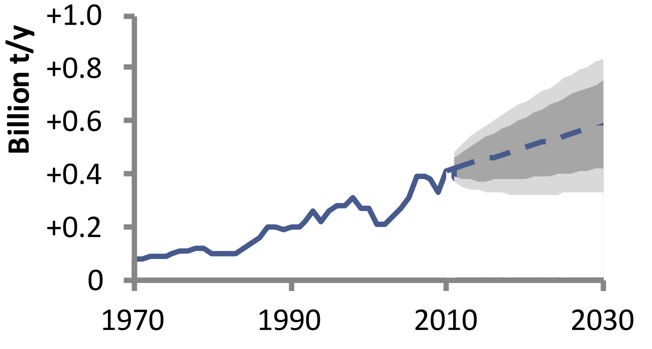
II.17 Thailand



ARIMA(0,1,1) with drift

	MA(1)	Drift
Coefficient	0.4046	4164549
Standard Error	0.1478	6034122

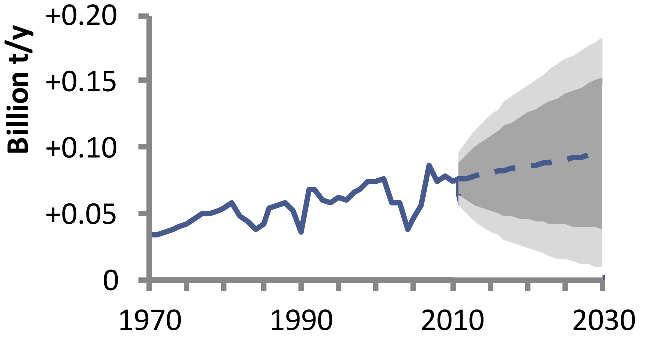
II.18 Turkey



ARIMA(0,1,0) with drift

	Drift
Coefficient	8507525
Standard Error	4515892

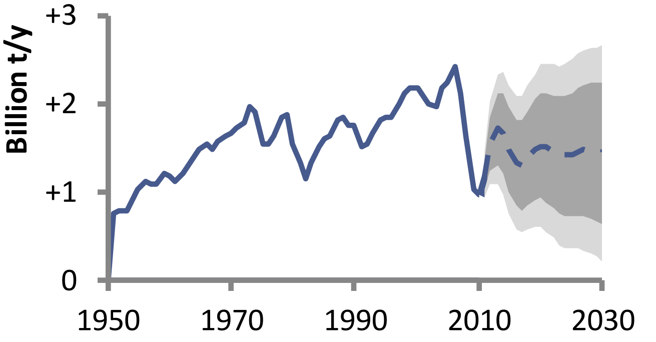
II.19 Venezuela



ARIMA(0,1,0) with drift

	Drift
Coefficient	1035950
Standard Error	1569190

II.20 USA



ARIMA(3,1,0)

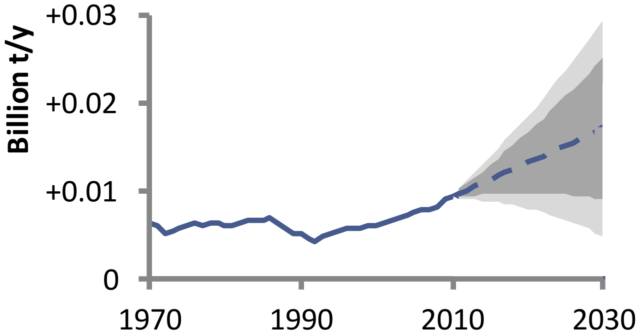
	AR(1)	AR(2)	AR(3)
Coefficient	0.5436	-0.1846	-0.3595
Standard Error	0.124	0.1545	0.1425

Notes for the USA:

1. The ARIMA model selection was conducted on the Levels series, whose model is ARIMA(3,2,0). The coefficients are by definition the same.
2. Note the longer horizontal (time) axis.

2.c. Category III – non-stationary acceleration, overall increasing acceleration (15 countries + World)

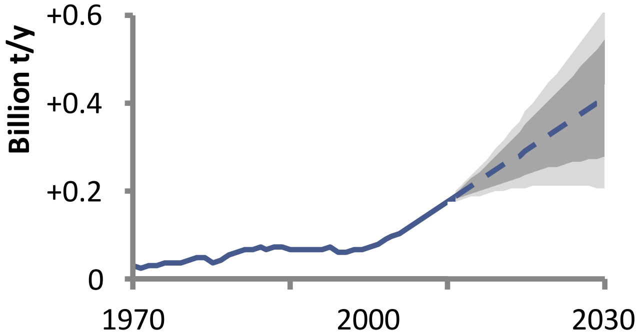
III.1 Afghanistan



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.7265
Standard Error	0.1795

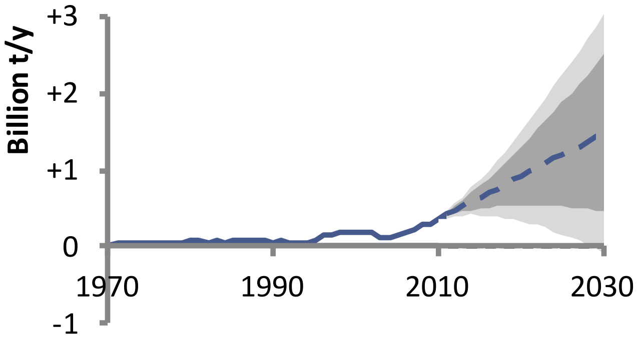
III.2 Algeria



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.7156
Standard Error	0.0996

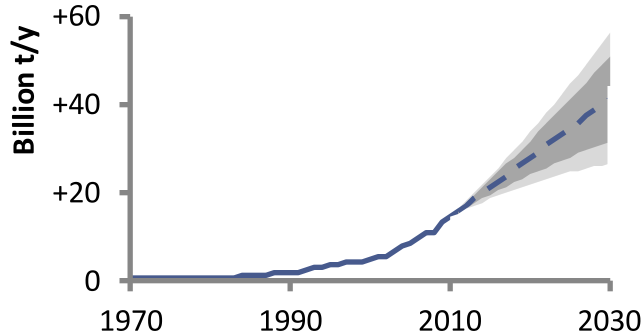
III.3 Brazil



ARIMA(1,2,0)

	AR(1)
Coefficient	-0.5826
Standard Error	0.1523

III.4 China

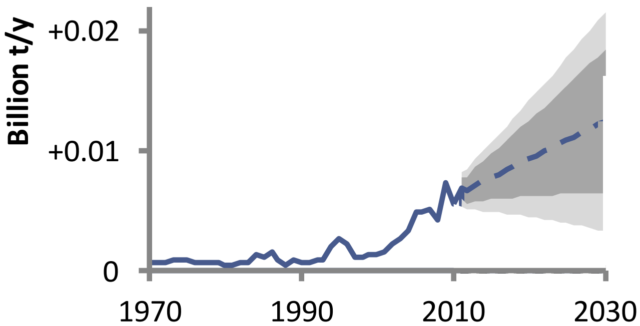


ARIMA(0,2,1)

	MA(1)
Coefficient	-0.571
Standard Error	0.1154

2.c. Category III – non-stationary acceleration, general trend of increasing speeds (15 countries + World), continued

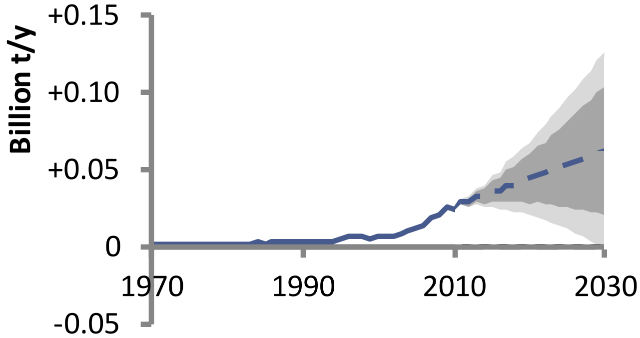
III.5 DR Congo



ARIMA(1,2,1)

	AR(1)	MA(1)
Coefficient	-0.4376	-0.8987
Standard Error	0.1746	0.0873

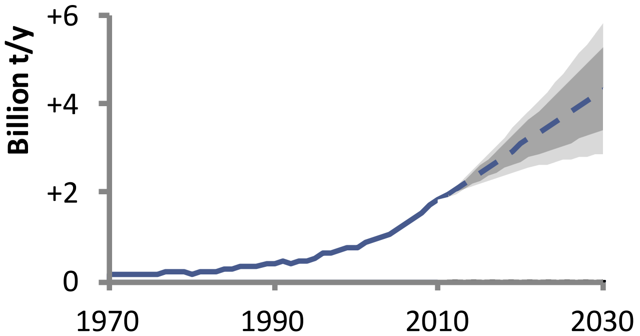
III.6 Ethiopia



ARIMA(1,2,0)

	AR(1)
Coefficient	-0.9046
Standard Error	0.0941

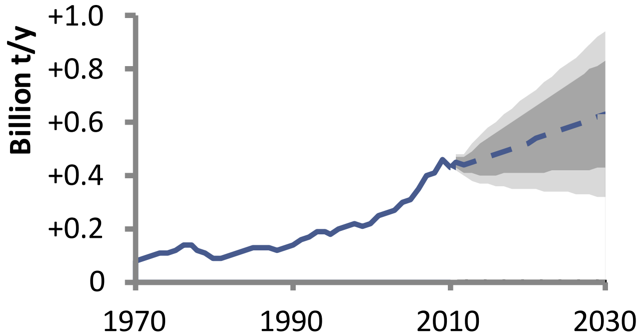
III.7 India



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.5155
Standard Error	0.1363

III.8 Iran

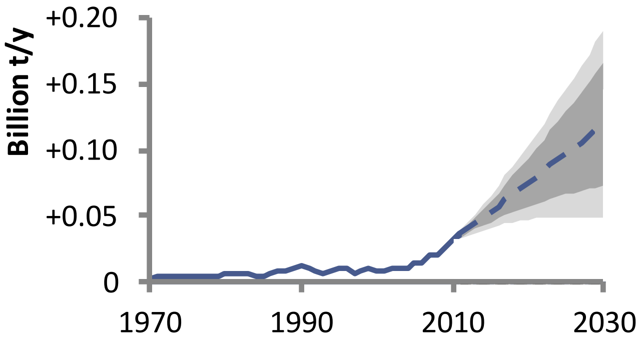


ARIMA(0,2,3)

	MA(1)	MA(2)	MA(3)
Coefficient	-0.9085	0.5565	-0.5734
Standard Error	0.1586	0.1991	0.1408

2.c. Category III – non-stationary acceleration, general trend of increasing speeds (15 countries + World), continued

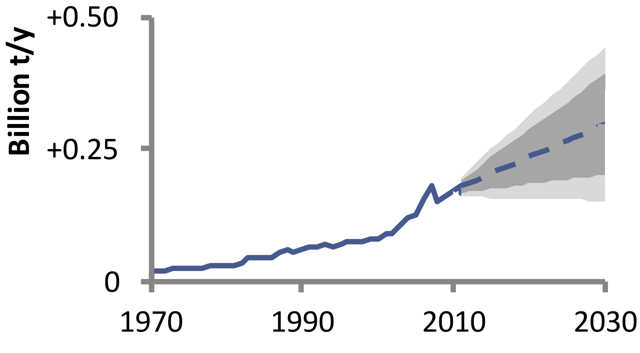
III.9 Kenya



ARIMA(0,2,2)

	MA(1)	MA(2)
Coefficient	-0.991	0.3259
Standard Error	0.1562	0.1473

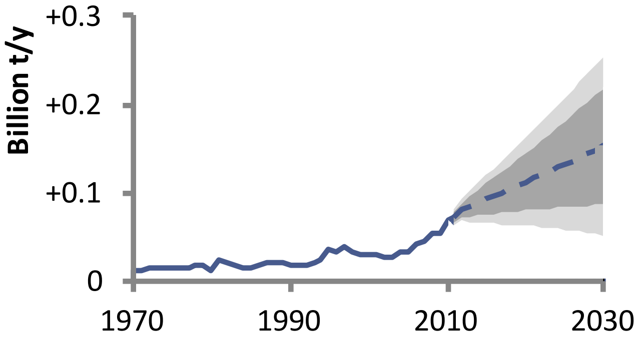
III.10 Pakistan



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.9149
Standard Error	0.0755

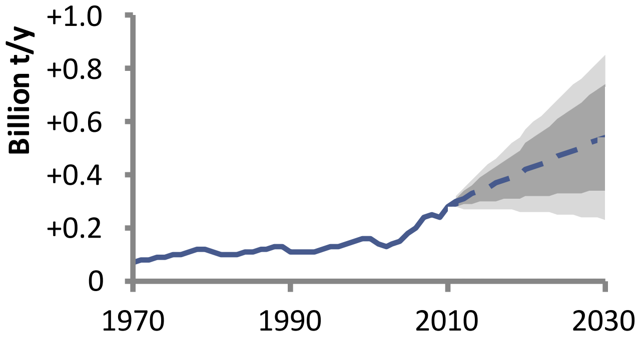
III.11 Poland



ARIMA(1,2,1)

	AR(1)	MA(1)
Coefficient	0.3551	-0.8946
Standard Error	0.1938	0.1148

III.12 Peru

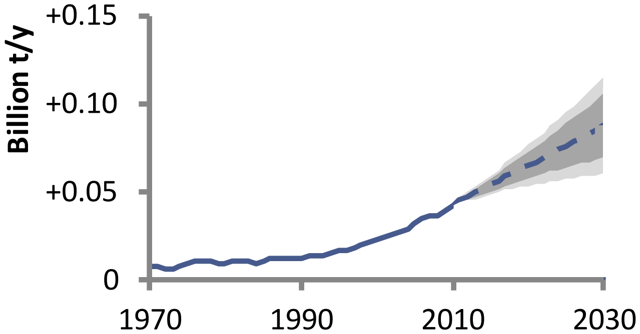


ARIMA(0,2,3)

	MA(1)	MA(2)	MA(3)
Coefficient	-0.945	0.4931	-0.4
Standard Error	0.1572	0.1981	0.1705

2.c. Category III – non-stationary acceleration, general trend of increasing speeds (15 countries + World), continued

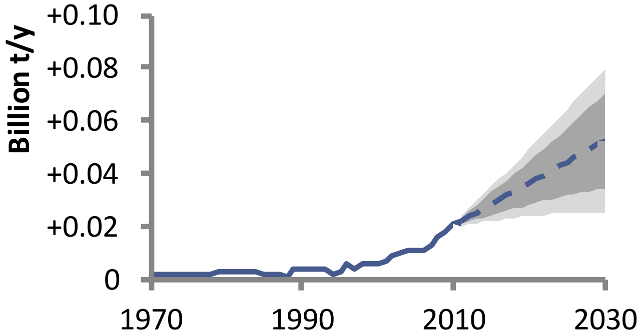
III.13 Sudan



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.6923
Standard Error	0.1075

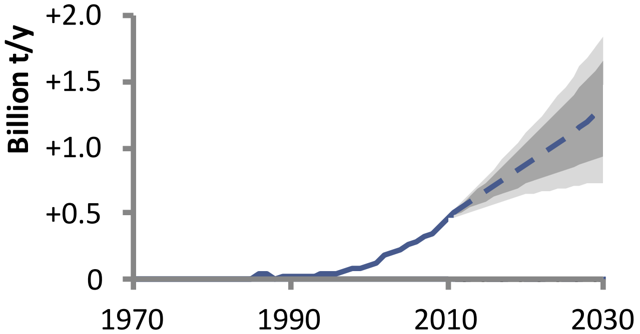
III.14 Tanzania



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.8137
Standard Error	0.087

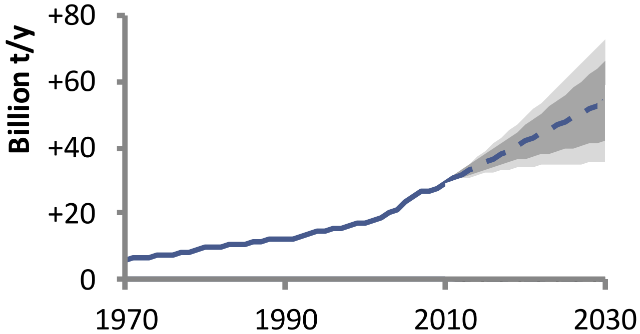
III.15 Vietnam



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.6999
Standard Error	0.0967

III.16 World

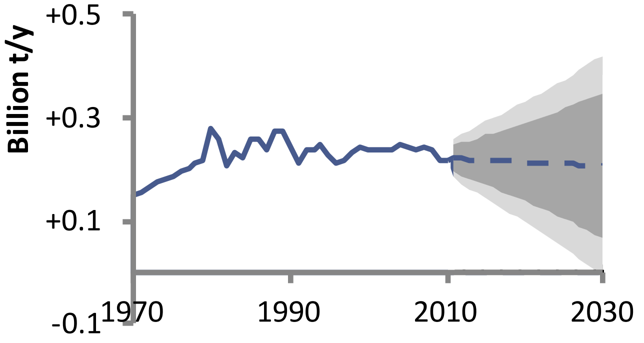


ARIMA(0,2,1)

	MA(1)
Coefficient	-0.6554
Standard Error	0.1573

2.d. Category IV– non-stationary acceleration, varying phases (8 countries)

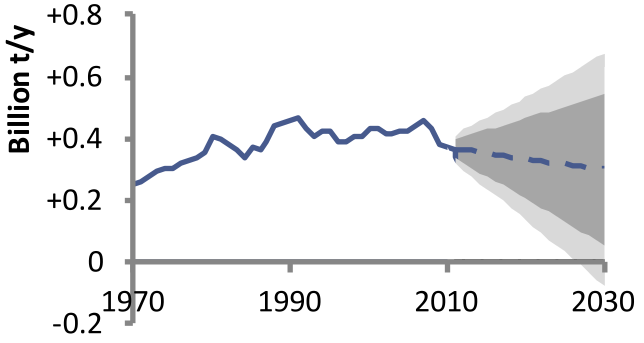
IV.1 Canada



ARIMA(2,2,1)

	AR(1)	AR(2)	MA(1)
Coefficient	-0.169	-0.3082	-0.9178
Standard Error	0.1573	0.1545	0.0838

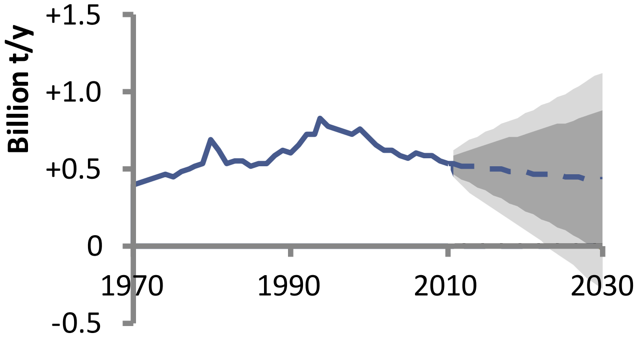
IV.2 France



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.9117
Standard Error	0.0834

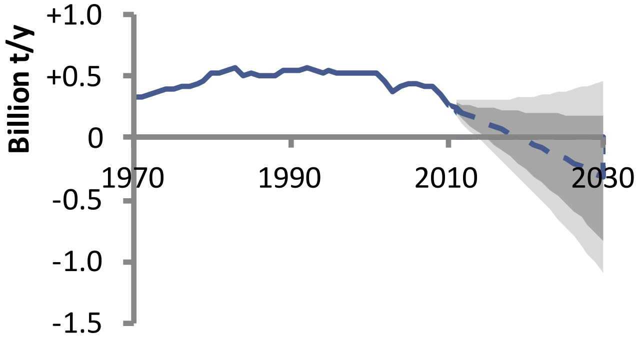
IV.3 Germany



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.9249
Standard Error	0.0844

IV.4 Italy

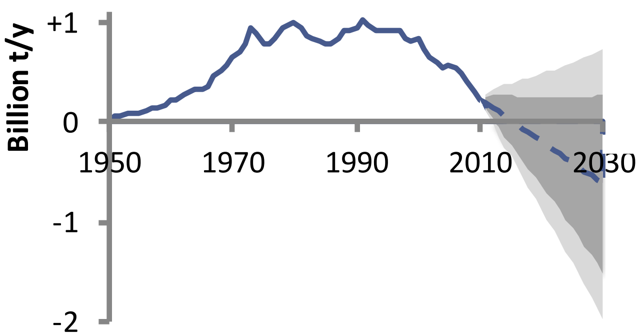


ARIMA(0,2,1)

	MA(1)
Coefficient	-0.8206
Standard Error	0.1095

2.d. Category IV– non-stationary acceleration, varying phases (8 countries), continued

IV.5 Japan



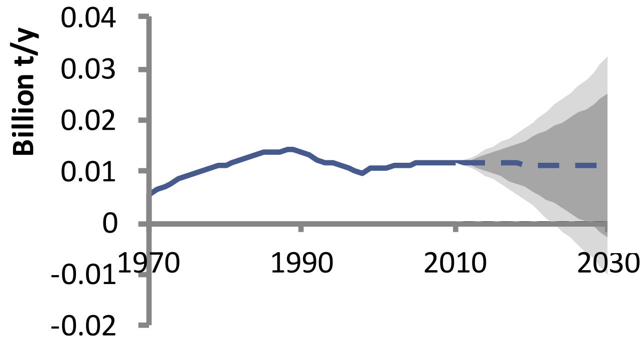
ARIMA(0,2,2)

	MA(1)	MA(2)
Coefficient	-0.1682	-0.6475
Standard Error	0.1066	0.1048

Notes for Japan:

1. The ARIMA model selection was conducted on the Levels series, whose model is ARIMA(0,3,2). The coefficients are by definition the same.
2. Note the longer horizontal (time) axis.

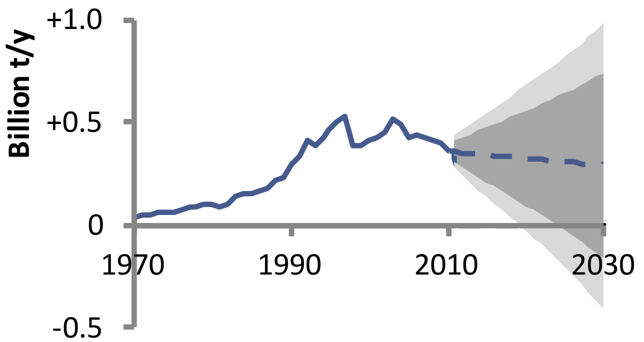
IV.6 North Korea



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.3331
Standard Error	0.1556

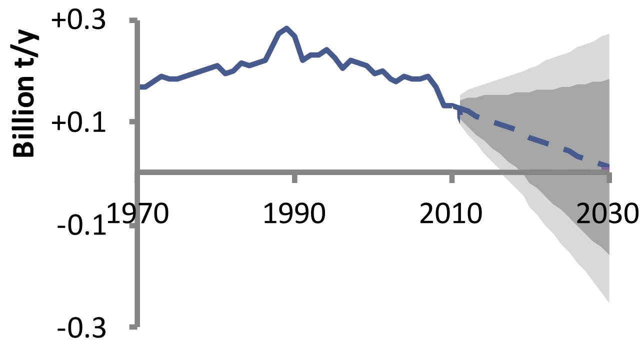
IV.7 South Korea



ARIMA(0,2,1)

	MA(1)
Coefficient	-0.8978
Standard Error	0.1215

IV.8 United Kingdom



ARIMA(,2,)

	MA(1)
Coefficient	-0.9001
Standard Error	0.074