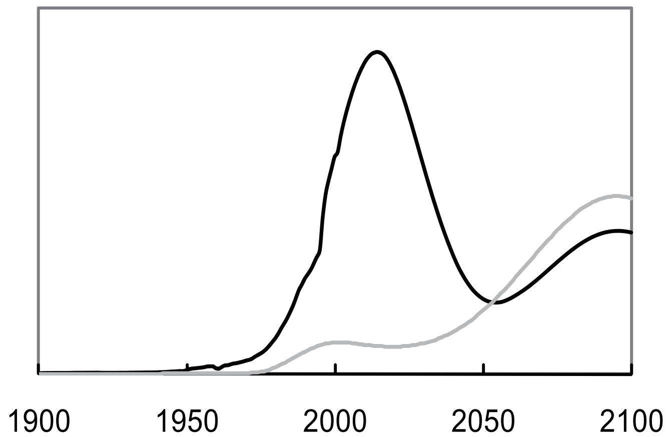
Dynamic Material Flow Analysis to Support Sustainable Built Environment Development

with Case Studies on Chinese Housing Stock Dynamics



Mingming

Dynamic Material Flow Analysis to Support Sustainable Built Environment Development

with Case Studies on Chinese Housing Stock Dynamics

Proefschrift

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus prof. mr. P.F. van der Heijden,
volgens besluit van het College voor Promoties
te verdedigen op dinsdag 18 mei 2010
klokke 11.15 uur

door

Mingming Hu

geboren te Sichuan, China
in 1975

Promotiecommissie:

Promotors:	Prof. dr. Sjoerd M. Verduyn Lunel Prof. dr. ir. Michiel Haas (Delft University of Technology)
Co-promotors:	Dr. Ester Van der Voet Dr. Gjalt Huppes
Overige Leden:	Prof. dr. Daniel B. Müller (Norwegian University of Science and Technology) Prof. dr. ir. Hong Ren (Chongqing University, China) Prof. dr. ir. Guiwen Liu (Chongqing University, China)

In memory of Michele

The work described in this thesis was facilitated in part by Chongqing University (China) and Delft University of Technology. It was made possible by the financial support from the Asia-Link project "Human Resources Development for the improvement and protection of Environment in Asia (ProtEA)" of European Union (No. CN/ASIA-LINK (110-744)) and the China Exchange Programme "Innovative Methodologies for Sustainable Waste Management (InnoMan)" of the Dutch Academy of Art and Science (No. 09CDP009).

Dynamic Material Flow Analysis to Support Sustainable Built Environment Development, with Case Studies on Chinese Housing Stock Dynamics

Institute of Environmental Sciences (CML)
Leiden University
PO Box 9518, 2300 RA
Leiden, The Netherlands

E-mail: hu@cml.leidenuniv.nl

ISBN 978-90-5191-167-1

Contents

Summary

This thesis describes the development of a stock-driven dynamic material flow analysis model that can be used to analyze the long-term metabolism of the built environment stocks in rapidly urbanizing emerging regions.

Introduction

Many of the sustainability challenges raised by developments in the built environment are related to the significant mobilization of materials, which leads to two types of problems. On the inflow side these include resource depletion and emission problems due to materials production, while on the outflow side they include problems of construction and demolition waste (CDW). The challenges are especially severe for the emerging countries, where nearly all of the additional world population in the next half century is expected to be absorbed by their urban areas. Meanwhile, theory for 'sustainable built environment development' is still being developed. Although the concepts and goals are not yet well-defined, the need for a long-term systems perspective to support the development of a sustainable built environment seems clear. A visionary perspective can only be achieved if we understand the long-term metabolism of the built environment stocks, by applying dynamic material flow analysis. Previously, a stock-dynamics-driven approach has been successfully used for dynamic material flow analysis in several housing stock studies in developed countries. This approach has, however, never been applied to newly emerging countries, where the combined influences of very rapid economic development and urbanization have to be considered.

Research design

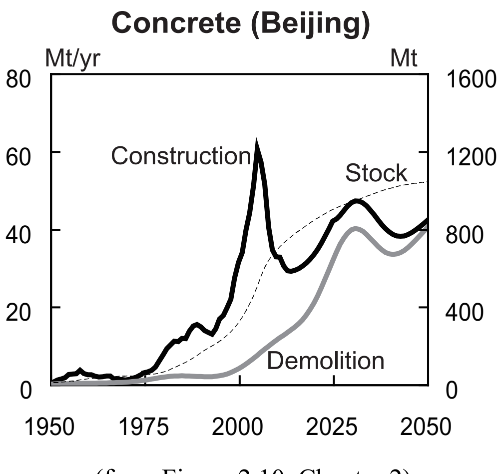
The present study has added to the currently available approaches by including general socio-economic and specific urbanization-driven factors in China. The study involved three consecutive stages, embodied in three case studies (Case I ~ Case III in Chapters 2 ~ 4) on Chinese housing stocks, each published as a separate paper. In addition, Chapter 1 presents a general introduction, and Chapter 5 provides a discussion, conclusions and recommendations on using the dynamic MFA approach to support sustainable development of the built environment.

- Case I (Chapter 2) examines the long-term impacts of Beijing's economic growth on its demand for construction materials and on demolition waste generation, using a stock dynamics model.
- Case II (Chapter 3) investigates the long-term impacts of China's urbanization on its urban and rural floor area demand for housing, using a two-sub-systems model of floor area dynamics.
- Case III (Chapter 4) investigates the long-term dynamics of the iron and steel used in China's residential buildings, in view of the ongoing urbanization, using an extension of the two-sub-systems model to the level of materials.

Case studies

The models we developed were used to answer four research questions, viz. 'What are the *Trends for inflow*?'*;* 'What are the *Trends for outflow*?', 'What are the *Environmental impacts*?' and 'What are the *Implications for industry*?'; all of which relate to the future development of Chinese housing stocks.

Case I: Dynamic material flow analysis for strategic construction and demolition waste management in Beijing

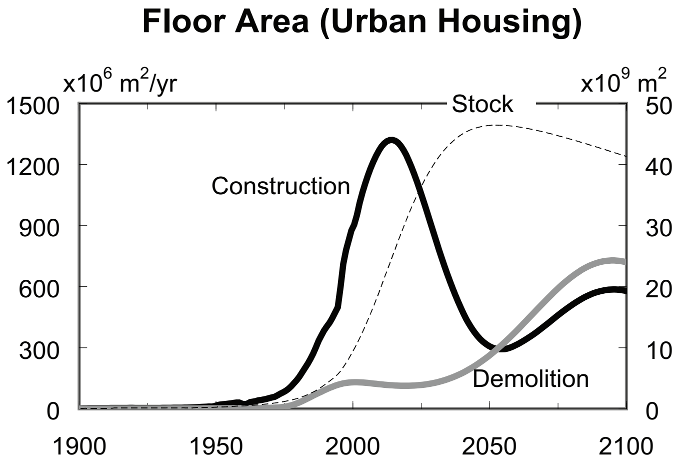


(from Figure 2.10, Chapter 2)

This study developed a per capita GDP driven dynamic MFA model to examine the concrete diffusion in Beijing's urban housing system. It first identifies a strong correlation between per capita floor area and local per capita GDP, through international comparison. Based on the historical correlation, the model can then assess the effect of GDP growth on future housing stock changes. This study focused on understanding '*Trends for outflow*', as its purpose was to support CDW management. The outcome of the model suggests that the amounts of concrete released by residential demolition in Beijing will rise dramatically over the next 50 years. It also indicates that the volume of CDW generated in the near future depends very much on the lifetime of the buildings; a high growth of per capita floor area resulting from continuing GDP increases will raise the volume of CDW, especially in the long run. A strategy to reduce demolition waste should therefore concentrate its efforts on extending the service lifetime of the buildings. This could be achieved by renovation activities and high building quality standards for new construction. However, all the scenario calculations imply that the rise in the volume of CDW generated is unavoidable. A long-term strategy should therefore emphasize recycling to limit the pressure on landfills in the future and reduce the demand for primary materials.

Case II: Dynamics of urban and rural housing stocks in China

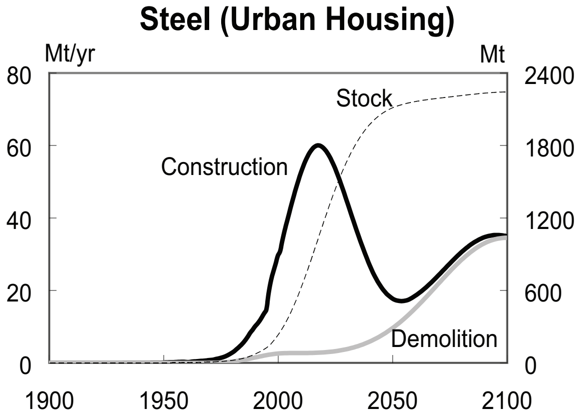
This study developed a two-sub-systems dynamic MFA model including the driving force of urbanization, for the investigation of floor area dynamics in the entire Chinese urban and rural housing stocks. It uses the urbanization rate, dividing the population of China into rural and urban, to derive the housing floor area stocks in the two systems. This study focused on understanding '*Trends for inflow*'. The modeling results indicate a substantial oscillation in the demand for new urban housing construction in the coming decades. This study offers an early warning for the changing trends in China's demand for housing construction. Even in view of the ongoing urbanization, China's present high level of urban housing construction will not continue. The turning point of the trend may well be right now or in the near future. The sensitivity analysis shows that the oscillation phenomenon in new construction is mainly dependent on the lifespan of the buildings. Only the extremely short lifetime scenario (less than 30 years) results in a



(from Figure 3.4, Chapter 3)

very limited oscillation in the simulation result. A better understanding of the lifespan of buildings is essential for anticipating future housing stock dynamics.

Case III: Iron and steel in Chinese residential buildings: a dynamic analysis



(from Figure 4.4, Chapter 4)

This study extended the two-sub-systems dynamic MFA model of floor area developed in the study on Chinese urban and rural housing stock dynamics, to analyze changes in the amounts of iron and steel used in Chinese residential stocks. To this end, it investigated the historical evolution and potential future developments in steel intensity in Chinese residential construction. The study focused on understanding '*Environmental impacts*' and '*Implications for industry*'. The results obtained with the model indicate that the oscillation phenomenon identified at the housing production level also occurs at the materials level, as regards the demand for residential iron and steel. The longer the lifespan of buildings and the lower the floor area stock, the stronger the proportional oscillation will be. In contrast to most projections, this study indicates that the coming decades will see a significant reduction in steel demand from China's residential sector, which currently accounts for 20% of the country's steel consumption. The use of dynamic MFA makes it possible to include stock ageing, which is not included in more trend-oriented forecasts. This is of primary importance. The expected reduction in steel demand has obvious benefits both from an environmental point of view and from a resource conservation point of view. In the long run, the longer the lifespan of the buildings, the lower the CO_2 emissions from construction activities, and the lower the use of potentially scarce resources. However, if the current Chinese steel production were to continue, the reduction of residential steel demand in China implies that a serious overcapacity would develop in the Chinese steel industry. Given its substantial size, this is likely to exert a substantial impact on the global markets involved.

Main conclusions

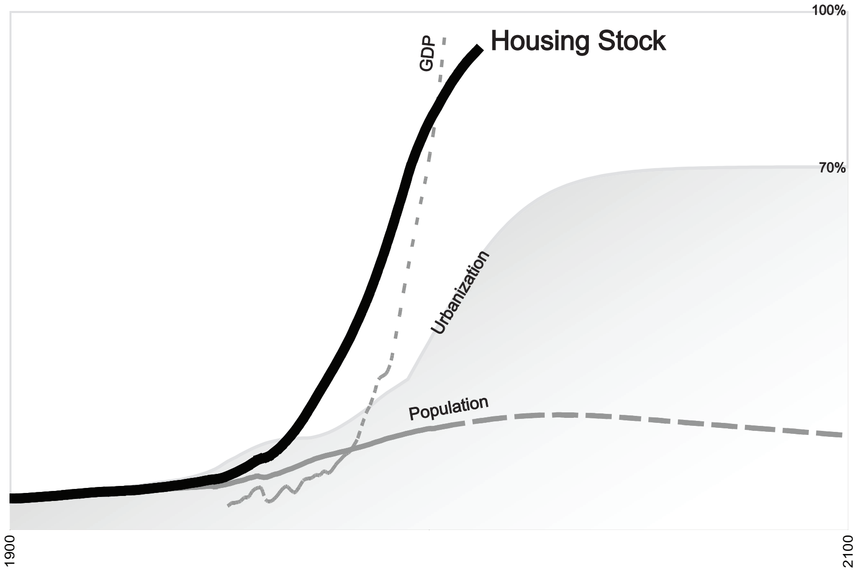
1. Stock dynamics models are suitable for investigating the long-term metabolism of the built environment stocks; this is also true for a rapidly developing economy in the process of ongoing urbanization.
2. The lifespan of buildings, which determines the patterns of future construction and demolition demand, is the most crucial factor in forecasting the long-term dynamics of the housing stock metabolism.
3. Demolition activity in China will inevitably rise in the course of the 21^{st} century. In terms of reducing environmental impacts, we conclude that in the near future, the shorter the lifespan of buildings, the more critical recycling secondary materials from CDW will be.
4. A shrinking demand for new residential construction may be expected over the next few decades. If the current level of steel production continues, a severe overcapacity in Chinese steel industry may be foreseen. The effect on the global market will be substantial: a decrease in global steel consumption of up to 10%.

Recommendations for further research

Some interesting subjects for the future development and use of dynamic material flow analysis to support sustainable construction strategies are:

- understanding the factors that determine the lifespan of buildings;
- combining dynamic MFA models with economic models;
- analyzing the dynamics of other built environment subsystems (e.g. non-residential buildings and urban infrastructures);
- using dynamic MFA in combination with LCA;
- translating the systems knowledge obtained by dynamic MFA into practical action knowledge that can be used by the construction professions.

Chapter 1   Introduction



1.1 Sustainability challenges in built environment development

The notion of 'built environment' is relatively recent[1]. In common use, the built environment refers to the:

> man-made surroundings that provide the setting for human activity, ranging in scale from personal shelter to neighborhoods to the large-scale civic surroundings[2].

It is generally accepted that the built environment is a key factor in the move towards a more sustainable future (Jones et al. 2007). Buildings and transport infrastructures have enabled mankind to thrive in numbers and to a standard not possible in less organized communities. However growing populations and the extravagant lifestyles of the most successful people threaten the natural resources of the earth (Carpenter 2001). For example, the building related activities, constituting approximately 44% of the total material use and 30 – 40% of the society's total energy demand, as well as roughly 1/3 of the total CO_2 emission (Erlandsson and Borg 2003; Li 2006).

Many of the sustainability challenges are related to the extensive mobilization of materials caused by built environment development. People's will to urbanize and to enlarge the built environment drives the major flux of solid materials in the world (Baccini and Brunner 1991) and leads to one of the greatest transformations of the landscape on the Earth (Douglas and Lawson 2002; Moffatt and Kohler 2008), by depositing in urban areas the large stocks of materials brought from other places. On one side, raw materials are extracted from lithosphere to build up the built environment, which leaves huge pits and waste heaps on the mining sites, leads to resource depletion and causes emission problems due to extensive energy consumption in metals (e.g. iron and steel) and cement production. For instance, in

[1] In common use in the literature since the mid-1970s. The origin is clearly in anthropological and behavioral studies concerning the influence of form and space on the individual and social behavior (Rapoport 1976). The concept has evolved in anthropology and in more recent research the built environment is understood as the result of a process of social construction (Lawrence and Low 1990, p. 455).

[2] A quotation from Wikipedia (January 2010), as one typical example of conventional usage of the term 'the built environment'.

the year of 2000 about 45% of global iron entering use is devoted to construction (Wang et al. 2007), for the last 25 years of the 20th century, the structural steelwork and build/civil engineering have been consistently the largest application for iron and steel in an already well developed country like the UK (Davis et al. 2007) and steel has been identified as having globally the highest environmental impact of all mined metals (Staal 2009). On the other side, the maintenance, refurbishment of the existing built environment stock and the replacement of the obsolete part of it generate a big amount of construction and demolition waste (CDW) which leads to waste management pressure. CDW is by far the largest solid waste fraction (Kourmpanis et al. 2008; Wang et al. 2004), accounting for at least 50% of total generated solid waste in industrialized countries (Schachermayer et al. 2000). Sustainably managing CDW – the quantitatively vast solid waste fraction is considered a priority in waste management in densely populated countries, because of the shortage of landfill capacities for final disposal (Duran et al. 2006).

Some other sustainable challenges are related to the use of the built environment stock. For instance, the energy used to heat, cool, ventilate and light buildings represents over 30% of Canada's national energy use (Cole and Kernan 1996). In China, building operation energy is estimated to account for 17 – 27% of China's total energy use (Yang and Kohler 2008; Yao 2005). It is widely recognized considerable energy savings can be achieved by upgrading the existing building stock but currently there is little incentive to do so in the UK (Jones et al. 2007), and it has been found in Germany that the issues of energy upgrading are not crucial for maintaining or demolishing decisions (Kohler 2006). European Union (2002) points out that if the built environment is to be made more sustainable and if targeted carbon dioxide reductions in the medium term of two decades are to be realized, the problem of how to improve the existing built environment must be addressed.

Furthermore, sustainability challenges in built environment development are not globally balanced and the emerging/developing countries deserve special attention. According to United Nation studies, the world population is expected to surpass 9 billion by 2050 (UNPD 2009) and the urban areas of developing countries are projected to absorb all the additional 2.3 billion population up from now (UNPD 2007). Consequently, the demand for expansion of the built environment will be mainly from the rapidly urbanizing developing areas for the next few decades.

Historical figures show that in emerging countries, the rapid industrialization and population migration of the last 30 years have led to fast growing urbanization and doubling the building and partially the infrastructure stocks in 20 – 30 years (Yang 2006; Yang and Kohler 2008). China has the largest building stock in the world, the amount of which has been growing unprecedentedly through last three decades (Kohler and Yang 2007; Yang and Kohler 2008). Should it continue, Kohler and Yang state that, a shortage of available building materials, and at the same time a continuously high level of resulting environmental impacts might be expected.

Taking into account the depleting scarce resources on our planet, the alarming global warming problem, the limited local dumping capacities and the ongoing urbanization in developing regions, considering the significant resource extraction, high life cycle energy consumption and enormous solid waste generation of the built structures, it is crucial to orient the development of built environment in the 21st century to a more sustainable direction.

1.2 The need for a long-term systems perspective of sustainable built environment development

Yet, the concept of 'sustainable built environment development' is developing. Twenty years ago, the influential Brundtland Report (WCED 1987) envisaged 'sustainable development' as a means by which the global system would satisfy:

> the needs of the present without compromising the ability of future generations to meet their own needs (WCED 1987, pp.43).

This concept is certainly an objective in global terms and involves a strong element of intergenerational ethics (Doughty and Hammond 2004). Efforts to translate the sustainability concept into practical measurement led to conceiving sustainable development as: balancing economic and social development with environmental protection (the "people, planet, prosperity", or the so-called 'triple bottom line' (Hammond 2000; Parkin 2000)). Based on this understanding, sustainability can then be measured, by embodying indicators of economic, social and environmental concerns (e.g. Global Reporting Initiative 1999). Although how the indicators should be selected or valued may involve lots of debate, the understanding that the three critical dimensions (economic, social and environmental) should be concerned in sustainable development is so far widely accepted. Recently there is an emerging body of literature on sustainability of the built environment, or the construction sector. The late David Pearce (Pearce 2003; Pearce et al. 2006; Pearce 2006, pp. 202) suggested defining sustainability as rising per capita well-being. The capability of an individual to generate its well-being can be observed by wealth – the sum of available man-made, human, natural and social capitals. Built environment stocks are the dominant part of man-made capital. In the light of these definitions, "the contribution of the construction industry to sustainable development can be gauged by assessing its role in contributing to the capital stocks" (Pearce 2003, pp. x). This proposal has been considered by many other researchers (e.g. Kohler 2006; Atkinson 2008; Brattebø et al. 2009) can be useful to assess the sustainability of the construction sector or activities affecting the built environment because it may allow for an integrated perspective. However, Moffatt and Kohler (2008) argue that in complex situations like building and urban design, there is no simple optimum. Also, how to substitute the losses from one capital stock (e.g. resource depletion in lithosphere) with the gains in another capital stock (e.g. enlarged city and better educated farmer-construction worker) is very debatable, as there is not one single method to justify the value of different capitals, and not even one for a specific capital good. Theory-searching for sustainable built environment development has just started[3]. Concepts and goals are not yet well defined. Nevertheless, the precious searches on defining sustainable built environment development give the direction to look into, which has at least two implications.

First of all, there is a need for a broad systems perspective. This is because based on all proposed sustainability definitions, (a) understanding sustainability needs a global perspective, (b) analyzing sustainability needs a multi-dimension perspective to embrace concerns of environmental, economic and social dimensions, (c) assessing options for sustainable built environment development needs an integrated

[3] Theory-building in built environment tends to be fragmented, under-resourced and explored from the limited perspectives of individual disciplines or interest groups within the construction/property industry (Koskela 2008). With a Symposium in June 2007 in Salford, UK (Koskela and Roberts 2007) and a special issue of the journal Building Research & Information (Koskela 2008), recently, an interdisciplinary discussion on theory of the built environment has been opened. It recognizes the many dimensions embraced by the built environment and used for understanding it: as an artifact, as a process and as an ecosystem, but seeks a more holistic approach.

perspective to allow effects on all man-made, natural, human and cultural capitals be counted; based on the character of built environment, (d) only in a broader 'systems' perspective, dynamic relationships existing between a greater number of built elements can be examined. And the trade-offs can be explored between, for example, building design and infrastructure requirements, or urban form and resource efficiency (Moffatt and Kohler 2008).

Secondly, there is a need for a long-term perspective. This is because (a) based on the ever proposed sustainability definitions, understanding sustainability needs an intergeneration long-term view, for instance, Parkin (2000) suggests 2050 – 2100 or beyond, and (b) based on the character of built environment elements, Brattebø and colleagues (2009) point out that due to the long service life of built structures and their significant mobilization of physical land monetary flows – such as materials, energy, land use, emissions, wastes and costs – a systems approach to the built environment must apply wider borders not only in space but also in time. Only from a long-term perspective, the dynamics of the built environment stocks in service can be examined, and based on it the overall sustainability of a built environment development, including construction, renovation and demolition will be allowed for analysis.

In order to gain a broad systems and long-term perspective of sustainable built environment development, pioneering attempts show that, the 'metabolism' of built environment stocks should be first understood.

1.3 Metabolism metaphor as a basis for a long-term systems perspective of sustainable built environment development

The term 'metabolism' was introduced as early as 1815 to refer primarily to material exchanges within the human body, related to respiration and digestion (Fischer-Kowalski 2002). Metabolism was first applied to society by Marx and Engels:

> Labor is, first of all, a process between man and nature, a process by which man, through his own actions, mediates, regulates and controls the metabolism between himself and nature. (Marx 1976[1867], pp. 283)

The notion of metabolism was expanded from a biological concept to include energy flows and material flows in society, as well as across nature and society. As acknowledged by many researchers (e.g. Jelinski et al. 1992; Erkman 1997; Graedel and Allenby 2003) that metabolic metaphor is the most essential concept, on which the new, sustainability oriented field – industrial ecology is based. Industrial ecology emerges at a time when it is becoming increasingly clear that the traditional de-pollution approach (end-of-pipe) is insufficient (Erkman 1997). The notion of industrial ecology is to tackle the environmental problems based on a systems analysis of (parts of) the technosphere, the *physical link* between economy and environment, in order to avoid sub-optimization and problem shifting. The core concept enabling such systems analysis is *industrial metabolism*. Defined by Ayres (1989), the concept industrial metabolism argues the analogy between the economy and environment on a material level: the economy's 'metabolism' in terms mobilization, use and excretion of materials and energy to create 'technomass' is compared to the use of materials in the biosphere to create biomass. This concept has enlightened the economy-environment relationship and been fruitfully applied in many studies. One of the first applications was identified as supporting a regional material management (Baccini and Brunner 1991; Brunner and Baccini 1992; Baccini 1996, 1997). The authors called this the *metabolism of the anthroposphere*.

With much of the world's population moving to urban areas, interest in sustainable cities is entering the industrial ecology sphere (Brattebø et al. 2005). Since the late 1960s and early 1970s, with the environmental movement and the first oil crisis, industrial ecology and its application to *urban metabolism* (Wolman 1965; Duvigneaud and Denaeyer-De Smet 1977; Baccini and Brunner 1991) are followed by the establishment of a new field of research into urban ecology (Moffatt and Kohler 2008). Fischer-Kowalski and Weisz (1999) propose the concepts *socio-economic metabolism* and the colonization of natural processes, to synthesize a transdisciplinary framework that facilitates a unified built environment theory. In their proposal, metabolism refers to the balanced flows of energy and materials between the human and natural subsystems of the material realm. Colonization describes "the intended and sustained transformation of natural processes by means of organized social interventions for the purpose of improving their utility for society" (Weisz et al. 2001, pp. 124). Moffatt and Kohler (2008) acknowledge the socio-economic metabolism as a central concept to understand the relation between the built environment and the ecosystem upon a broader systems perspective. They point out that 'metabolic profile' developed for built environment on scales of global, a country, a region, a town, and for flows of energy, aggregates, water, people, organic matter, information, or money can reveal (1) the 'ecological efficiency' for the built environment as a system, (2) the extent of interdependencies within this system, and (3) by creating a time-series material flow analysis, can help to identify trends in resource use. For example, there may be a tendency in advanced economies for dematerialization of certain processes over time, and the replacement of mass flows by information flows (Kohler 1998).

Although emphases of observation vary from production-focused *industrial metabolism*, human-activity-focused *metabolism of the anthroposphere*, city-focused *urban metabolism* to culture-processes-involved *socio-economic* metabolism, the core is the same. That is, using metabolism metaphor to obtain a broad systems, long-term comprehension and physical understanding of the processes occurring in our societies. In the light of metabolism metaphor, the physical links between the socio-economic, the built environment and the ecologic systems might be constructed and the changes of their interactions over time might be understood. Thus, further debate on sustainable built environment development can be based on the analysis of the long-term metabolism of the built environment from a broad systems perspective.

1.4 Material flow analysis as a tool to analyze metabolism of the built environment

Application of the metabolic viewpoint involves detailed accounting of the flows of materials and energy through society (Ausubel et al. 1989). The analytical tool employed for calculating and displaying a balanced set of flows through the built environment is called MFA (Material/Mass Flow Accounting/Analysis) in general, which refers to the analysis of the throughput of materials of a region, based on accounts in physical units (Bringezu and Moriguchi 2002). The subjects of the accounting can be either *bulk flows of specific materials*, e.g. concrete in Kelly

(1998), sand and gravel in Bergstedt and Linder (1999), window frame materials in Kandelaars and van den Bergh (1997), *mass flows through an economic system* (e.g. Adriaanse et al. 1997; Mathews et al. 2000) or *chemically defined substances* (e.g. Van der Voet et al. 1994). In some context, the analysis of flows at the substance level is defined as SFA (Substance Flow Analysis) (Van der Voet 1996), while MFA refers to only mass and bulk flow studies[4], in a narrow sense. SFA and MFA may differ in the applications[5], but the methodology is similar. For all materials flow studies, the *materials balance* principle derived from Lavoisier's *Law of Mass Preservation* is the common basis (Van der Voet 1996). The general framework for conducting the analysis comprises the three-step procedure: (i) definition of the system, (ii) quantification of the overview of stocks and flows, and (iii) interpretation of the results (Van der Voet 2002). *Definition* step defines the system with regard to the space, function, time and materials. *Quantification* step involves identifying and collecting the relevant data on the one hand, and modeling the system by either (a) bookkeeping, (b) static modeling or (c) dynamic modeling, on the other hand. *Interpretation* step includes evaluating the robustness of the overview quantification, and translating the overview into policy-relevant terms (Van der Voet et al. 1999, 2000). *Dynamic MFA/SFA* refers to the analysis based on dynamic modeling for *Quantification*.

The method of MFA/SFA was for the first time applied to study the metabolism or physiology of cities by Wolman (1965), followed by Newcombe and colleagues (1978)[6]. It then has been applied in developed countries to understand densely populated regions (Brunner and Baccini 1992), to trace pollutants through watersheds or urban regions (Bergbäck et al. 1994; Van der Voet et al. 1994; Kleijn et al. 1994), and in developing countries to understand the environmental impact of human activities (Binder 1996), to support water resource management (Binder et al. 1997) and planning (Erkman and Ramaswamy 2003). These studies have determined

---

[4] MFA studies on bulk and mass flow are also referred to as "bulk-MFA" (Kleijn 2001) or at a national level as "economy-wide MFA" (Eurostat 2001).

[5] SFA studies can be related to specific environmental problems and thus provide input for a pollutants policy (Van der voet 2002), while MFA studies provide macroeconomic indicators (Adriaanse et al. 1997).

[6] For a review on MFA history see Brunner and Rechberger (2004), Fischer-Kowalski (1998), Fischer-Kowalski and Hüttler (1999).

anthropogenic contribution to various natural resources and pollutants, which are all useful for sustainable built environment development. They, however, provide only a static snapshot, either over a one-year time period or averaged over a few years and do not depict the temporal dynamics of stocks and flows in the built environment development. Previous researches show that MFA is useful to investigate optimizing opportunities of sustainable built environment practices from a static systems perspective, while dynamic MFA is essential to capture the optimizing opportunities along temporal dimension, from a long-term perspective.

1.5 Dynamic material flow analysis as a tool to analyze long-term metabolism of the built environment

Stocks of goods with a long residence time in society cause a disconnection between the inflows and outflows through the economic subsystem. For all countries analyzed so far, MFA studies show the mass balance for modern economies is characterized by the accumulation of large physical stocks of man-made assets: buildings and transport infrastructures (e.g. Bringezu and Schutz 1997; Kelly 1998; Bergstedt and Linder 1999; Brunner 1999, 2004; Smith et al. 2003; Hashimoto et al. 2007). As buildings and infrastructures last for decades, if not centuries and, in rare cases, millennia (Douglas and Lawson 2002), their long residence time causes a disconnection between the inflow of new construction and the outflow of demolition of obsolete part, and forms the built environment stock. During the last two centuries, human efforts, organization and technical achievements have changed many people’s lifestyles and largely expanded the built environment stock. Most of the structures especially infrastructures now standing have been built within the last 100 years (Carpenter 2001). Similar to ecological resources (natural capital), this built environment capital (stock) is becoming difficult or impossible to replace a big share in a few decades (Moffatt and Kohler 2008). The use of dynamic models helps to evaluate the accumulation of the stock of materials, either in use or deposited in waste repositories in asthroposphere (Kapur et al. 2008). An understanding of both the current material stocks and flows and their dynamics is necessary for a well-founded planning of future waste flows (Wittmer and Lichtensteiger 2007). In order to support strategy development in sustainable built environment, a long-term perspective is required and dynamic material flow analysis is needed.

Dynamic MFA/SFA differs from static analysis on that it includes the investigation for stocks in society (Elshkaki 2007) and so is possible to explore future flows of emissions and wastes, based on past and future inflows and stock characteristics (Kleijn et al. 2000). There are basically two types of techniques in modeling dynamics of stocks and flows. One is *flow dynamics* driving, as applied in Zeltner and colleagues (1999), Kleijn and colleagues (2000), Kohler and Hassler (2002), van der Voet and colleagues (2002), Elshkaki and colleagues (2004, 2005), Bergsdal and colleagues (2007b), Bohne and colleagues (2007), Bradley and Kohler (2007) and Hashimoto and colleagues (2007). It assumes that the material stock is driven by its inflow and outflow. The future inflow is either assumed (Kleijn et al. 2000) or estimated based on socio-economic variables using different techniques, such as intensity of use (Tilton 1990), demand function (Fisher et al. 1972), production function (Kopp and Smith 1980), Input Output Analysis (IAO) (Leontief et al. 1983; Myers 1986) and regression analysis (Elshkaki et al. 2004). While the outflow is determined either by a leaching or delay process (van der Voet et al. 2002). The other type of modeling approaches is *stock dynamics* driving, as applied in Binder and colleagues (2001), Johnstone (2001a, b), Müller (2004, 2006), Yang (2006), Bergsdal and colleagues (2007a), Sartori and colleagues (2008) and Yang and Kohler (2008). It assumes that the stock of service units is the driver for the material flows. The stock can be estimated by an assigned ‘development pattern’ (Binder et al. 2001), ‘stock expansion rate’ (Johnstone 2001a, b) or can be defined as a function of population and its lifestyle (Müller 2006; Yang 2006; Yang and Kohler 2008). The outflow of materials, coupled with the obsolete service units is determined by delay process, while the inflow of materials, coupled with the new add-in service units is introduced to maintain the development pattern of stock in use. The question as to whether flow dynamics driving or stock dynamics driving should be used depends on whether the focus of the question is short- or long-term (Müller 2006). For long residence-time goods, stock dynamics approach, using stock in service instead of production (inflow) to stimulate the system evolution, reflects better the understanding that consumption behavior of people is “stock oriented” (Binder et al. 2001).

The stock dynamics driving dynamic MFA has been first applied for examining the metabolic consequences of housing by Müller (2006). This study analyzes and projects the diffusion of concrete in the Dutch dwelling stock for a two centuries' period of 1900 – 2100, through estimations of the population, its lifestyle, material intensity and service lifetime of dwellings. This approach was then applied by Bergsdal and colleagues (2007a) for analyzing the dynamics of concrete and wood in the Norwegian dwelling stock for the same two centuries' time and followed by Sartori and colleagues (2008) for projecting the future activity levels of construction, renovation and demolition in the Norwegian residential sector. Results of these studies support the hypothesis that service stocks in use play a prominent role in understanding long-term changes of societal metabolism. The limit of this stock dynamics driving dynamic MFA model is that it analyzes only one subsystem – housing stock of the built environment stock. However, this narrowed boundary allows this model investigate more deeply the causal relations between material consequences of housing development, people's demand for housing service, and industries' improvement potential. The limited number of variables involved in the model is also a big merit for sensitivity analysis to test the robustness of the results. Theoretically, this model should have strength on capturing the long-term trends of housing demand for recently expanding stock. However their approach has never been applied to any newly emerging country. And it is also a new topic for this approach to include the urbanization effects in the analysis. In the following chapters of this thesis, this approach has then been adapted and further developed for investigating the long-term stock dynamics and material consequences of the housing systems in the fast developing and urbanizing country – China.

1.6 Research questions

This PhD work aims to contribute to systems analysis of sustainable built environment development in an expanding economy. The hypotheses underlying the study are:

(1) the metabolism metaphor is a useful one for assessing the options of sustainable building and construction;

(2) the dynamic material flow analysis is essential for understanding the long-term metabolism of the built environment stocks;

(3) the stock dynamics driving dynamic MFA approach is suitable for examining the long-term metabolic consequences of built environment development in rapidly urbanizing developing regions.

Based on the hypotheses, three dynamic MFA models for Chinese housing stocks are constructed. In response to the sustainability challenges, especially those related to material mobilization of the built environment development, four main research questions are investigated in the thesis:

Q1. Trends for inflow
How will the demand for housing floor area and related construction materials in China develop over the next decades, in view of the ongoing income rise and urbanization? Is it probable that the present steep increase in demand continues?

Q2. Trends for outflow
Will there be problems in China related to the generation and handling of construction and demolition waste? If there are problems in the supply of (specific) construction materials in China, can we expect recycling to help prevent supply problems from arising to a substantial degree?

Q3. Environmental impacts
What will be environmental impacts, especially related to energy use and greenhouse gas emissions for the production of construction materials? What is the influence of recycling on these environmental problems?

Q4. Implications for industry
What is the influence of the development in the demand and supply of construction materials on the stability of the material supply and construction sectors in China?

Facilitated by the dynamic MFA models, these questions are examined during the case studies (Case I ~ Case III) and addressed from Chapter 2 to 4, as indicated in Table 1.1.

Table 1.1 Overview of research questions addressed in each chapter of this thesis

	Research questions			
	Q1	*Q2*	*Q3*	*Q4*
Chapter 2 (Case I)	●	●		
Chapter 3 (Case II)	●	●		●
Chapter 4 (Case III)	●	●	●	●

1.7 Thesis outline

Chapter 2 investigates the construction and demolition waste (CDW) issues of the built environment development, in the context of a fast developing economy, by conducting a dynamic MFA for the future waste concrete generation in Beijing's urban housing sector (Case I). In this study, the effect of economic growth on the demand for housing floor area has been explored by introducing the factor of GDP into the stock dynamics model, and the relationship between the GDP growth and the PCFA (per capita floor area) have been identified by international comparison. Three scenarios, representing the current trend extension, high GDP growth and lengthening lifetime of buildings are analyzed. The results of analysis provide a better understanding of the effectiveness and limitations of the prolonging lifetime strategy and recycling strategy for the CDW management in the built environment development from a long-term perspective.

Chapter 3 explores the impacts of urbanization for the built environment development, by conducting a dynamic MFA for the floor area of the urban and rural residential buildings in China (Case II). In this study a two-sub-systems stock dynamics model is developed from the generic stock dynamics model (Müller 2006). It involves urbanization rate as a driver to project the future demand for new construction and replacement of the urban and rural residential buildings in China. A wide range of possible development paths for population, urbanization, PCFA and dwelling lifetime have been investigated. The results signal out a dramatic change in the future demand for urban residential construction, which has strong implications for the construction industries.

Chapter 4 examines the resources issues in the built environment development, in the course of urbanization, by conducting a dynamic MFA for steel in Chinese residential buildings. The two-sub-systems service stock dynamics model developed in Case II is expanded in this study to investigate the iron and steel demand and scrap availability in both the urban and rural housing stocks in China. By assuming three potential paths of steel use in residential construction, the material consequences of the housing stock dynamics result. In this study, the roles of the urban and rural subsystems in future iron and steel cycle are clarified and the influences of lifetime, material intensity and service stock pattern on future steel demand and scrap supply are identified. Environmental consequences of different development scenarios for no recycling and 100% recycling of scrap are assessed by calculating the accumulated net steel use and the net CO_2 equivalent emission. This study provides highly relevant projections for iron and steel industry and profound information for further sustainability debates like "to what extent can the demand for steel in construction be met by secondary materials, and what are limiting factors?", "what are trade-offs between recycling and durability?", "how can we stabilize markets with the least possible environmental and resource impacts?".

Chapter 5 is dedicated to a general discussion, conclusions and recommendations of aspects related to using dynamic material flow analysis models to support construction strategies.

Reference to Chapter 1

Adriaanse, A. et al. 1997. Resource flows : The material basis of industrial economies. World Resources Instititute, Washington, DC.

Atkinson, G. 2008. Sustainability, the capital approach and the built environment. Building Research & Information 36(3):241 – 247.

Ausubel, J.H. et al. 1989. Technology and environment: an overview. In: Ausubel, J.H. and Sladovich, H.E. (Ed.) 1989. Technology and Environment. Nathional Academy Press, Washington. D.C. pp. 1-20.

Ayres, R.U. 1989. Industrial metabolism. In: Ausubel and Sladovich (eds): Technology and environmental. National Academy Press. Washington DC. pp. 23-49.

Baccini, P. 1996. Understanding regional metabolism for a sustainable development of urban systems. Environmental Science and Pollution Research 3(2): 108 – 111.

Baccini, P. 1997. A city's metabolism: towards the sustainable development of urban systems. Journal of Urban Technology, 4(2): 27 – 39.

Baccini, P. and P.H. Brunner. 1991. Metabolism of the anthroposphere. Springer-Verlag, Berlin Heidelberg.

Bergsdal, H. et al. 2007a. Dynamic material flow analysis for Norway's dwelling stock, Building Research & Information, 35(5): 557 – 570.

Bergsdal, H. et al. 2007b. Projection of construction and demolition waste in Norway, Journal of Industrial Ecology 11(3): 27 – 39.

Binder, C. 1996. The early recognition of environmental impacts of human activities in developing countries. Ph.D. dissertation 11748, Swiss Federal Institute of Technology Zurich, Switzerland.

Binder, C. et al. 1997. Regional water balance as a tool for water management in developing countries. Water Resources Development 13(1): 5 – 20.

Binder, C. et al. 2001. Dynamic models for managing durables using a stratified approach: the case of Tunja, Colombia, Ecological Economics 38: 191 – 207.

Bohne, R.A. et al. 2007. Dynamic eco-efficiency projections for C&D waste recycling strategies at the city level, Journal of Industrial Ecology 11(4).

Bradley, P.E. and N. Kohler. 2007. Methodology for the survival analysis of urban building, Building Research & Information 35(5): 529 – 542

Bringezu, S. and Y. Moriguchi. 2002. Material flow analysis. In: Ayres R.U. and L.W. Ayres (ed.) A Handbook of Industrial Ecology, Edward Elgar Publishing Limited.

Bringezu, S. and H. Schutz, 1997. Material flow accounts. Part II: Construction materials, packaging, indicators. Wuppertal Institute. Wuppertal, Germany.

Brattebø, H., J. Ehrenfeld and K. Røine. 2005. Framing industrial ecology. In: Textbook in Industrial Ecology.

Brattebø, H., H. Bergsdal, N.H. Sandberg, J. Hammervold and D.B. Müller. 2009. Esploring built environment stock metabolism and sustainability by systems analysis approaches. Building Research & Information 37(5-6): 569 – 582.

Brunner, P.H. 1999. In search of the final sink. Environmental Science and Pollution Research 6(1): 1.

Brunner, P.H. 2004. Material flow analysis and the ultimate sink. Journal of Industrial Ecology 8(3): 4 – 7.

Brunner, P.H. and P. Baccini. 1992. Regional material management and environmental protection. Waste Management & Research 10: 203 – 212.

Brunner, P.H. and H. Rechberger 2004. Practical Handbook of Material flow analysis. Lewis, New York.

Carpenter, T.G. 2001. Preface. In Environment, construction and sustainable development. The environmental impact of construction, Vol. 1, edited by T.G. Carpenter, New York: John Wiley & Sons.

Cole, R.J. and P.C. Kernan. 1996. Life-cycle energy use in office buildings. Building and Environment 31(4):307 – 317.

Davis, J. et al. 2007. Time-dependent material flow analysis of iron and steel in the UK, Part 2. Scrap generation and recycling. Resource, Conservation and Recycling 51: 118 – 140.

Doughty, M.R.C. and G.P. Hammond. 2004. Sustainability and the built environment at and beyond the city scale. Building and Environment 39:1223 – 1233.

Douglas, I. and N. Lawson, 2002. Material flows due to mining and urbanization. In: Ayres R.U. and L.W. Ayres (ed.) A Handbook of Industrial Ecology. Edward Elgar Publishing Limited.

Duran, X. et al. 2006. A model for assessing the economic viability of construction and demolition waste recycling – the case of Ireland. Resource, Conservation and Recycling. 46: 302 – 320.

Elshkaki, A., et al. 2004. The environmental and economic consequences of the developments of lead stocks in the Dutch economic system, Resources, Conservation and Recycling 42: 133 – 154.

Elshkaki, A., et al. 2005. Dynamic stock modeling: A method for the identification and estimation of future waste streams and emissions based on past production and product stock characteristics, Energy 30: 1353 – 1363.

Elshkaki, A. 2007. Systems analysis of stock buffering: Development of a dynamic substance flow-stock model for the identification and estimation of future resources, waste streams and emissions. Thesis, Leiden, The Netherlands.

Erkman, S. 1997. Industrial ecology: an historical view. Journal of Cleaner Production 5(1-2): 1 – 10.

Erkman, S. and R. Ramaswamy. 2003. Applied industrial ecology: a new platform for planning sustainable societies. Aicra Publishing, Bangalore, India.

Erlandsson, M. and M. Borg. 2003. Generic LCA-methodology applicable for buildings, constructions and operation services – today practice and development needs. Building and Environment 38:919 – 938.

European Union. 2002. Directive 2002/91/EC of the European Parliament and of the Council on Energy Performance of Buildings. December 2002.

Eurostat. 2001. Economy-wide Material Flow Accounts and Derived Indicators: A Methodological Guide. Eurostat, Luxembourg.

Fischer-Kowalski, M. 1998. Society's metabolism: the intellectual history of material flow analysis, Part I, 1860-1970. Journal of Industrial Ecology 2(1): 61 – 78.

Fischer-Kowalski, M. 2002. Exploring the history of industrial metabolism. In: Ayres R.U. and L.W. Ayres (ed.) A Handbook of Industrial Ecology, Edward Elgar Publishing Limited.

Fischer-Kowalski, M. and W. Hüttler. 1999. Society's metabolism: the intellectual history of material flow analysis, Part II, 1970-1998. Journal of Industrial Ecology 2(4): 107 – 37.

Fischer-Kowalski, M. and H. Weisz. 1999. Society as hybrid between material and symbolic realms: towards a theoretical framework of society-nature interaction. Advances in Human Ecology (8): 215 – 251.

Global Reporting Initiative. 1999. Sustainability Reporting Guidelines, Coalition for Environmentally Responsible Economies, Boston, MA.

Graedel, T.E. and B.R. Allenby. 2003. Industrial Ecology, Second Edition. Englewood Cliffs, N.J: Prentic Hall.

Hammond, G.P. 2000. Energy, environment and sustainable development: a UK perspective. Trans IChemE Part B: Process Safety and Environmental Protection 78:304 – 323.

Hashimoto, S. et al. 2007. Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan. Waste Management 27(12): 1725-1738.

Jelinski, L.W. et al. 1992. Industrial ecology: concepts and approaches. Proc. Natl. Acad. Sci. USA, vol. 89, pp 171-182.

Johnstone, I. 2001a. Energy and mass flows of housing: a model and example. Building & Environment 36(1): 27 – 41.

Johnstone, I. 2001b. Energy and mass flows of housing: estimating mortality. Building & Environment 36(1): 43 – 51.

Jones, P., J. Patterson and S. Lannon. 2007. Modelling the built environment at an urban scale – Energy and health impacts in relation to housing. Landscape and Urban Planning 83:39 – 49.

Kapur, A. et al. 2008. Dynamic modeling of in-use cement stocks in the United States. Journal of Industrial Ecology 12 (4), 539 – 556.

Kandelaars, P. and J. van den Bergh. 1997. Materials-product chain analysis of window frames, Ecological Economics 22: 41 – 61.

Kelly, T. 1998. Crushed cement concrete substitution for construction aggregates: a material flow analysis. US Geological Survey Circular 1177. US Geological Survey, USA.

Kleijn, R., E. van der Voet and H.A. Udo de Haes. 1994. Controlling substance flows: the case of chlorine. Environmental Management (8): 523 – 542.

Kleijn, R., R. Huele and E. van der Voet. 2000. Dynamic substance flow analysis: the delaying mechanism of stocks, with the case of PVC in Sweden. Ecological Economics 32 (2): 241 – 254.

Kleijn, R. 2001. Adding it all up – The sense and non-sense of bulk-MFA. Journal of Industrial Ecology 4(2): 7 – 8.

Kohler, N. 1998. Sustainability of new work practices and building concepts. In: Streitz, N., S. Konomi and H.J. Burkhardt (eds.) Cooperative Buildings – Integrating Information, Organization, and Architecture. Lecture Notes in Computer Science. Springer, Heidelberg, pp. 154 – 162.

Kohler, N. 2006. A European perspective on the Pearce report: policy and research. Building Research &Information 34(3): 287 – 294.

Kohler, N. and U. Hassler. 2002. The building stock as a research object, Building Research & Information 30(4): 226 – 236.

Kohler, N. and W. Yang. 2007. Long-term management of building stocks. Building Research & Information 35(4): 351 – 362.

Koskela, L. and P. Roberts. (eds.) 2007. Towards the foundation of theory for the built environment. International Symposium towards the Formation of Theory for the Built Environment, Digital World Centre, Salford, UK.

Koskela, L. 2008. Is a theory of the built environment needed? Building Research & Information 36(3): 211 – 215.

Kourmpanis, B. et al. 2008. Preliminary study for the management of construction and demolition waste. Waste Management Research 26: 267 – 275.

Lawrence, D.L. and S.M. Low. 1990. The built environment and spatial form. Annual Review of Anthropology 19: 453 – 505.

Li, Z. 2006. A new life cycle impact assessment approach for buildings. Building and Environment 41:1414 – 1422.

Mathews, E. et al. 2000. The Weight of Nations: Material Outflows from Industrial Economies. World Resources Institute (WRI), Washington DC. USA.

Marx, K. 1976(1867). Capital I, New York: Vintage.

Moffatt, S. and N. Kohler. 2008. Conceptualizing the built environment as a social-ecological system. Building Research & Information 36(3): 248 – 268.

Müller, D.B. et al. 2004. Long-term coordination of timber production and consumption using a dynamic material and energy flow analysis, Journal of Industrial Ecology 8(3).

Müller, D.B. 2006. Stock dynamics for forecasting material flows – case study for housing in The Netherlands. Ecological Economics 59: 142 – 156.

Newcombe, K. et al. 1978. The metabolism of a city: the case of Hong Kong. Ambil 7: 3 – 15.

Parkin, S. 2000. Sustainable development: the concept and the practical challenge. Proceedings of the Institution of Civil Engineers, Civil Engineering 138:3 – 8.

Pearce, D.W. 2003. The social and economic value of construction: The construction industry's contribution to sustainable development. nCRISP, London.

Pearce, D.W. 2006. Is the construction sector sustainable?: definitions and reflections. Building Research & Information 34(3): 201 – 207.

Pearce, D.W., G. Atkinson and S. Mourato. 2006. Cost-Benefit Analysis and the Environment: Recent Developments, OECD publication, Paris.

Rapoport, A. (ed.) 1976. The Mutual Interaction of People and Their Built Environment: a Cross-cultural Perspective, Aldine, Chicago, pp. 7 – 35.

Sartori, I. et al. 2008. Towards modeling of construction, renovation and demolition activities: Norway's dwelling stock, 1900 – 2100, Building Research & Information 36(5): 412 – 425.

Schachermayer, E. et al. 2000. Assessment of two different separation techniques for building wastes. Waste Management & Research 18: 16 – 24.

Staal, Y. 2009. Prioritisation of metals regarding their environmental impact. Master thesis, Leiden university, Leiden, The Netherlands.

United Nations Population Division (UNPD). 2007. World urbanization prospects: the 2005 revision. United Nations, available on http://www.un.org/esa/population/publications/WUP2005/2005WUPHighlights_Exec_Sum.pdf, retrieved on: 2009-10-16.

UNPD. 2009. World population prospects: the 2008 revision. United Nations, available on http://esa.un.org/unpd/wpp2008/pdf/WPP2008_Executive-Summary_Edited_6-Oct-2009.pdf, retrieved on: 2009-10-16.

Van der Voet, E. et al. 1994. Cadmium in the European Community – a policy oriented analysis. Waste Management & Research 12: 507 – 526.

Van der Voet, E. 1996. Substance from cradle to grave: development of a methodology for the analysis of substance flows through the economy and the environment of a region. Ph.D. Thesis, Leiden, The Netherlands.

Van der Voet, E. et al., 1999. Using SFA indicators to support environmental policy. Environmental Science and Pollution Research, 6(1), 49 – 53.

Van der Voet, E. et al. (eds.), 2000. Heavy metals: a problem solved? Methods and models to evaluate policy strategies for heavy metals. Kluwer Academic Press, series Environment & Policy.

Van der Voet, E. 2002. Substance flow analysis methodology. In: Ayres R.U. and L.W. Ayres (ed.) A Handbook of Industrial Ecology. Edward Elgar Publishing Limited.

Van der Voet, E. et al. 2002. Predicting future emissions based on characteristics of stocks. Ecological Economics 41:223 – 234.

Wang, J.Y. et al., 2004. A systems analysis tool for construction and demolition wastes management. Waste Management 24: 989 – 997.

Wang, T. et al. 2007. Forging the anthropogenic iron cycle. Environmental Science & Technology 41(14): 5120 – 5129.

Weisz, H., M. Fischer-Kowalski, C.M. Grünbühel, H. Haberl, F. Krausmann, V. Winiwarter. 2001. Global environmental change and historical transitions. Innovation 14(2): 117 – 142.

Wittmer, D. and T. Lichtensteiger. 2007. Exploration of urban deposits: long-term prospects for resource and waste management. Waste Management & Research 25: 220 – 226.

Wolman, A. 1965. The metabolism of cities. Scientific American, 213 – 179.

World Commission on Environment and Development (WCED). 1987. Our common future. Oxford: Oxford University Press.

Yang, W. 2006. Modeling the Evolution of the Chinese Building Stock in a Sustainable Perspective, PhD Thesis, Tianjin University, Tianjin, China (in Chinese).

Yang, W. and N. Kohler. 2008. Simulation of the evolution of the Chinese building and infrastructure stock, Building Research & Information 36(1): 1-19.

Yao, R., B. Li and K. Steemers. 2005. Energy policy and standard for built environment in China. Renewable Energy 30:1973 – 1988.

Zeltner, C. et al. 1999. Sustainable metal management exemplified by copper in the USA, Regional Environmental Change 1 (1): 31 – 46.

Chapter 2 Case I: Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing*

Abstract

Of all materials extracted from the earth's crust, the construction sector uses 50%, producing huge amounts of Construction and Demolition Waste (CDW). In Beijing, presently 35 Mt/yr of CDW is generated. This amount is expected to grow significantly when the first round of mass buildings erected in the 1990s will start to be demolished. In this study, a dynamic Material Flow Analysis (MFA) is conducted for Beijing's urban housing system, taking the demand for the stock of housing floor area as the driver. The subsequent effects on construction and demolition flows of housing floor area and the concurrent consumption and waste streams of concrete are investigated for Beijing from 1949 and projected through 2050. The per capita floor area (PCFA) is a key factor shaping the material stock of housing. Observations in Beijing, the Netherlands and Norway indicate PCFA has a strong correlation with the local GDP. The lifetime of dwellings is one of the most important variables influencing future CDW generation. Three scenarios, representing the current trend extension, high GDP growth and lengthening lifetime are analyzed. The simulation results show CDW will rise, unavoidably. A higher growth rate of GDP and the consequent PCFA will worsen the situation in the distant future. Prolonging the lifetime of dwellings can postpone the arrival of the peak of CDW. From a systematic view, recycling is highly recommended for long-term sustainable CDW management.

Keywords: dynamic modeling, waste projection, per capita floor area, GDP, concrete, dwelling.

---

* Reprinted from "Hu, M., E. van der Voet and G. Huppes. 2010. Dynamic material flow analysis for strategic construction and demolition waste management in Beijing. Journal of Industrial Ecology 14(3)". This is the author's version of the work. It is posted here by permission of Journal of Industrial Ecology for personal use, not for redistribution. The definitive version was published in Journal of Industrial Ecology, Volume 14 Issue 3, May 2010. doi: 10.1111/j.1530-9290.2010.00245.x

2.1 Introduction

The solid waste generated by the construction sector is called Construction and Demolition waste (CDW). In Beijing, three types of CDW are distinguished and monitored: excavated soil, demolition waste and furnishing waste (Chen 2004). Together, these three form a waste stream even larger than Municipal Solid Waste. Records of the Beijing Solid Waste Administration Department (BSWAD; see Table 2.1) show that the total CDW has almost doubled from 1998 to 2004, while the demolition waste has more than tripled to reach 2.8 Mt/yr in 2004 (BSWAD 2007). Previous studies in several industrialized countries and regions indicate that the magnitude of CDW may increase even more substantially in the next few decades, as the result of the combination of socio-economic, demographic changes, and an ageing building stock (Fatta et al. 2003; Poon et al. 2004a,b; Müller 2006; Bergsdal et al. 2007a,b).

Table 2.1 Annual construction and demolition waste (CDW) generation in Beijing in 1998 - 2004

Year	***Total CDW***	***Excavated Soil***		***Demolition Waste***		***Furnishing Waste***	
		Quantity	***%***	***Quantity***	***%***	***Quantity***	***%***
1998	18.0	16.7	92.5%	0.85	4.7%	0.50	2.7%
1999	23.7	22.0	92.9%	1.06	4.5%	0.60	2.5%
2000	27.6	25.5	92.1%	1.45	5.2%	0.72	2.6%
2001	29.9	27.1	92.8%	1.87	6.3%	0.85	2.8%
2002	32.0	28.6	89.4%	2.36	7.4%	1.04	3.3%
2003	33.4	29.7	88.8%	2.58	7.7%	1.15	3.4%
2004	35.0	30.9	88.1%	2.80	8.0%	1.35	3.9%

Note: CDW is reported in million metric tons per year (Mt/yr). *Source*: BSWAD (2007).

Demolition concrete, the fastest growing CDW flow in Beijing, is investigated in this study for Beijing's urban housing sector, with implications for the future total CDW generation and the possible optimal management strategies. The research questions are:

- How the amount of future waste concrete will develop in Beijing's urban housing sector;
- If the trend found in housing sector applies to the whole built environment, where the challenges and opportunities are for future CDW management in Beijing;
- And what strategies should be preferred accordingly.

Future waste flows can be modeled either directly as a function of socio-economic factors, or through mass balance relating to the inflows and/or stocks of the materials, which are determined by socio-economic factors. The former approach assumes that the volume of waste streams is directly related to demographic and socio-economic development (e.g., Grossman et al. 1974; Chang et al. 1993, 1997; Chen and Chang 2000). Because it avoids the complexity in analyzing the underlying dynamic systems, this approach is commonly used to characterize the future waste flows from long-lifespan goods (Binder et al. 2001). While it has some value on a general level, the approach clearly leads to dubious outcomes when looking at waste streams of specific materials (Elshkaki 2007) and it has been shown, that this analysis is very data intensive (Bossel 1994).

The latter approach is called Material Flow Analysis (MFA). Because it integrates the physical accounting into the socio-economic dynamics analysis, this analysis respects physical laws, and at the same time, decreases the data demand for waste streams, by using the relatively easier accessible figures of inflow and stock. Depending on whether or not the residence time of materials is considered, it is further classified into dynamic MFA and static MFA. The static MFA is generally preferable for the ease of calculation. For instance, estimating the demolition floor areas of buildings by an assigned 'replacement rate' (Yang and Hui 2008) or 'reconstruction rate' (Baccini and Brunner 1991) of stocks belongs to this method. However, this calculation may lead to doubtful results, because the 'replacement rate' cannot be obtained by trend extension. Van der Voet and colleagues (2002) pointed out that in cases where a recent steep growth of long lifespan applications of goods exists, the present amount of waste generation is no indication at all of the future development of waste generation. Therefore, for long lifespan goods such as buildings, dynamic MFA is required to project future waste flows.

There are two main types of dynamic MFA models that have been applied to estimate future waste streams. One is flow dynamics driving, as applied in Zeltner and colleagues (1999), Kleijn and colleagues (2000), Kohler and Hassler (2002), Van der Voet and colleagues (2002), Elshkaki and colleagues (2004, 2005), Bergsdal and colleagues (2007b), Bohne and colleagues (2007), Bradley and Kohler (2007), Hashimoto and colleagues (2007) and Kohler and Yang (2007). It assumes that the material stock is driven by its inflow and outflow; the inflow is predicted as a function of socio-economic factors, while the outflow is determined either by a leaching or delay process (Van der Voet et al. 2002). The other type of dynamic MFA is stock dynamics driving, as applied in Binder and colleagues (2001), Johnstone (2001a,b), Müller (2004, 2006), Yang (2006), Bergsdal and colleagues (2007a), Sartori and colleagues (2008) and Yang and Kohler (2008). It assumes that the stock of service units is the driver for the material flows. The stock can be estimated by an assigned 'development pattern' (Binder et al. 2001), 'stock expansion rate' (Johnstone 2001a,b) or can be defined as a function of population and its lifestyle (e.g. Müller 2006). The outflow of materials, coupled with the obsolete service units is determined by delay process, while the inflow of materials, coupled with the new add-in service units is introduced to maintain the stock in use. This approach, using stock of service instead of consumption (inflow) to stimulate the system evolution, reflects better the understanding that consumption behavior of people is "stock oriented" (Binder et al. 2001). This study uses stock dynamics model to analyze the future concrete diffusion in Beijing's urban housing to generate insights for future CDW generation in Beijing.

This article first introduces the stock dynamics MFA model and the calibration for the parameters. A comparison analysis for the per capita floor area (PCFA) in Beijing, the Netherlands and Norway is made to project the future PCFA in Beijing. Then, scenario analysis is conducted to check the impacts of high PCFA growth and a lengthening lifetime strategy on future waste generation. Finally, recommendations are provided for CDW management in Beijing based on the dynamic MFA study.

2.2 Methodology and data

2.2.1 Stock dynamics model

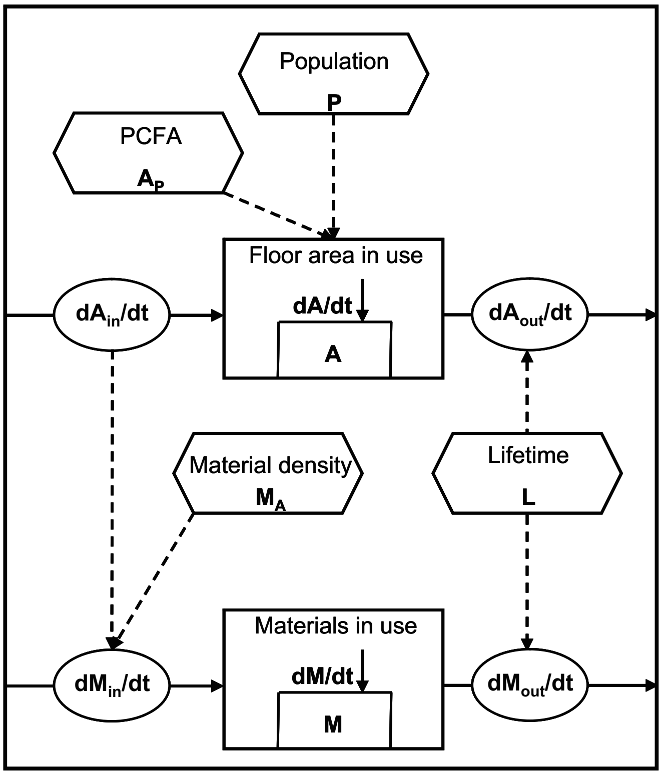


Figure 2.1 Conceptual outline of the stock dynamics model. PCFA = per capita floor area. Rectangles represent processes, ovals depict flows, and hexagons illustrate determinants or drivers. Dashed lines represent influences between variables: A = floor area stock; M = materials stock; dA/dt = net stock accumulation of floor area; dM/dt = net stock accumulation of materials; A_{in}/dt = input flow of floor area; dM_{in}/dt = input flow of materials; A_{out}/dt = output flow of floor area; M_{out}/dt = output flow of materials. Determinants are denoted as P for Population, A_P for per capita floor area (PCFA), L for dwelling Lifetime and M_A for Material density.

The model presented herein represents a material flow analysis (MFA) for the floor area and selected construction material (concrete) in Beijing's residential building stock. It is based on the stock dynamics approach. The conceptual outline of the model was first presented by Müller (2006) for concrete in Dutch dwelling stock and was then applied by Bergsdal and colleagues (2007a) for concrete/wood in Norwegian dwelling stock. Its main aspects are illustrated in Figure 2.1. Processes are represented by rectangles, flows by ovals, and drivers and determinants by hexagons. Dashed lines represent influences between variables. Stocks of floor area and materials are denoted by A and M, respectively, and the net stock accumulation by dA/dt and dM/dt. Input flows to stock are given by A_{in}/dt and dM_{in}/dt, while output flows are represented correspondingly as A_{out}/dt and M_{out}/dt. Determinants are denoted as P for Population, A_P for PCFA, L for dwelling Lifetime and M_A for Material density. The stock dynamics model can be described mathematically with seven equations.

$$A(t) = P(t) \cdot A_P(t) \tag{1}$$

$$\frac{dA_{out}(t)}{dt} = \int_{t_0}^{t} L(t,t') \cdot \frac{dA_{in}(t')}{dt} dt' \tag{2}$$

$$L(t,t') = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(t-t'-\tau)^2}{2\sigma^2}} \tag{3}$$

$$\frac{dA_{in}(t)}{dt} = \frac{dA(t)}{dt} + \frac{dA_{out}(t)}{dt} \tag{4}$$

$$\frac{dM_{in}(t)}{dt} = \frac{dA_{in}(t)}{dt} \cdot M_A(t) \tag{5}$$

$$\frac{dM_{out}(t)}{dt} = \int_{t_0}^{t} L(t,t') \cdot \frac{dM_{in}(t')}{dt} dt' \tag{6}$$

$$\frac{dM(t)}{dt} = \frac{dM_{in}(t)}{dt} - \frac{dM_{out}(t)}{dt} \tag{7}$$

Equation (1) describes the driving forces of the model. The floor area of housing stock is driven by the population and its lifestyle (here PCFA), representing the engine for the system to evolve. Equation (2) describes the delay character of the floor area stock in use. The outflow of floor area is determined by the previous inflow by delaying it by a certain service lifetime. Since dwellings may have different service lifetimes before they are demolished, a lifetime distribution L(t, t') is used in equation (2), representing the probability that the housing units entering service at the time t' are going to be removed from the stock at the time t. Equation (3) provides a default lifetime distribution L(t, t') for the model, which is estimated by a normal distribution with mean lifetime τ and standard deviation σ. Equation (4) describes that the future inflow of floor area is dependent on additional stock demand and outflow of floor area in future. Equation (5) links the service system of the housing floor area to the related material system. The inputs of materials and new floor areas are coupled through the material density parameter $M_A(t)$. Corresponding to equation (2), equation (6) represents that the material outflow is determined by previous material inflow after delaying a lifetime L(t, t'). Equation (7) represents that the material stock in the housing system can be calculated according to the material inflow and outflow.

2.2.2 Data and modeling parameters

Four determinants are used in the model as external parameter functions: Population (P), PCFA (A_P), Lifetime (L) and Material density (M_A). As will be discussed, the Gross Domestic Product (GDP) is also enclosed in this study as an expletory variable for PCFA. The calibration for each of the five modeling parameters and the data sources are described in the section.

Per capita floor area

Per capita floor area (PCFA) is a most important factor in shaping the demand for housing floor area stock. It is frequently used as a social indicator to measure how adequately the basic human need for shelter is being fulfilled. A low value for the indicator is a sign of overcrowding (UN/ESA, 2009). An increase of PCFA indicates an improvement in living standards (in terms of quantity) and represents a major driving force for the stock growth in housing floor area. In the two European cases, Müller (2006) and Bergsdal and colleagues (2007a) have related PCFA to the social and technical context by disaggregating it into two explanatory variables: floor area per dwelling and persons per dwelling. The former reflects changes in dwelling construction, while the latter, corresponding to the average number of persons per household or household size, indicates the social structure change of households. A significant decrease of the household size and a continuous increase of average floor area per dwelling have been observed in the Netherlands and Norway, which consequently led to the dramatic growth of PCFA in the both countries during the 1950s and the 1990s (Figure 2.2). However, to the end of 20th century, both variables show a tendency towards flattening. If the current trends continue, a saturated PCFA will be expected in both the Netherlands and Norway as projected by Müller (2006) and Bergsdal and colleagues (2007a) in their medium scenarios.

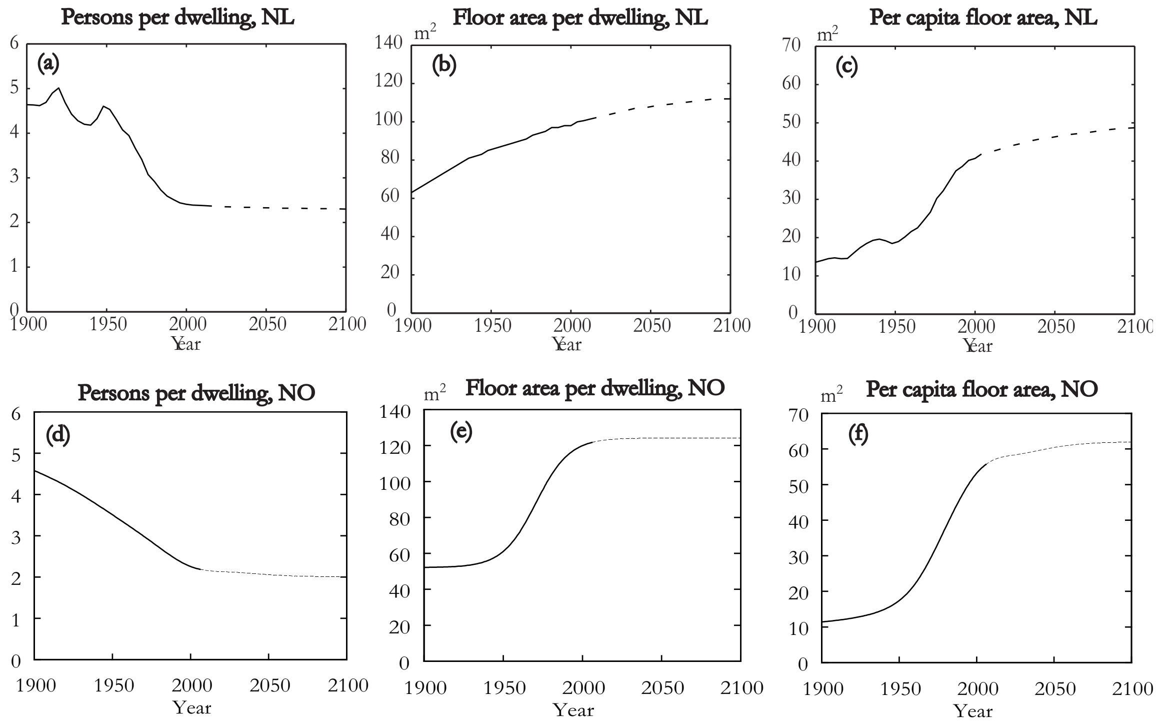


Figure 2.2 Historical figures and future projections (medium scenario) for persons per dwelling, floor area per dwelling and per capita floor area in the Netherlands and Norway. NL = the Netherlands; NO = Norway. *Source*: Müller (2006); Bergsdal et al (2007a).

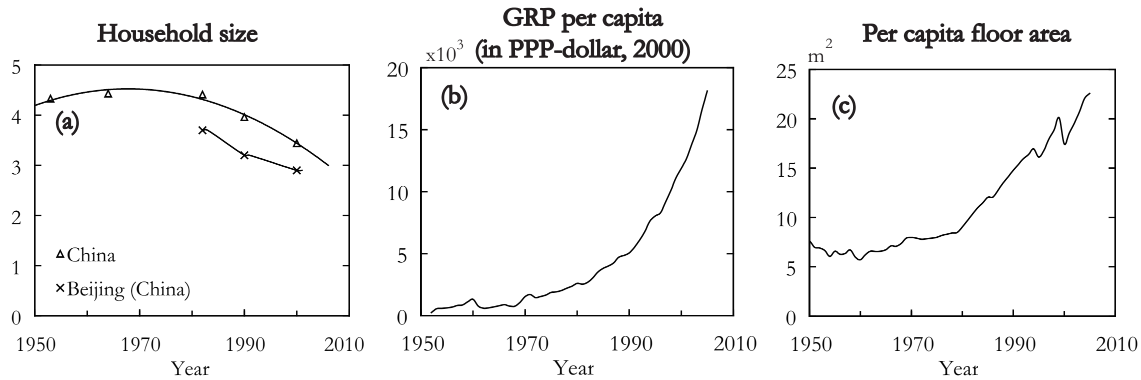


Figure 2.3 Historical figures of household size in Beijing (and all of China), gross regional product (GRP) per capita, and per capita floor area in Beijing. PPP = purchasing power parity. *Source*: BMBS (1999, 2000 – 2007); NBSC (2005); UNCDB (2008).

In Beijing, the historical figures of PCFA are available from statistical yearbooks. In 1950, the PCFA occupied by an urban resident in Beijing is 7.6 square meters. This number fluctuated to reach 9 by 1980, and then climbed at an accelerated speed to 23.3 at 2005 (Figure 2.3 (c)). Meanwhile, the household size, corresponding to the number of persons per dwelling, began to decrease in the whole of China as well as in urban Beijing since the 1980s (Figure 2.3 (a)). However, in contrast to the two European cases, no sign of flattening, neither in the growth of PCFA nor in the decrease of household size, can be deduced from the recent development in Beijing. It is shown that the growth of PCFA has strongly coupled with that of Gross Regional Product (GRP[7]) per capita in Beijing, especially for the last couple of decades (Figure 2.3 (b), (c)). This observation suggests that for a period of fast economic development, the growth of the local GDP per capita may be a suitable explanatory variable for the growth of PCFA. It is based on the hypothesis that, in the course of development, as people become wealthier, they demand more living space. A comparison analysis is conducted for the historical PCFA development in Beijing, the Netherlands and Norway to test the hypothesis.

The historical data for both PCFA and GRP per capita in Beijing can be found from 1952 to 2006 (BMBS 1999, 2000 – 2007; NBSC 2005). The historical figures of PCFA for the Netherlands and Norway are extracted from Müller (2006) and Bergsdal and colleagues (2007a) respectively. The GDP per capita are available for the Netherlands from 1969 to 2006 and for Norway from 1970 to 2005 from Eurostat (2009). For the purpose of comparison, the data series of GRP per capita in Beijing is converted into the constant market price at year 2000 in Chinese currency RMB, while those of GDP per capita for the Netherlands and Norway are extracted from Eurostat at constant market price refer to year 2000 in Euro. The data are then converted into current international dollar in 2000 with purchasing power parity (PPPs) estimated by World Bank for the use of international comparison (UNCDB 2008). The historical figures since 1950 and the extension of current trends by 2030 for PCFA and GDP per capita are illustrated for the three regions in Figure 2.4.

---

[7] Similar to GDP (Gross Domestic Product) which is defined as the market value of all final goods and services produced within the borders of a nation in a year, GRP (Gross Regional Product) is a measure of the size of a metropolitan area's economy. In this article, the term of GDP is used when it refers to only a nation or both nation (e.g. the Netherlands, Norway) and an area (e.g. Beijing), while the term GRP is used when it refers to only an area (e.g. Beijing).

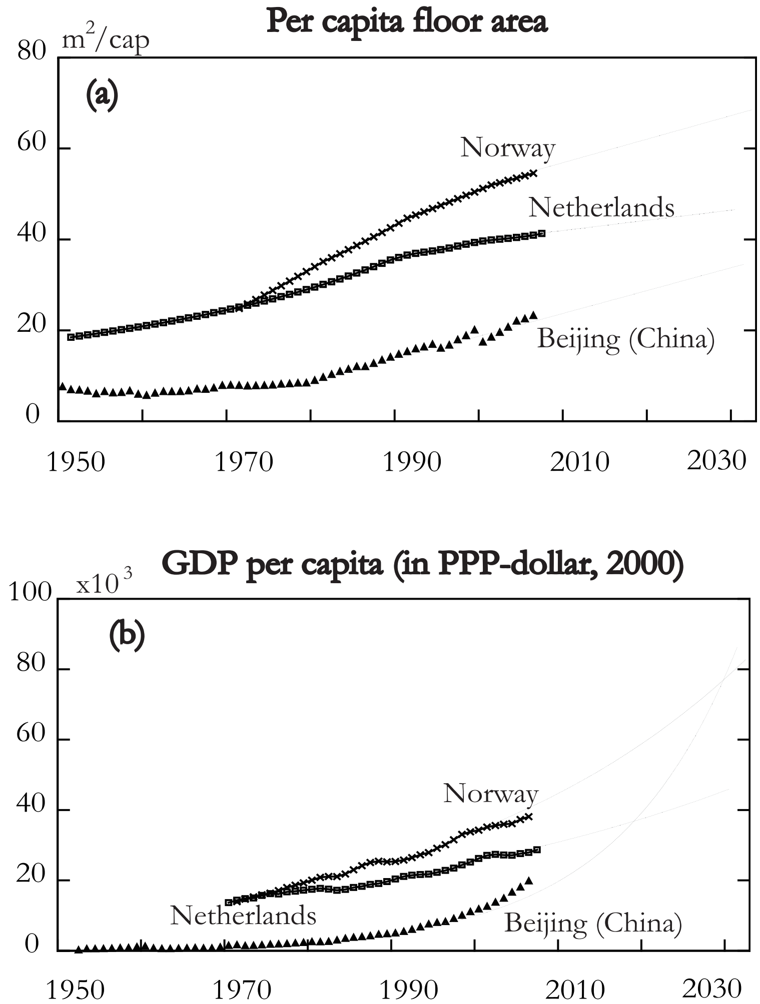


Figure 2.4 Historical figures of per capita floor area and gross domestic product (GDP) per capita in the Netherlands; Norway; and Beijing, China. m^2/cap = square meters per capita; PPP = purchasing power parity. *Source*: Müller (2006); Bergsdal et al (2007a); Eurostat (2009); UNCDB (2008); BMBS (1999, 2000 – 2007); NBSC (2005).

The figure shows:

- All the three regions have experienced a rapid increase in both PCFA and GDP per capita during the last 2 to 3 decades.
- Either PCFA or GDP per capita in Beijing was and is still far behind that in the two European countries.
- Beijing has had the highest GRP growth rate for the past several decades. If the trend continues, GDP per capita in Beijing will overtake the Netherlands in 20 years and Norway in 30 years, but such cross points are not indicated in the field of PCFA.

The relations between PCFA and GDP per capita in the three regions are plotted in Figure 2.5.

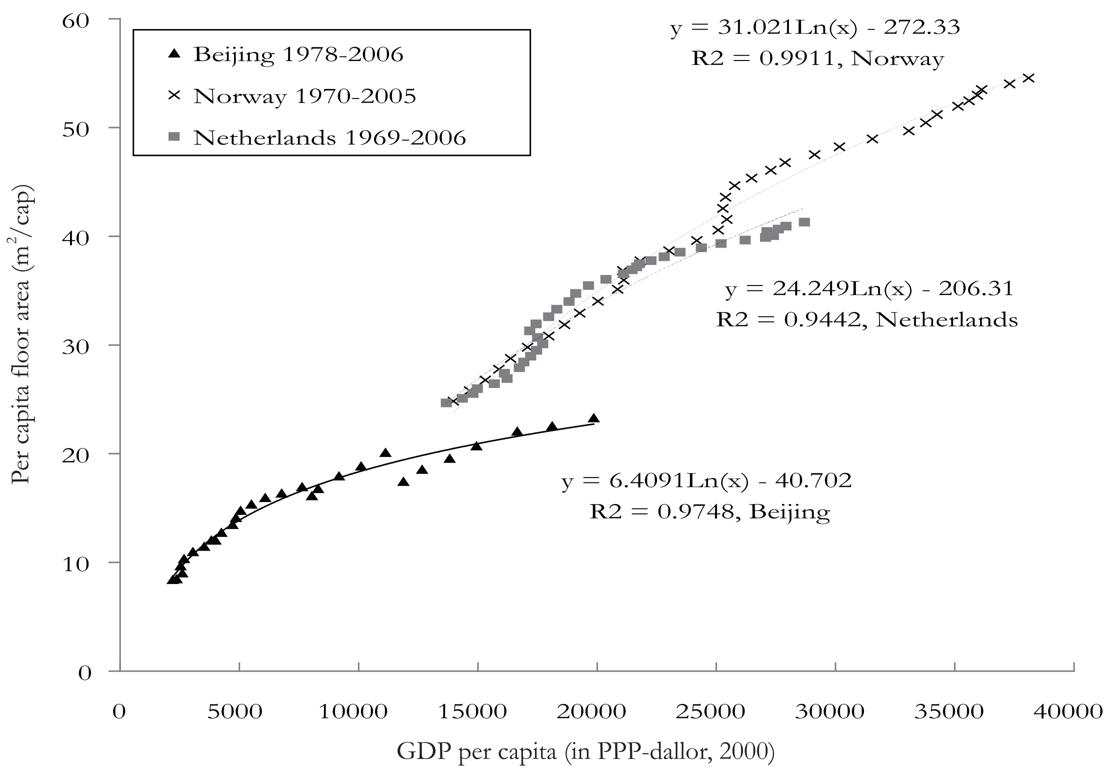


Figure 2.5 Historical regression of per capita floor area to gross domestic product (GDP) per capita in the Netherlands; Norway; and Beijing, China. PPP = purchasing power parity. *Source*: Müller (2006); Bergsdal et al (2007a); Eurostat (2009); UNCDB (2008); BMBS (1999, 2000 – 2007); NBSC (2005).

The figure shows:

- In all the cases, the PCFA and the local GDP per capita are strongly related, suggesting that to a certain extent, it is sound to forecast the future PCFA according to the projection of GDP per capita.
- Within each of these regions, a higher GDP per capita also occurs with a higher PCFA, which provides evidence that it is rational to assume the wealthier people are the more affluent living space they demand.
- The growth curves of PCFA per unit GDP per capita for the Netherlands and Norway are much closer and more towards upper-right corner than that for Beijing. It indicates that when compared to the two European countries, the housing development in Beijing is slower than its GDP growth.

Two possibilities can be considered to explain the slower PCFA development in Beijing. One is from the demand side, meaning that Beijing residents may not need as much living space as the Europeans. The other possibility is from supply side, and is based on the hypothesis that the physical and social conditions in Beijing cannot provide the living space needed. From the demand point of view, the household size in urban Beijing is comparable with the two European countries when they existed at a similar economic stage (Figure 2.2 (a), 2.2 (d), 2.3 (a)). From the supply point view, the observation that the housing provision in Beijing is below the level its GRP can afford may mean the GRP in Beijing has increased too fast, and that the housing development sector has not had time to catch up. If this is the case, the PCFA may suddenly increase in the future through successful reformation in housing policies or through rearrangements in urban plan. However, it may also mean that other physical conditions in Beijing have constrained the growth of the PCFA. This argument sounds reasonable, because Beijing is an over-crowed metropolis and it is unfair to compare the housing condition there to the two national cases. However, such reasoning is out of the scope of this study. Nevertheless, the comparison analysis between Beijing, the Netherlands and Norway shows that PCFA has a powerful correlation with the local GDP per capita. Although understanding why this relationship is different in each of the regions requires a wider consideration of other social, economic or physical factors, the PCFA-GDP relationship discovered for each region provides a good tool to forecast the future PCFA growth according to the projected GDP development in the certain area.

Therefore, the PCFA-GRP relation, based on the historical regression for the development in Beijing during 1978 and 2006 (see Figure 2.5), is used in this study for future PCFA projection. Two growth scenarios for GRP per capita and, consequently, the PCFA in Beijing are investigated, named *Baseline* and *High-growth* scenarios. The *Baseline scenario* adopts the GDP projection from Guest and McDonald (2007). Per capita GDP growth in overall China has been projected by Guest and McDonald (2007) through 2100 with annual growth rates as 4.3% for 2000 – 2025, 2.9% for 2025 – 2050 and 2.6% for 2050 – 2100. This projection is borrowed for Beijing for the period from 2011 to 2050, while the figures for GRP per capita during 2007 and 2010 are interpolated in order to smoothly connect the historical data and projected figures. The *High-growth scenario* assumes an extreme situation if the annual growth rate of GRP per capita in Beijing were to stay at 10% from 2007 through 2050. This is not intended to represent reality, but is used to investigate a scenario of extreme growth of PCFA in Beijing. The projections for PCFA and the GRP per capita in both scenarios are illustrated in Figure 2.6. The Baseline scenario projects the PCFA in Beijing will gradually increase to 34 square meters, while the High-growth scenario shows in an extreme situation the number might reach 50 by 2050.

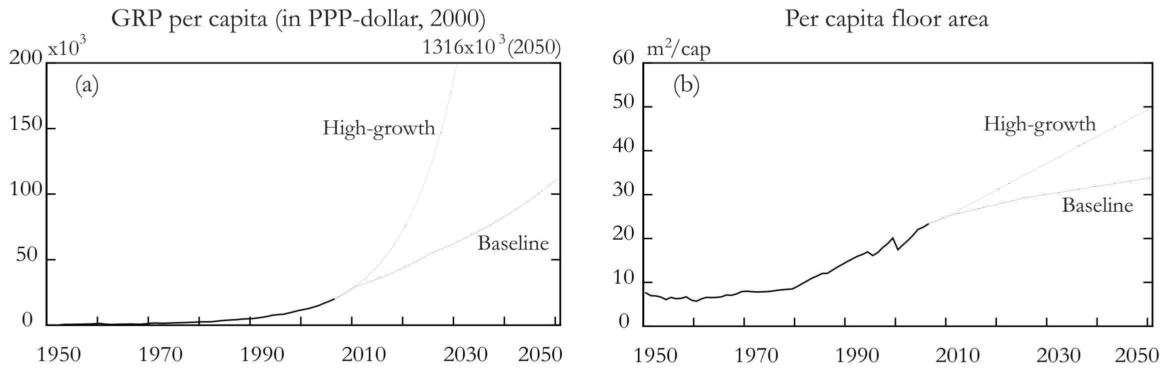


Figure 2.6 Historical figures and projections of gross regional product (GRP) per capita in Beijing and per capita floor area. PPP = purchasing power parity. *Source*: UNCDB (2008); BMBS (1999, 2000 – 2007); NBSC (2005).

Population

Besides PCFA, population is another parameter determining the demand for stock of housing floor areas. In Beijing historical data on the urban population is available for all years (BMBS 1999, 2000 – 2007). This shows that the population has increased about 6.5 times in the last fifty-eight years, indicating the urban population growth is the most important factor for the housing floor area expansion in Beijing for the past period. No future projection for Beijing's urban population has been found. However, the number for registered permanent residents has been forecasted by the Beijing Population Research Institute (Ma 2000) from 2000 through 2050. The research shows that the population development in Beijing is and will be mainly driven by immigration from outside the city during the next half century. Being already crowded, Beijing sets target to restrain its urban population within 18 million till 2020 (BMG 2005), by residence registration system. Compared with the target, the medium scenario is recognized as most realistic, which suggests that Beijing's number of registered residents will rise 24% from 2000 to 2035 then gradually decline until 2050 by about 3%. The low and high scenario forecasts a 12% lower or 10% higher peak level than medium scenarios, at 2020 and 2047 respectively. All the scenarios show saturation of the population in Beijing in the next four decades. This suggests that the extent to which the future stock of housing floor area will expand depends mainly on the development of future PCFA instead of the population growth. The medium scenario result for registered permanent residents by Ma (2000) is used as the base to forecast the future urban population. In 2007, the urban population is 1.16 times of the registered permanent residents figure in Beijing. This number is used as a conversion factor for the projection from 2007 through 2050. The historical figures and projection for the urban population in Beijing are illustrated in Figure 2.7.

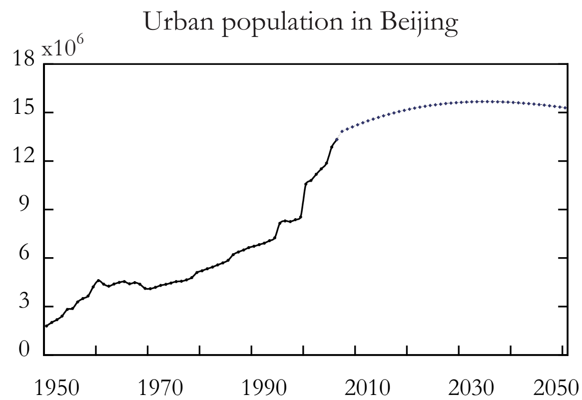


Figure 2.7 Historical figures and projection of urban population in Beijing. *Source*: BMBS (1999, 2000 – 2007).

Lifetime

The lifetime parameter, determining the delay of demolition flow compared to the peak of construction, is the most important but poorly understood factor. No profound research has been found for the lifetime distribution of dwellings in Beijing. However, it is generally acknowledged that the service lifetimes of buildings in China are rather short. Although the design lifetime is 50 years, the real lifetime of building is often observed much less, because of the low construction level in the past, a lack of regular maintenance and refurbishment, and inappropriate demolition due to the expansion of urbanization (Chen 2005; Shi and Xu 2006; Yang 2006). Some Chinese experts estimate the real lifetime of existing urban buildings to be only 15 to 30 years (Song 2005; Huang 2006; Yang 2006). This is especially true in Beijing, where during China's Cultural Revolution, provisions of cheap urban housing were promoted around 1966 – 1971, resulting in a generation of low quality, functionally defective houses, which were mostly replaced by the end of the century (BMCCC 1999).

Due to the absence of empirical data, a normal distribution has been applied in both European cases and is adopted in the study for the estimation of service lifetimes of dwellings. The short lifetime understanding is embodied in the *Baseline scenario*, assuming a mean lifetime of 25 years, with a standard deviation of 5 years. However, in the future, the housing lifetime in Beijing may increase, as the recently constructed residential buildings are mainly large apartment blocks built to a higher standard. A *Long-life scenario* is designed so that the new dwellings to be built in the future and the existing buildings erected after 1985 will be well maintained to reach a mean lifetime of 50 years, with a standard deviation of 10 years, while the dwellings built before 1980 have the same lifetime distribution as in the baseline scenario and those built from 1981 to 1985 have gradually increasing mean lifetimes with the standard deviations of 20% of the mean values. The estimations of the mean lifetimes of dwellings in Beijing are illustrated in Figure 2.8 (a) and the lifetime distributions for both scenarios are presented in Figure 2.8 (b).

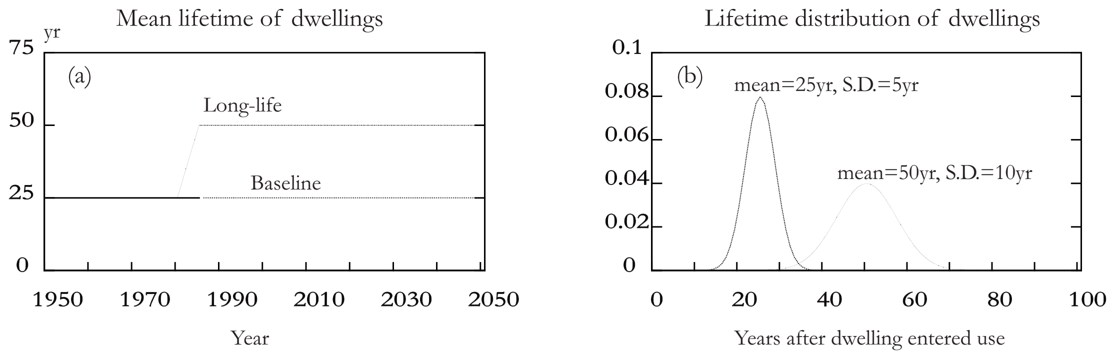


Figure 2.8 Estimations of the mean lifetime of dwellings (by year built) and lifetime distribution of dwellings (by years after dwelling entered use) in Beijing. S.D. = standard deviation.

Material density

The material density parameter links the sub-systems of floor areas and materials. For the purpose of comparison, this study focuses only on concrete, as it is the common material which has been analyzed in both European cases. The material density is therefore expressed as the concrete use per square meter of housing floor area construction. No direct historical figures on concrete intensity are available. However, a project of Chinese Academy of Sciences (Liu and Hu 2006) has sampled 100 Beijing residential buildings of various ages and structures and documented the material densities of six main construction materials: cement, steel, gravel, sand, wood and brick for three main dwelling structures: Brick-Concrete, Concrete Frame and Shearing-Force (Table 2.2). This information is used to derive the concrete intensity for Beijing's residential building.

Table 2.2 Material composition of three main structures of residential buildings in Beijing

Structures	*Cement*	*Steel*	*Sand*	*Gravels*	*Wood*	*Brick*
Brick-Concrete	148.1	23.4	573.5	657.8	15.5	364.3
Concrete Frame	212.3	46.6	452.9	838.3	14.9	42.8
Shearing-Force	285.7	97.1	579.0	1204.8	13.0	14.0

Note: Values are kilograms per square meter (kg/m^2). *Source*: Liu and Hu (2006).

Concrete is a composite material made up of cement, water, gravel, and sand. The concrete intensity for each type of structure can be computed by the cement density (Table 2.2) and the cement content in concrete, here assumed to be 12%, as used in the projection of concrete debris in China by Shi and Xu (2006). The average concrete intensity in Beijing's dwelling construction can be calculated by weighting according to the floor area distribution of the building structures in the yearly new completed floor areas. However, the annual completed residential floor areas are classified in Beijing statistical yearbooks only by the number of stories and not by the structure of the building. Assumptions are made as that all dwellings below and including three-stories are made with a Brick-Concrete structure, those of four to eight-stories are made with a Concrete Frame structure and the other higher dwellings are made with a Shearing-Force structure. The weighted average concrete intensity in Beijing housing construction is calculated for 1949 to 2006. Since no clear indication exists as to how it will develop, the future average concrete intensity in Beijing is assumed to stay at the same level as in 2006 till 2050. The historical and projected concrete intensity used in housing construction in Beijing, the Netherlands and Norway are illustrated in Figure 2.9 for the purpose of comparison.

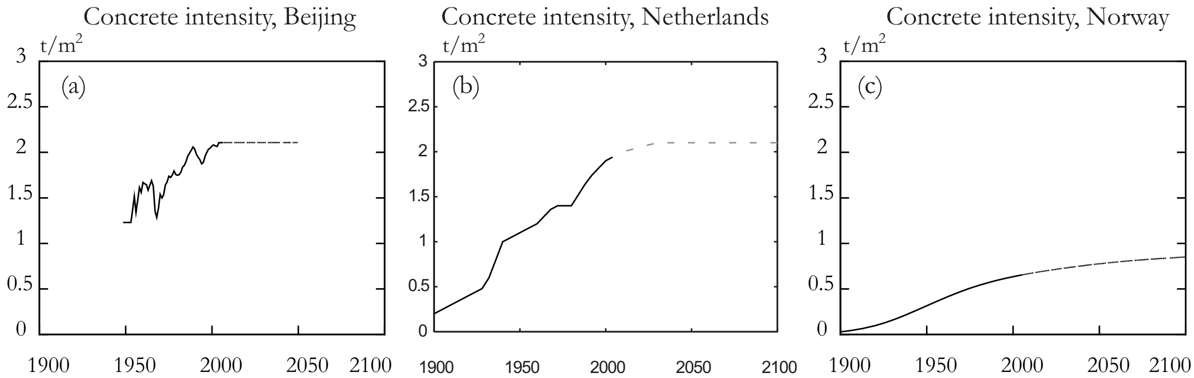


Figure 2.9 Historical figures and projections of the concrete intensity (tones per square meter floor area [t/m^2]) in housing construction in Beijing, China; the Netherlands (medium scenario); and Norway (medium scenario). One tonne (t) = 10^3 kilograms (kg, SI). *Source*: Liu and Hu (2006); BMBS (1999, 2000 – 2007); Müller (2006); Bergsdal et al (2007a).

The figures show in the last couple of decades, all three places have been increasing the use of concrete in dwellings. Beijing and the Netherlands have a similar concrete intensity, about 1.5 to 2 tons per square meter floor area, while Norway holds a much lower level, around 0.5 to 0.7 tons per square meter floor area. This can be understood since large amounts of wood is used in the dwelling construction therefore less concrete is needed to form a single square meter of floor area in Norway. The more distant historical concrete intensity in Beijing may be overestimated because it is based on later sampled data.

2.3 Scenario analysis

Three scenarios mentioned in the previous section are investigated to understand how the future housing stock and related concrete flows in Beijing will develop (1) if current trends continue, (2) if future PCFA will grow to a high extreme, or (3) if the dwelling lifetime will be prolonged. The *Baseline scenario* assumes future per capita GRP in Beijing will grow at the rate that economists have projected for China and that the short lifetime situation of the residential buildings in Beijing will continue. Calibration for the parameters are presented in Figures 2.6 (PCFA), 2.7 (Population), 2.8 (Lifetime) and 2.9 (a) (Concrete intensity). The *High-growth scenario* assumes future per capita GRP in Beijing will develop at an annual growth rate of 10% till 2050 (Figure 2.6). The *Long-life scenario* assumes future service lifetime of the dwellings in Beijing will be prolonged to 50 years (Figure 2.8). Other parameters for High-growth and Long-life scenarios have the same values as in Baseline scenario. Scenario results for both floor areas and concrete are presented in Figure 2.10 and summarized in Table 2.3.

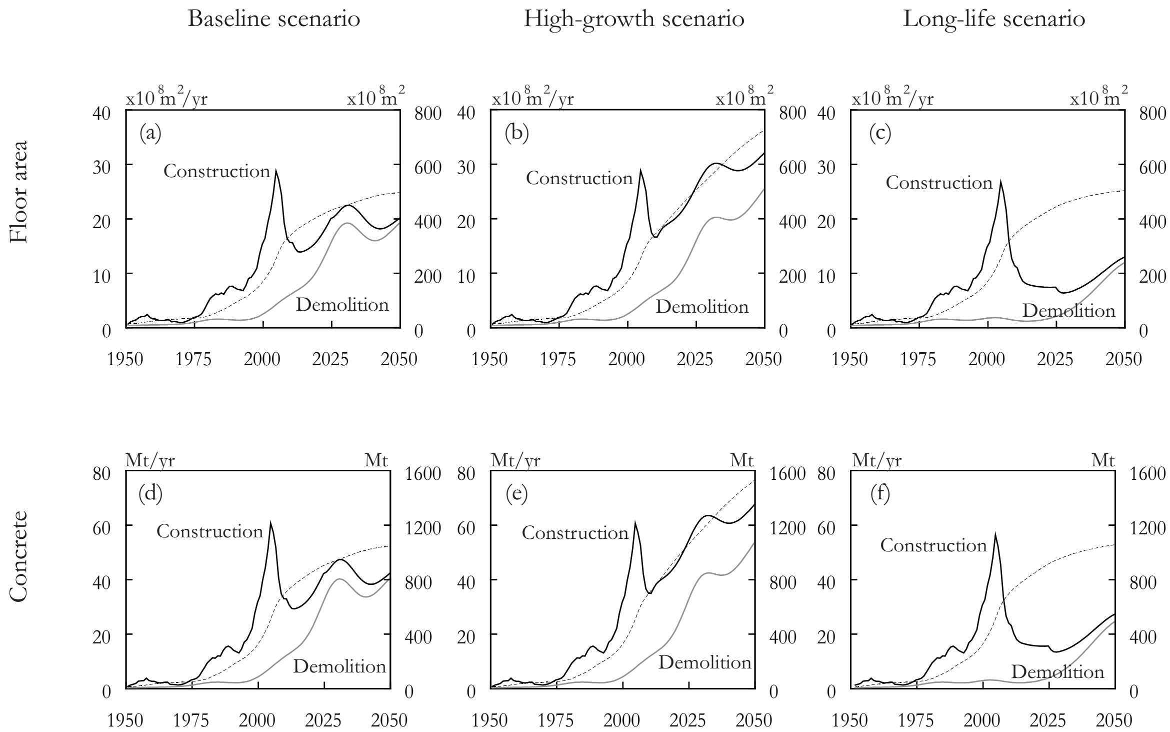


Figure 2.10 Housing floor area and concrete stock (dashed line), input flow (construction), and output flow (demolition) for the baseline, high-growth, and long-life scenarios. Stocks are measured on the right axis and flows on the left. Mt/yr = million metric tons per year.

The results of the simulations for the floor area of housing stock and flows show the following:

- The stock of housing floor area in Beijing has grown explosively over the last couple of decades and will keep expanding, however, at an expected slower rate.
- Statistical data until 2006 shows that residential construction in Beijing starts to fall after a peak in 2005. It may be explained partly as the effects of preparation for the 2008 Olympic game in Beijing. But all the scenarios suggest the oscillation in construction activity is unavoidable anyway, because of the slowing down of the expansion of the dwelling stock around 2006.

- Over the last 50 years, the exploding construction activities in Beijing were not reflected in higher demolition flows. In fact, demolition activities have been negligible due to the fact that the large stock of newly constructed buildings has not yet entered the waste stage. In the decades to come, Beijing is going to face a rapid increase in the volume of demolition waste. Assuming a continued short dwelling lifetime, Beijing will meet the first demolition peak at ca. 2030 and enter the second rise since ca. 2040. A higher PCFA growth will make the second rise even more serious. However, if the dwelling lifetime can be prolonged, the intensive demolition pressure can be postponed or even reduced altogether.

Simulation results for the housing related concrete show a similar behavior as for the housing floor area.

- Due to the high construction activity, the annual concrete use in Beijing housing has surged to nearly 60 Mt/yr at ca. 2005. Except when assuming an extreme PCFA growth, such high demand is unlikely to happen again, at least until 2050.
- So far, the concrete demolition waste flow is negligible compared to the concrete demand. However, all the scenarios show a dramatic increase of concrete waste, on the long run up to a level that is comparable to the new inflow. This equilibrium will not yet be reached in the investigated period (up to 2050). This suggests that waste concrete can be a stable secondary resource to meet future demand and thus save virgin resources.
- The concrete outflow will probably reach a first peak more than 40 Mt/yr around 2030. An extreme PCFA growth will raise a second waste wave of more than 50 Mt/yr by 2050. If the lifetime of residential buildings can be doubled, the peak of waste concrete can be pushed forward.
- New concrete will continue to be stocked in Beijing's dwellings for the next few decades to build up a size of nearly double the current level by ca. 2050. An extreme PCFA growth will bring the number even 50% higher to about 1.5 billion tons at 2050.

Table 2.3 gives the magnitudes of floor area and concrete stocks and flows for the Baseline, High-growth and Long-life scenarios for 2030 and 2050. The Baseline value of each item at year 2005 is chosen as a current base to evaluate the volume change in all scenarios. Input parameters for the simulation are listed in the bottom.

Table 2.3 Simulation results and input parameters for floor areas and concrete in housing Beijing

Stocks/flows		**Baseline**			**High-growth**		**Long-life**	
		2005	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Floor area	A (m^2)	*2.77E08*	4.51E08	4.97E08	5.61E08	7.26E08	4.67E08	5.04E08
	(%)	*100%*	163%	179%	203%	262%	168%	182%
	dA_{in}/dt (m^2/yr)	*2.72E07*	2.25E07	2.02E07	3.00E07	3.22E07	6.70E06	1.30E07
	(%)	*100%*	83%	74%	110%	118%	25%	48%
	dA_{out}/dt (m^2/yr)	*4.60E06*	1.92E07	1.93E07	2.01E07	2.56E07	3.52E06	1.20E07
	(%)	*100%*	418%	419%	436%	555%	76%	260%
Concrete	M (t)	*5.59E11*	9.49E11	1.05E12	1.18E12	1.53E12	9.66E11	1.06E12
	(%)	*100%*	170%	187%	211%	274%	173%	189%
	dM_{in}/dt (t/yr)	*5.74E10*	4.74E10	4.25E10	6.31E10	6.77E10	1.41E10	2.74E10
	(%)	*100%*	83%	74%	110%	118%	25%	48%
	dM_{out}/dt (t/yr)	*8.49E09*	4.03E10	4.07E10	4.20E10	5.39E10	6.94E09	2.47E10
	(%)	*100%*	474%	479%	495%	635%	82%	291%

Input parameters			**Baseline**		**High-growth**		**Long-life**	
		2005	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Per capita floor area	A_p (m^2/cap)	*22.6*	30.1	33.8	37.4	49.6	30.1	33.8
	(%)	*100%*	134%	150%	166%	220%	134%	150%
Population	P (cap)	*1.29E07*	1.56E07	1.53E07	1.56E07	1.53E07	1.56E07	1.53E07
	(%)	*100%*	122%	119%	122%	119%	122%	119%
Lifetime	L (yr)	*Normal distribution , mean = 25, S.D. = 5*			Normal distribution , mean = 25, S.D. = 5		Normal distribution , mean = 50, S.D. = 10	
Concrete intensity	M_a (t/m^2)	*2.1*	2.1	2.1	2.1	2.1	2.1	2.1

2.4 Strategic suggestions for CDW management

The dynamic MFA for the concrete in Beijing's housing system provides a base to understand the mechanism of future CDW generation in Beijing and the potential of various CDW management strategies. It indicates the CDW generation in the near future strongly depends on the lifetime of the buildings, while a higher PCFA growth will raise the waste generation level especially in the more distant future. Therefore, for a mid-term strategy, efforts should be put on prolonging service life of the buildings whenever it is possible. However, all the scenarios suggest the dramatic rise of CDW generation will arrive sooner or later. With this large amount of waste output being unavoidable, recycling should be emphasized to limit the pressure on landfills.

2.4.1 Strategy for prolonging the lifetime of buildings

Future demolition flows will follow a cyclical behavior based on the service lifetime and the primary construction peak. Dynamic MFA for concrete in Beijing housing suggests that demolition waste may peak around 2030, following the first surge of construction in Beijing during 1990s. If the lifetime of the buildings can be doubled, the rise of the waste peak will be pushed to next half of the century. Therefore, for mid-term waste minimization, the most important is to prolong the lifetime of the buildings. The first instrument is to assure a reasonable service lifetime for the new construction through the improvement of construction techniques and better urban planning. The second instrument is to enhance the existing building stock management by, for instance, regular renovation.

2.4.2 Recycling strategy

The dynamic MFA for Beijing housing shows that a dramatic rise of CDW generation is unavoidable, especially under the assumption of a continued rapid growth of GRP. Recycling is a strongly indicated strategy to cope with the coming CDW increase while limiting the pressure on landfills. All scenarios show that, even if 100% of the obsolete concrete can be recycled, the resulting amount of secondary material will still not be enough to supply the demand for concrete. At least up to 2050, the demand for new residential buildings in Beijing is sufficient to provide a sink for all the materials recycled from waste streams. Therefore, it seems a useful long-term strategy for Beijing to increase CDW recycling capability, and invest in improving CDW recycling technology, promoting high recyclability design and so on, to prevent the city's landfill capacity being used up completely by massive amounts of demolition waste.

2.5 Conclusions and discussions

The PCFA is one of the most important variables determining the material stock dynamics of housing. PCFA shows a powerful correlation with the local GDP in all three investigated areas. The relationship is, however, different in each of the regions, indicating that other social, economic or physical factors are important as well as driving forces for PCFA. The investigation of the stock dynamics of construction materials leads to a number of recommendations for strategic CDW management:

- The service lifetime of buildings in Beijing is presently very short. If this situation will continue, demolition waste will rise dramatically over the next 50 years. If the PCFA will keep up its present high growth rate, this will make the situation even worse with more than 6 times of the current level of concrete demolition waste to deal with by the year of 2050.
- Lengthening the lifetime of buildings is crucial for keeping the consequences of this rapid growth in check. Renovation activities and high building quality standards are recommended to realize this, wherever possible.
- For existing buildings, however, the question is whether their quality is sufficient to actually realize a significantly longer lifespan. Future demolition waste depends for a large part on past construction, therefore, to some extent, the rise in demolition waste may not be prevented, and must be dealt with. Moreover, there may be a trade-off: a high building quality standard might lead to a higher material intensity. This implies that the reduction of future demolition waste flows may not keep pace with the lengthening of lifespan.
- Putting more effort into recycling of construction and demolition waste is highly recommended, because it may reduce the size of the waste flow to be landfilled, while at the same time reducing the need for virgin construction materials.

Reference to Chapter 2

Baccini, P. and H.P. Brunner. 1991. Metabolism of the anthroposphere. Berlin: Springer. ISBN 3-540-53778-3.

Bergsdal, H. et al. 2007a. Dynamic material flow analysis for Norway's dwelling stock. Building Research & Information 35(5): 557 – 570.

Bergsdal, H. et al. 2007b. Projection of construction and demolition waste in Norway. Journal of Industrial Ecology 11(3): 27 – 39.

Binder, C. et al. 2001. Dynamic models for managing durables using a stratified approach: the case of Tunja, Colombia. Ecological Economics 38: 191 – 207.

BMBS (Beijing Municipal Bureau of Statistics). 1999. Fifty years in Beijing (in Chinese).

BMBS. 2000 – 2007. Beijing statistical yearbook. 2000 – 2007.

BMCCC (Beijing Municipal Chorography Compiling Council). 1999. Beijing Chorography. Sections: Life of the People (in Chinese). Accessible on: http://www.bjdfz.gov.cn/search/markChapterFrameSet.jsp?Page_No=329&Identifier=ISBN7-200-06816-0&Period_Diff=&Mark_Name=人民生活志. Accessed on May, 2009.

BMG (Beijing Municipal Government). 2005. Master Plan of Beijing Urban Development 2004-2020 (in Chinese).

Bohne, R. A. et al. 2007. Dynamic eco-efficiency projections for C&D waste recycling strategies at the city level. Journal of Industrial Ecology 11(4).

Bossel, H. 1994. Understanding dynamic systems: shifting the focus from data to structure, In: Hiltg L.M., Jaeschke A., Page B., Schwabl A., (eds), Informatik für den Umweltschutz, 8. Symposium Hamburg, Marburg.

Bradley, P.E. and N. Kohler. 2007. Methodology for the survival analysis of urban building. Building Research & Information 35(5): 529 – 542.

BSWAD (Beijing Solid Waste Administration Department). 2007. Current Status of Construction and Demolition Waste Management in Beijing (internal material, in Chinese).

Chang, N.B. et al. 1993. Time series forecasting of solid waste generation. Journal of Resources Management Technology 21: 1 – 10.

Chang, N.B. and Y.T. Lin. 1997. An analysis of recycling impacts on solid waste generation by time series intervention modeling. Resources, Conservation and Recycling 19: 165 – 186.

Chen, H.W. and N.B. Chang. 2000. Prediction analysis of solid waste generation based on grey fuzzy dynamic modeling. Resources, Conservation and Recycling 29: 1 – 18.

Chen, Y. 2005. Analysis of material flow of residential buildings in Beijing, Master thesis, Tsinghua University, China (in Chinese).

Chen, Z. et al. 2004. Current situation and solution of C&D waste management in Beijing. Environmental Science Trends 2 (in Chinese).

Elshkaki, A. et al. 2004. The environmental and economic consequences of the developments of lead stocks in the Dutch economic system. Resources, Conservation and Recycling 42: 133 – 154.

Elshkaki, A. et al. 2005. Dynamic stock modeling: A method for the identification and estimation of future waste streams and emissions based on past production and product stock characteristics. Energy 30: 1353 – 1363.

Elshkaki, A. 2007. Systems Analysis of Stock Buffering – Development of a Dynamic Substance Flow: Stock Model for the Identification and Estimation of Future Resources, Waste Streams and Emissions. PhD Thesis, Leiden, Netherlands, ISBN 978-90-9022084-0.

Eurostat (European statistics). 2009. Available on line: http://epp.eurostat.ec.europa.eu/. Accessed on May 2009.

Fatta, D. et al. 2003. Generation and management of construction and demolition waste in Greece – an existing challenge. Resources, Conservation and Recycling 40: 81 – 91.

Grossman, D. et al. 1974. Waste generation methods for solid waste collection, Journal of Environmental Engineering. ASCE 6: 1219 - 1230.

Guest, R. S. and I. M. McDonald. 2007. Global GDP shares in the 21st century – An equilibrium approach. Economic Modelling. 24: 859 - 877.

Hashimoto, S. et al. 2007. Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan. Waste Management 27(12): 1725-1738.

Huang, W. 2006. The speech on the meeting of 'Building New Countryside of the Socialist Society', 21 March, Beijing, Ministry of Construction of China (in Chinese).

Johnstone, I. 2001a. Energy and mass flows of housing: a model and example. Building & Environment 36(1): 27 – 41.

Johnstone, I. 2001b. Energy and mass flows of housing: estimating mortality. Building & Environment 36(1): 43 – 51.

Kleijn, R. et al. 2000. Dynamic substance flow analysis: the delaying mechanism of stocks, with the case of PVC in Sweden. Ecological Economics, 32: 241 – 254.

Kohler, N. and U. Hassler. 2002. The building stock as a research object. Building Research & Information, 30(4): 226 – 236.

Kohler, N. and W. Yang. 2007. Long-term management of building stocks. Building Research & Information, 35: 351 – 362.

Liu, T. and D. Hu. 2006. Environmental impact of residential building construction in Beijing: 1949-2003 - assessing the construction materials' environmental impact by LCA. Journal of the Graduate School of the Chinese Academy of Sciences 23(2): 231-241 (in Chinese).

Ma, X. 2000. Projection for next fifty years' registered permanent residents in Beijing. Beijing Population Research Institute. Available on line: http://www.bjpopss.gov.cn/bjpopss/xzlt/xzlt20050411b.htm.zh (in Chinese). Accessed on June 2009.

Müller, D.B. et al. 2004. Long-term coordination of timber production and consumption using a dynamic material and energy flow analysis. Journal of Industrial Ecology 8(3).

Müller, D.B. 2006. Stock dynamics for forecasting material flows – case study for housing in the Netherlands. Ecological Economics 59: 142 – 156.

NBSC (National Bureau of Statistics of China). 2005. Statistical Compendium of China 1949 – 2004. China Statistical Press, Beijing (in Chinese).

Poon, C. et al. 2004a. Minimizing demolition wastes in Hong Kong public housing projects. Construction Management and Economics 22: 799 – 805.

Poon, C. et al. 2004b. Management of construction waste in public housing projects in Hong Kong. Construction Management and Economics 22: 575 – 689.

Sartori, I. et al. 2008. Towards modeling of construction, renovation and demolition activities: Norway's dwelling stock, 1900 – 2100. Building Research & Information 36(5): 412 – 425.

Shi, J. and Y. Xu. 2006. Estimation and forecasting of concrete debris amount in China. Resources, Conservation and Recycling 2006.

Song, Ch. H. 2005. Whole life and highgrade quality-stick to the implement housing performance certification. Housing Science, 290(8): 287-302.

Voet, E. van der, et al. 2002. Predicting future emissions based on characteristics of stocks. Ecological Economics 41: 223 – 234.

UNCDB (United Nations Common Database). 2008. United Nations Statistic Division. Available on line: http://unstats.un.org/unsd/cdb_discontinued/cdb_discontinued.asp. Accessed on May 2009.

UN/ESA. 2009. Division for sustainable development: indicator floor area per person. Available on line: http://www.un.org/esa/sustdev/natlinfo/indicators/isdms2001/isd-ms2001socialB.htm#floorarea. Accessed on May 2009.

Yang, H. and J. Hui. 2008. Forecasting housing supply and demand in China for next five years. Shanghai Real Estate. July 2008: 26-30 (in Chinese).

Yang, W. and N. Kohler. 2008. Simulation of the evolution of the Chinese building and infrastructure stock. Building Research & Information 36(1): 1-19.

Yang, W. 2006. Modeling the Evolution of the Chinese Building Stock in a Sustainable Perspective, PhD Thesis, Tianjin University, Tianjin, China (in Chinese).

Zeltner, C. et al. 1999. Sustainable metal management exemplified by copper in the USA. Regional Environmental Change 1(1): 31– 46.

Chapter 3 Case II: Dynamics of Urban and Rural Housing Stocks in China*

Abstract

The massive migration flows from rural to urban areas in China, combined with an expected decline in total population over the next decades, leads to two important challenges for China's housing: the growth of its urban housing stock and the shrinkage of its rural housing stock. The rural and urban housing systems in China were analyzed using a dynamic material flow analysis model for the period 1900 - 2100 for several scenarios assuming different development paths for population, urbanization, housing demand per capita, and building lifetime. The simulation results indicate that new housing construction is likely to decline for several decades due to the fast growth over the past 30 years and the expected increased longevity of dwellings. Such an oscillation of new construction activity would have significant implications for construction industry, employment, raw material demand, and greenhouse gas emissions to produce the construction materials. Policy and practical options for mitigating the negative impacts are considered.

Keywords: building stocks, construction demand, dynamic material flow analysis, housing stock, longevity, trends, urbanization, China.

---

* Reprinted from "Hu, M., H. Bergsdal, E. van der Voet, G. Huppes and D.B. Müller. 2010. Dynamics of urban and rural housing stocks in China. Building Research & Information 38(3):1–17". This is the author's version of the work. It is posted here by permission of Building Research & Information for personal use, not for redistribution. The definitive version was published in Building Research & Information, Volume 38 Issue 3, May 2010. doi:10.1080/09613211003729988 (http://dx.doi.org/10.1080/09613211003729988).

3.1 Introduction

Unprecedented urbanization is taking place in China. Since the adoption of reform and open-door policies in 1978, China's level of urbanization has risen from 18 percent in 1978 to 45 percent in 2007 (NBSC 2005; 1980–2008). It is expected that China will reach 55 percent of urbanization by 2020 (Liu et al. 2003; Lan 2008; Song and Ding 2007). The fast growing urbanization has been doubling Chinese building and partially the infrastructure stocks in the last 30 years (Kohler and Yang 2007). Accompanying it, the rapid conversion of land from low-density agricultural to new urban zones of high density and material-intensive commercial and residential buildings has consumed enormous quantities of domestic and imported resources (Fernández 2007). If the trend continues, China will inevitably face a shortage of domestic resource supply (Shen et al. 2005) and exert pressure on global markets over next two decades (Garnaut and Song 2006). However, the relationship between the urbanization progress in China and its resource demand is not understood sufficiently. There is need for a model to quantify the relationship. If we would understand it, we could make predictions for future resource demand.

Yang and Kohler (2008) analyze Chinese building and infrastructure stock from 1978 to 2050 to calculate its material and energy implications during the ongoing urbanization process. Two different models are employed to do so: the period previous to 2005 is compressed in a static model for the reference year at 2005, in which the age classes of the exiting stock is omitted; the period after 2005 employs a cohort approach, which allows for a more realistic analysis of aging understood as the phasing out of individual cohort with their characteristic material composition and energy use. This study provides plenty of valuable details about the composition of Chinese built environment stock. However, its neglect of cohort approach for the existing building stock is challengeable, because the rapid expansion of Chinese building stock during 1978 and 2005 may have great material and energy implications for the coming decades. Further, the broad scope of the study (housing, non-housing, infrastructure etc.) and its wide involvement of modeling parameters (demolition and refurbishment rates of exiting stock, lifespan and refurbishment interval of new completed cohorts etc.) make it is not only impossible to verify the results but also difficult to identify which factor is more influential on the uncertainty. Nevertheless, the detailed historical analysis and carefully designed scenarios of this study form a good basis for the future researches.

In order to capture the essential relation between the urbanization progress and its material consequences, we narrow our research on Chinese residential buildings, which represents around 80% of the annual completed floor area in China over the last two decades (NBSC 2005; 1980–2008). The research comprises two stages. The work presented here is the first stage. It aims to indentify the long-term dynamics of the floor area in the rural and the urban housing stocks in China, including the demand for new housing construction and obsolete housing demolition in rural and urban China during the urbanization process. We anticipate the trends, identify the influential parameters and discuss the uncertainties. The second stage of this research investigates the dynamics of the housing related construction material - iron and steel, which is presented in Hu and colleagues (2010b).

3.2 Urbanization and housing in China

Since 1958, the Chinese government has used the household registration system, called Hukou, to control the movement of people between rural and urban areas. This division led, among others, to a detachment between the rural and the urban housing systems, which are largely different in housing supply, renovation and transferring. In cities, up until 1978 urban housing were allocated by Chinese government as part of social welfare for urban households (Zhu et al. 2000). During this period, around 75% urban households were in the public rental housing sector (Huang 2004). Since the rents were extremely low[8], urban public housing was heavily subsidized and caused heavy financial burden on the state (Shaw 1997). Subsequently, insufficient state investment led to: (1) serious shortage of urban housing. Per capita living space in cities declined from $4.5m^2$ in the 1950s to $3.6m^2$ in 1978 (Center for Development Studies at the State Council 1991); (2) low-quality housing construction. Especially around 1966-1971[9], when 'building housing by laying dry mud' was advocated from Beijing as a land-saving and high-speed measure, resulted in a generation of low quality, functional defect dwellings (BMCCC 1999; Wu 1989); (3) inappropriate maintenance. As a result, housing ages quickly (Shaw 1997).

[8] Less than 1% of household income according to Wang and Murie (1999).

[9] During China's Cultural Revolution period (1966-1976).

In the late 1970s, when China's economic reform started, previously suppressed housing problems initiated Chinese urban housing reform (Xu 1993; Lee 2000). This reform, aiming to marketisation and privatisation of urban housing production and consumption, then triggered a strong wave of real estate development in many major Chinese cities during the 1980s and 1990s (Zhu et al. 2000). By 2005 only 8% of Chinese urban housing units were public rentals and most newly constructed owner-occupied housing in the future will be in the private sector (Logan et al. 2010). With the move from 'welfare' housing to commodity housing, the provision of an adequate quantity and the quality of housing units in urban China began to be addressed successfully (Rapanos 2002). However, this process is also companied by speculative investment. To curb soaring housing prices, Chinese central government requires that 70% of new completed residential units be smaller than 90 m^2 since June 2006. From June 2009, the central government further tightened financing for the purchase of second home to cool Chinese property market. Nevertheless, one positive effect of housing privatisation seems undeniable, that is, the lifetime expectancy of recently completed urban dwellings has increased largely. This is because: firstly, higher construction quality may have been achieved due to the expansion of housing construction for sale at market prices; secondly, better caring of the dwellings may be taken due to the owner-occupied housing; thirdly, land lease contract may support the expectation of urban households for using their purchased home no less than 70 years[10].

In rural area, China's public housing provision had not been extended to countryside (Zhang 1997). Rural home building depended on privately accumulated savings and some pooled community labor (McKinley and Wang 1992). Its quantity and quality are largely determined by the economic status of the peasants that has improved significantly since 1978. Before 1978, the older stock of rural houses was often built of adobe walls and thatched roofs (McKinley and Wang 1992). Chinese economic reforms started in countryside in 1978. The implementation of 'household production responsibility' system has substantially stimulated the rural economic growth (Lin 2007). When income increased, one first priority of rural residents was to improve their housing. An extraordinary boom in rural house construction then occurred in

[10] In China all land belongs to the state and is leased for housing development. The land lease period is normally 70 years.

the 1980s[11]. Between 1978 and 1988 rural per capita living space more than doubled, from about 8.1 square meters to 16.6 (NBSC 1999). The quality of rural housing also improved; many new houses were constructed of bricks, tiles, or reinforced concrete during the 1980s (McKinley and Wang 1992).

Following the economic reforms from 1978, the substantial rise in agricultural productivity has generated a large surplus rural labor force that needs to be transferred into non-farm sectors and possibly urban settlements. Responding to it, since 1984, Chinese government partially lifted the control over rural-urban migration[12] (Lin 2007). The massive rural-urban migration has then significantly raised the urbanization level in China (Zhang 2008), resulting in an expanding urban population and since 1995 a shrinking rural population (NBSC 2005; 1980-2008). It leads to, regarding resource management, two important challenges: the growth of the urban housing stock acting as a sink of raw materials and the shrinkage of the rural housing stock potentially becoming a source for secondary materials. In order to obtain a long-term vision of the challenges, this study aims to construct a robust physical base for future investigation on the relationship between urbanization in China and its material demand.

3.3 Method

The model developed in the study is based on a generic dynamic Material Flow Analysis (MFA) model presented by Müller (2006) for simultaneously determining resource demand and waste generation through estimations of the population, its lifestyle, material intensity, and product lifetime. This approach has been applied for analyzing stocks and flows dynamics of timber in Switzerland (Müller 2004), floor area and materials in dwelling stocks (Müller 2006; Bergsdal et al. 2007a), and for projecting construction waste (Bergsdal et al. 2007b) and for modeling renovation activities of dwelling stock (Sartori et al. 2008). It is adopted in Brattebø et al. (2009)

[11] Before 1978 only about 100 million square meters of new rural houses were built each year, but by 1986 this figure had reached 980 million square meters (McKinley and Wang 2002).

[12] Since 1984, Chinese government allowed peasants to enter towns for permanent settlement on the condition that they would look after their own needs for food grain and other welfare and would not cause new burdens upon the state (Lin 2007).

as the core of the generic model for exploring built environment metabolism. This approach tracks all vintage classes (year by year) individually and models the aging of the housing stock based on the estimates of probability distribution functions for the lifetimes of all vintage classes, and so has special advantages for capturing long-term trends. The previous applications are all for industrialized countries, where standards of living are relatively homogenous among the total population. In the case of China, there are significant differences in housing between urban and rural. We extend Müller's generic dynamic MFA model to reflect the urban-rural relationship in China, with a distinction between urban and rural housing stocks (Figure 3.1).

3.3.1 System definition

The system for the Chinese dwelling stock is divided into two sub-systems reflecting the urban and rural population and their housing stocks. The two sub-systems are linked through migration flows from rural to urban areas (m_u) and vice versa (m_r). The conceptual outline of the stock dynamics model (Figure 3.1) is developed from the generic dynamic MFA model presented by Müller (2006). Each sub-system involves two types of processes, illustrated with rectangles: population within the region (P) and housing floor area of the region (A). Both processes have a state variable (P_r, A_r for rural area or P_u, A_u for urban area) and a derivative, which is the net stock accumulation (dP_r/dt, dA_r/dt or dP_u/dt, dA_u/dt). Each population process has three pairs of input and output flows which are denoted respectively as: *b* and *d* for annual inflow and outflow of population led by birth and death, *i* and *e* for annual immigration and emigration crossing China's border, and m_u and m_r for internal migration flows from rural to urban and vice versa. The integrated effect of these flows on the share of people living in rural and urban can be indicated by the urbanization rate. In this study, the urbanization rate (u) and the total national population (P) are used as determinants for China's rural (P_r) and urban (P_u) population. The background flows (*b, d*, *i*, *e*, m_u, m_r) are not involved in modeling floor area dynamics but used to calculate the net internal migration flow (Appendix A) for the purpose of checking the consistence of the data sets with urbanization rates. Each housing floor area process has an input ($dA_{r,in}$ or $dA_{u,in}$) and an output flows ($dA_{r,out}$ or $dA_{u,out}$), represented with straight-line arrows and ovals. Housing floor area stocks and flows are shaped by determinants (hexagons) of per capita floor area A_{rc} or A_{uc}; output flow is the delay of past input, determined by lifetime function

$L_r \sim N(\sigma_r, \tau_r)$ or $L_u \sim N(\sigma_u, \tau_u)$; and the future input flow is formed to maintain the demanded size of in-use housing floor area stock for rural and urban respectively.

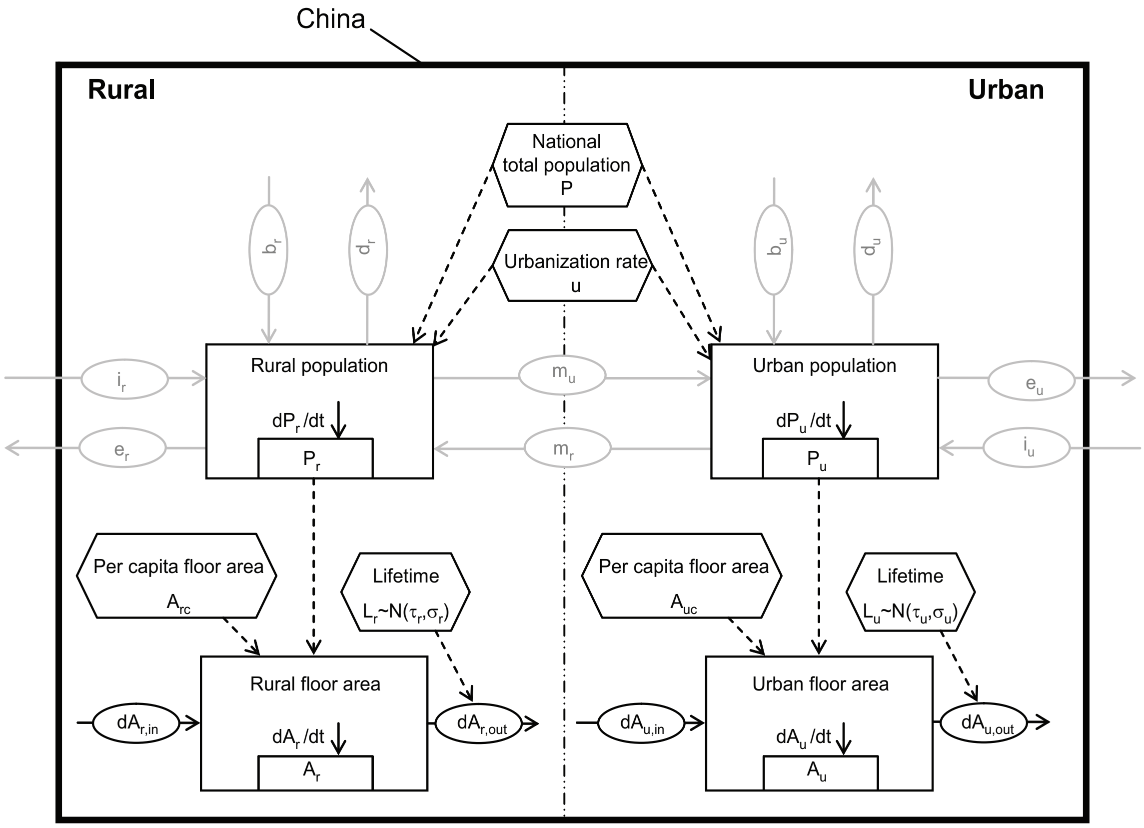


Figure 3.1 Conceptual outline of the stock dynamics model. Rectangles represent processes, ovals depict flows, hexagons illustrate determinants or drivers and dashed lines represent influences between variables. Light grey depicts background flows not appearing in modelling. b_r (b_u), d_r (d_u), i_r (i_u) and e_r (e_u) are annual population flows led by birth, death, immigration and emigration crossing China's border in rural (urban), respectively. m_u and m_r are internal migration flows of population from rural to urban and vice versa.

3.3.2 Mathematical model formulation

The generic stock dynamics model developed by Müller (2006) is applied to both the urban and rural housing sub-systems. The basic principle of the model is the law of mass conservation. Within either sub-system, the demand for dwelling stock in the region is driven by the corresponding population and living standard. Construction activity is determined by how much floor area that has to be replaced because of demolition activity, plus any additional demand caused by increasing stock demand. Demolition activity is determined by the past construction activity with a delay of the service lifetime of the houses. A normal distribution function is assumed for the lifetime of all houses, though the mean and standard deviation of the function is estimated individually for rural and urban system. The underlying equations are given in Appendix B and the six external parameters for the model are listed as follows:

P	National total population
u	Urbanization rate
A_{rc}	Per capita floor area in rural region
A_{uc}	Per capita floor area in urban system
L_r	Lifetime distribution of rural housing ($L_r \sim N(\tau_r, \sigma_r)$)
L_u	Lifetime distribution of urban housing ($L_u \sim N(\tau_u, \sigma_u)$)

3.3.3 Calibration

The historical data from 1900 until around 2006 and the different projections for the period from 2006 until 2100 are inputs to calibrate the model (Figure 3.2). For each external parameter, a low, medium and high variant are estimated for the future period. Except for lifetime estimations and the total population, the low and high variants are chosen as below or above 20% of the medium level. The variations in these future assumptions allow us to cover a wide range of possible development paths and to compare the influence of changes in one or a group of parameters on the entire system (see section *Sensitivity analysis*).

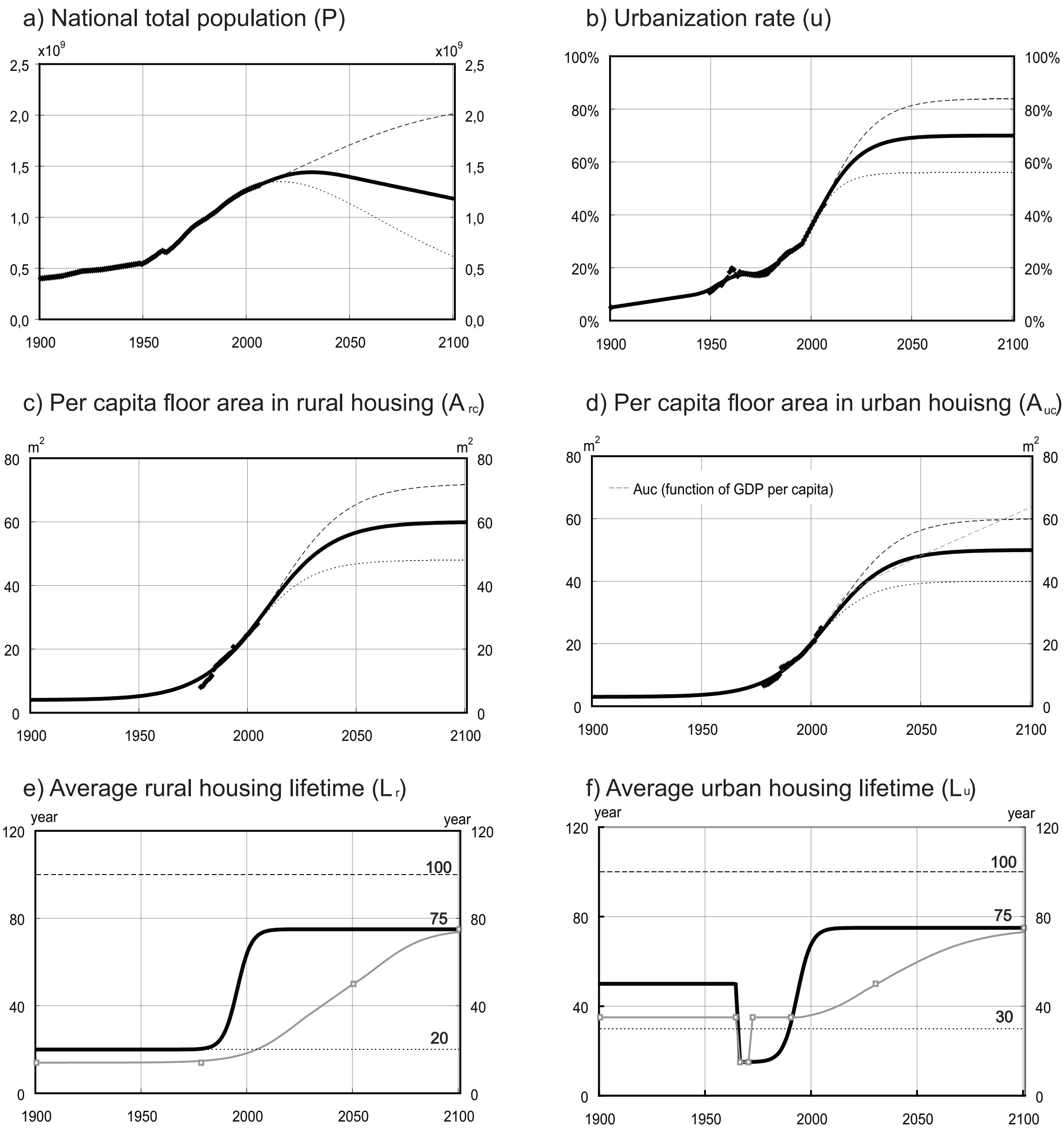


Figure 3.2 Calibration of input parameters, with historic data from 1900 until 2006 and estimation for variants low (dot line), medium (bold solid line), and high (dashed line) from 2006 until 2100. Dashed grey line represents GDP-driving-A_{uc} scenario and solid grey lines represent gradually-increasing-lifetime scenarios. Solid boxes are empirical figures (NBSC 2005; 1980–2008). Grey bordered boxes are estimated lifetime data dots.

Historical data on total national population, urbanization rate[13], and per capita floor area in rural and urban regions are collected from China Statistic Yearbooks (NBSC, 2005, 1980 – 2008) for 1949 to 2006. Total national population before 1949 is obtained from database of University of Utrecht (Ho 1959; http://www.library.uu.nl/wesp/populstat/Asia/chinac.htm). The population projections are quoted from the low, medium and high variants of China's population issued by the United Nations Population Division (UNPD 2003, 2006). The urbanization rate in 1900 is assumed as 5%, and the yearly data between 1900 and 1949 are inserted by linear interpolation. The future urbanization rate is assumed to saturate at a level of 70% for the medium variant, and 56% and 84% for low and high variants, respectively. Various previous forecasts for the future urbanization trend in China are illustrated in Appendix C for comparison. Data of per capita floor area in 1900 are assumed as 4 and 3 square meter per capita for residents in rural and urban areas respectively. In future, we assume, the figures will follow a logistic function to reach 60 m^2 (a level of US in the early 1990s (Guan et al. 2001)) and 50 m^2 (the current level of the Netherlands (Müller 2006)) in Chinese rural and urban areas by 2100, for the medium scenario. The high and low variants in 2100 are set as 20% higher and 20% lower than the medium value, which are 72 m^2 and 48 m^2 for rural area and 60 m^2 and 40 m^2 for urban area, respectively. Considering the rapid economic development in China and the hypothesis that the wealthier people are, the more affluent living space they demand, the GDP-driving-A_{uc} scenario is investigated for the purpose of comparison, in which urban per capita floor area is estimated as a function of China's per capita GDP (dashed grey line, Figure 3.2 (d)). The relation between per capita floor area and GDP per capita has been identified in Hu and colleagues (2010a) and is presented in Appendix D.

The lifetime parameter is a crucial but poorly understood factor. A general view is that the average lifespan of Chinese existing buildings is rather short. Some Chinese experts estimated the real lifetime of the urban buildings constructed in the 1970s

[13] The definition of "urban population" in China has changed in each of the five censuses carried out in 1953, 1964, 1982, 1990 and 2000. The pre-1982 statistical data series of urban population was readjusted by 1982 definition by National Bureau of Statistics of China in 1984(Liu et al. 2003). China's ever-changing official definitions of urban settlements have made it extremely difficult to give an accurate estimate of the magnitude of urbanization, though serious scholarly evaluations have suggested that the official estimate was "a reasonable figure" not far from the actual situation (Zhou and Ma 2003, p. 176; Chan and Hu 2003, p. 64).

and 1980s to be only 30 – 40 years (Song 2005) and for many rural houses not more than 15 years (Huang 2006) due to low quality (Zhao 2003; Ye 2003; Qu 2003). However, since China's economic reform in 1978, the quality of Chinese new house construction has improved greatly, so might the lifetime expectancy. In this study, a variable average lifetime is assumed for dwellings completed in different years for the medium scenario. A normal distribution is used to estimate the lifetime distribution of the dwellings erected at each year. The mean values of the lifetime functions are represented by the estimated average lifetime of dwellings, and the corresponding standard deviations are assumed to be 30% of the means.

Given the improving quality of housing since 1978, for the medium scenario it was assumed that by around 2020 the lifetime of newly completed dwellings, in both urban and rural China, would increase to 75 years, with reference to land lease for urban commercial housing (70 years). The transition of lifetime expectancy from the historical low level to the future high level follows a double logistical function. Rural housing constructed before 1978 is estimated to have a short lifetime of 20 years[14] (bold solid line, Figure 3.2 (e)). In cities, a lifespan of 50 years is estimated for dwellings built before 1966, and a lifespan of 15 year is assumed for the extremely bad quality cohort produced around 1966–1971 (bold solid line, Figure 3.2 (f)). However, these assumptions are uncertain, because the available data do not allow for an analysis of the historical evolution of the dwelling longevity. In addition, the question of how long existing buildings can last depends on current and future decisions on maintenance, etc. To analyze the sensitivity of the lifetime parameter, a variance of average lifetime is chosen, assuming the constant values of 100 and 20 years as the high and low variants for rural dwellings, and 100 and 30 years for urban dwellings. Furthermore, to understand how influential the development pattern of the lifetime is, the gradually-increasing-lifetime scenario is investigated. It assumes that, in the countryside, the lifetime of dwellings built before 1978 is 15 years (as estimated by Huang, 2006); it gradually increases to 50 years (as Chinese national standard, MCC 2005) by 2050 and finally reaches 75 years by 2100 (solid grey line, Figure 3.2 (e)). In cities, except for the 1966–1971 cohort with an extremely short lifetime as 15 years, dwellings completed before 1978 are estimated to have a

[14] Similar to Japanese wooden detached houses (ca. 13–40 years) (Komatsu et al. 1994; Hashimoto et al. 2007).

lifetime as 35 years (as in the study of Yang and Kohler, 2008), and will gradually increase to 50 years by 2030 and reach 75 by 2100 (solid grey line, Figure 3.2 (f)).

Using national total population (P), urbanization rate (u) and per capita floor area ($A_{rc,}$ A_{uc}) calibrated in Figure 3.2, the rural and urban stocks of population and housing in China are calculated and the medium paths of the stocks are presented in Figure 3.3. For each of the floor area stocks the highest and lowest variants are assembled. The product of high P, high u and high A_{uc} is used as the high variant of floor area stock in urban housing and that of low P, low u and low A_{uc} is used for the low variant, as illustrated in the heading picture of Figure 3.5. While for rural housing, the product of high P, low u and high A_{ur} is used as the high variant of floor area and that of low P, high u and low A_{ur} is used for low variant, as illustrated in the heading picture of Figure 3.6. The low and high scenarios represent extreme paths for the future urban and rural housing stocks. They are then used for the sensitivity analysis in the next section.

All the people shifting from rural pool to urban pool are considered as migration[15] (see Figure A.1, Appendix A). The forecast of national population from UNPD's medium projection, predicts that China's population will saturate by 2030. Combining this with the urbanization rate in the medium scenario for population, the rapidly increasing urban population in China will overtake the rural one between 2010 and 2015, and will reach the saturation point around 2040. The rural population in China, which has already been shrinking since 1995, will keep declining in the first half of the 21st century. It indicates that China has experienced the biggest internal migration period since 1996 with a figure of over 15 million migrants per year over the period of a decade. The combined result of the total national population growth and the urbanization trend predicts a steady decrease of the internal migration till the end of 2050, and around 300 million people in China will by then have shifted their lifestyle from rural to urban.

[15] The result is bigger than real internal migration flow, because there are people become urban without moving, such as in the case of rural-urban area transition.

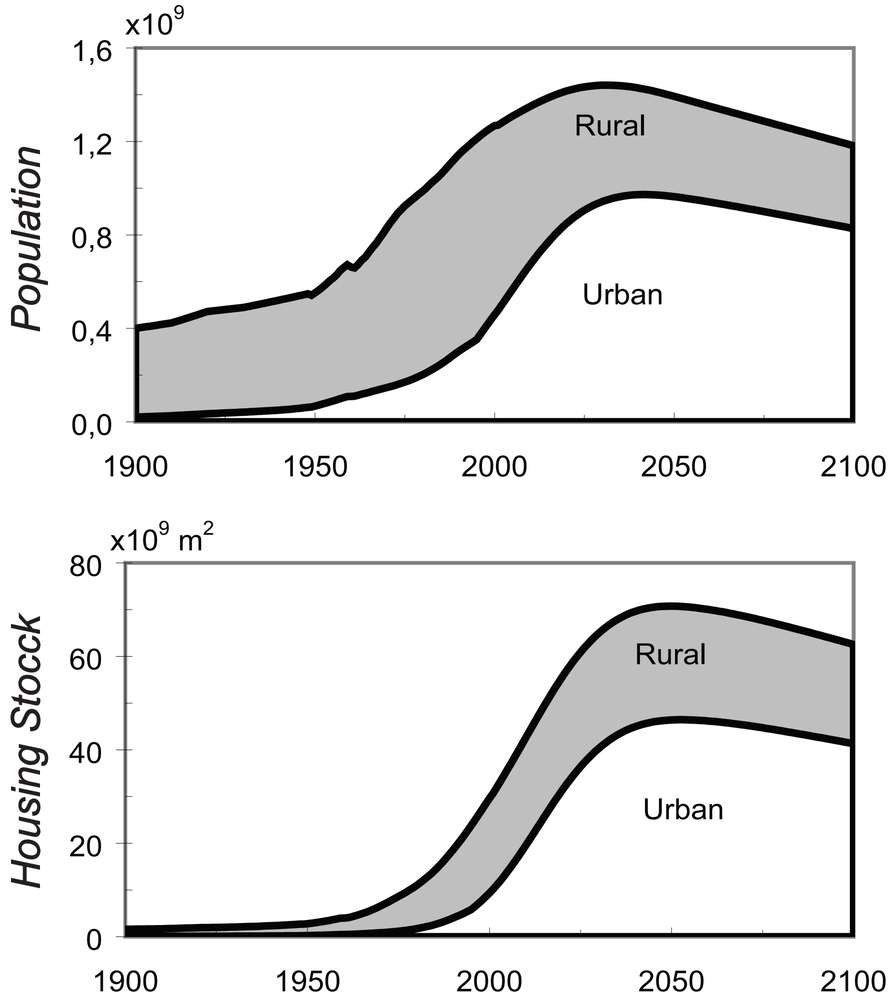


Figure 3.3 Population stocks and housing floor area stocks in rural (grey) and urban (white) China. All input parameters are set at medium values given in Figure 3.2.

3.3.4 Validation

The model was validated using historical data of newly completed residential buildings in rural and urban China, which are available in the statistical yearbook for 1984 until 2006 (see Figure 3.5 (c), (d) and Figure 3.6 (c), (d)). The validation shows that the medium scenario results fit with the climbing trend of urban housing construction. However, the modeling values tend to be higher than the statistical values. This could indicate an underestimation of the lifetime or an inconsistency in the official statistics for population, housing stock, and construction activities. For urban area, a third reason may be the fraction of "urbanization" resulting from the transition of rural to urban areas. According to Yang and Hui (2008), during 2001 – 2006, about 18 – 20 million people has shifted from rural to urban stock annually, among which nearly 5 million/year are due to official designation of new cities without really moving and do not demand housing from urban stock. It means about 30% of annual rural-urban migration should be subtracted from urban population stock when calculating the demand for new urban housing construction. This factor has been considered in the study and the adjusted result for medium scenario is presented in Figure 3.5 (d) (dotted grey line). As the rural-urban migration is expected to decrease through 2050, its effect on overestimation also decreases over the time. This adjustment amends the overestimated peak construction demand. It, however, does not affect the projected pattern of oscillation in Chinese demand for urban housing construction.

For rural area, the results correctly reflect the trend of declining rural housing construction. While, compared to the statistical data, the model seems also overestimate the rural housing construction. This might attribute to the poor statistics, considering that the rural houses are mainly built by individual farmers and less monitored by the government. Moreover, according to the historical data, there was a higher peak of rural new housing construction in 1986 and another lower peak in 1995. However, there is only one peak appearing in about 1995 in the simulation results. The reason for the delayed peak could be the underestimate of the lifetime of rural houses built in the past. The difference in the shape reflects that the power of this model is limited for capturing short-term fluctuations. Nevertheless, one should be aware that, this stock dynamics driving is designed for grasping long-term trend. In order to capture the essential long-term behavior, some short-term fluctuations are treated as noise and removed during smoothing the input data.

3.4 Stocks and flows of housing in China

This section presents the simulation results for stocks and flows of urban and rural housing in China. The base case scenario is defined as the alternative applying the medium values for all input parameters, and the results are shown in Figure 3.4.

3.4.1 Medium scenario results

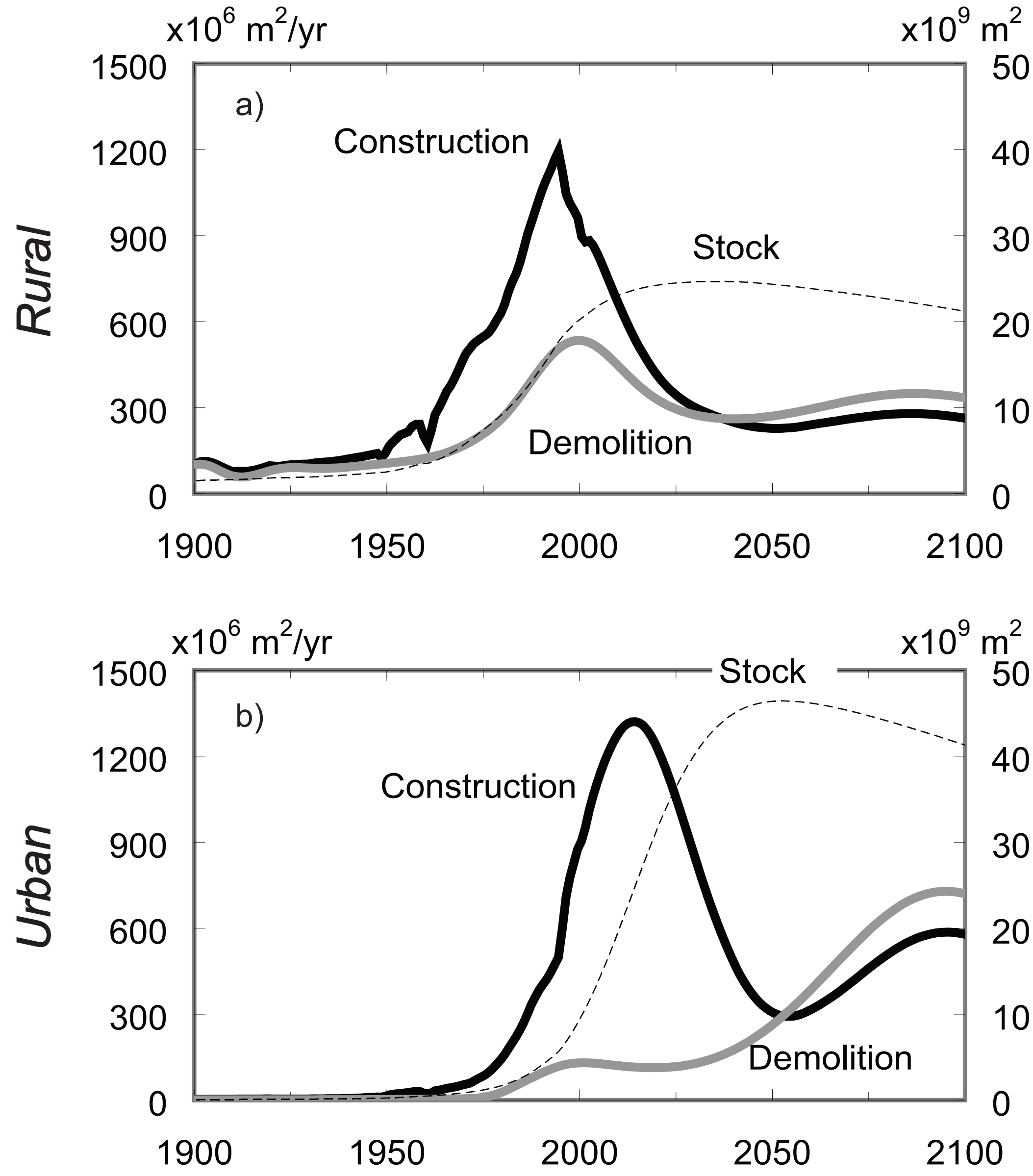


Figure 3.4 Simulation results for housing floor area stocks and flows in rural and urban China. Stocks are measured on the right axis and flows on the left. All input parameters are set at medium values given in Figure 3.2.

The medium scenario for the rural housing system (Figure 3.4 (a)) assumes a saturated housing stock around 2025 as the combined result of the declining rural population (Figure 3.3 (a)) and the increasing per capita housing space (Figure 3.2

(c)) in rural China. A strong oscillation has been found in new construction demand for the rural housing system as well, from 1.2 billion to 0.2 billion square meters, which is about a factor 6 of the peak of new construction. This significant drop has started about one decade ago and will reach its lowest level around 2050 and stay at roughly this low level through the end of the current century. Due to the short lifetime estimation (20 years before 1978) the demolition activity already peaked around 2000. Currently there are more demolition activities from rural area than from urban area, but the rural is shrinking, while the urban is increasing after 2030 and will overtake the rural one in the second half of this century.

The medium scenario for the urban housing system (Figure 3.4 (b)) assumes a saturated housing stock around 2050 due to the saturated urban population (Figure 3.3 (a)) and the stabilized per capita floor area (Figure 3.2 (d)). Demolition activity started climbing around 1975 because of the replacement of the low quality dwellings constructed during 1966-1971, and has stabilized at current level since about 1995. The demolition activity will stay more or less on the same level by 2030, and will rise only at the beginning of the second half of the century, when the houses built during the first building surge will start retiring. Rapid urbanization and fast improving living standard of urban habitants lead to an accelerated growth of housing construction in the last decades. The medium scenario indicates that new construction activity will reach a peak of 1.3 billion square meters around 2011, subsequently, new construction declines for about 40 to 50 years to 0.3 billion square meters per year, which is about a quarter of the peak of new construction. This peak, which marks the time when the stock growth starts to slow down (inflection point), can be expected to come very soon, if it has not arrived already. The oscillation is a consequence of the fast growth in the past: the build-up time of the housing stock (ca. 30 years), is shorter than the expected lifetime of the buildings. The first rise of new construction is caused by the growth in stock demand, and when the saturation of the stock occurs, the demand for new construction will be due to replacement only. Because of the expected lengthening lifetime of buildings since 1978, the demand for replacement will kick-in only after 2050, and a period of low demand for new construction emerges and the oscillation occurs.

3.4.2 Sensitivity analysis

The simulation results from the previous section are based on the medium variant for all parameters. As there are significant uncertainties regarding how these determinants will behave in the future, more simulations are performed to analyze the relative importance and influence of the parameters of floor area stock and housing lifetime for the variants assembled and described in section 'Calibration', while other parameters are on medium levels. The extreme values of the determinants on housing stock behavior and the average dwelling lifetime are investigated. Meanwhile, to understand the influence of development patterns of the parameters, the scenarios GDP-driving-A_{uc} and gradually-increasing-lifetime are examined. Quantification of the input parameters is presented in Figure 3.2. Results of the sensitivity analysis are illustrated in Figure 3.5 and Figure 3.6 for urban and rural housing systems, respectively.

The sensitivity analysis for floor area stock in urban area shows that:

- The impact of floor area stock to demolition activity is very small for the next couple of decades. But it will have a considerable impact for a very long term after 2050 and at the end of this century, because the demolition activity comes one lifetime delay after the new construction.
- The oscillation phenomenon in new construction is independent of stock scenarios, and increasing or decreasing the overall floor area stock, will not affect the oscillations within the projection period. While relatively speaking, the larger the future housing stock is, the less dramatic the oscillations will be. If the stock growth is prolonged, the peak can be delayed in time, but the decline cannot be avoided.
- If the level of China's urban per capita floor area is largely determined by its GDP development, China is at an even sharper downwards turning point in its demand for new urban housing construction.
- If the macro-control measures of Chinese government (e.g. requiring 70% of new constructed house units be smaller than $90m^2$, discouraging second home purchase) slow down the increase pace of its urban per capita floor area, a lower recent peak level is expected, followed by an even deeper shrinkage in the demand for urban housing construction until 2050.

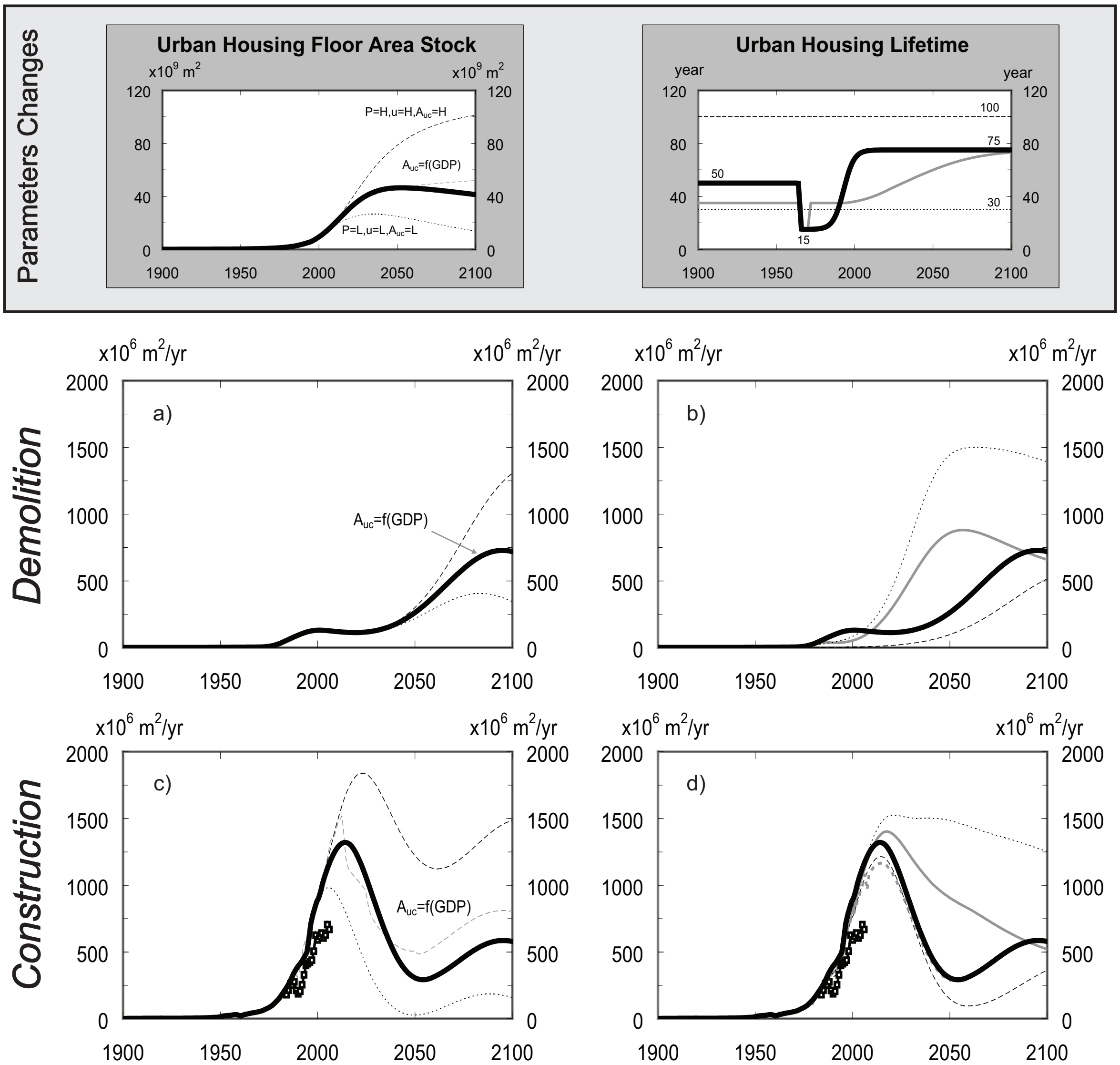


Figure 3.5 Sensitivity analysis for urban housing system. Outflow (Demolition) and inflow (Construction) in square meters per year, as influenced by floor area stock and lifetime variants low (dot line), medium (bold solid line), and high (dashed line). Dashed grey line represents GDP-driving-A_{uc} scenario, solid grey line represents gradually-increasing-lifetime scenario and dotted grey line denotes medium scenario results adjusted by rural-urban land transition. Boxes are empirical figures of annually completed residential floor areas in urban China (NBSC 2005; 1980–2008). H = high variant; L = low variant.

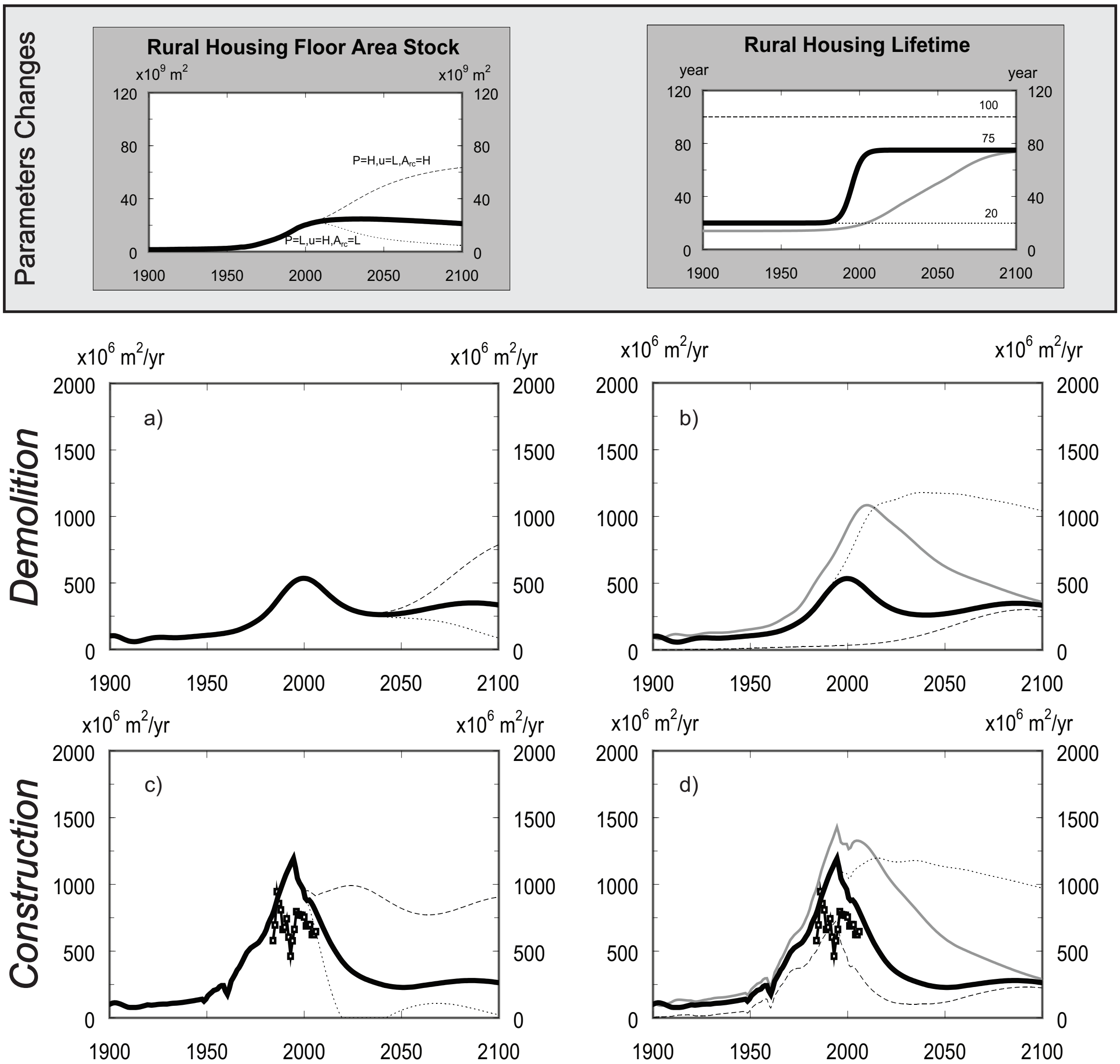


Figure 3.6 Sensitivity analysis for rural housing system. Outflow (Demolition) and inflow (Construction) in square meters per year, as influenced by floor area stock and lifetime variants low (dot line), medium (bold solid line), and high (dashed line). Solid grey line represents gradually-increasing-lifetime scenario. Boxes are empirical figures of annually completed residential floor areas in rural China (NBSC 2005; 1980–2008). H = high variant; L = low variant.

The sensitivity analysis for housing lifetime in urban areas shows that:

- The oscillation in new construction is mainly dependent on the lifetime of the buildings; the longer lifetime of the buildings is the stronger oscillation will be. For the extremely short lifetime scenario, almost no oscillation is observed in the simulation result. A better understanding of the building lifetimes is therefore essential for forecasting future construction and demolition activities.
- If the existing urban dwellings in China have a short lifespan of 30 years and if this situation will continue through all the 21st century, China may not encounter oscillation in urban housing construction. However, its continuous high construction level will be companied by a dramatic rise of demolition level, which can be rather problematic from resource supply and waste management points of view.
- If the lifespan of Chinese urban dwellings will gradually increase over the 21st century, a less steeper but continuous decrease may be expected in China's urban residential construction from a few years later till the end of this century.
- If the rural-urban land transition is considered, and the effect that about 30% of annual rural-urban migration, calculated according to Chinese urbanization development, does not demand new urban housing construction is adjusted, the simulated peak value of construction demand can be 20% lower, but the strong oscillation pattern remains.

It is important to remember that the results presented here reflect a national aggregate. Since construction activity varies greatly between different regions, we can expect that the oscillation may be much more severe in some areas than in others. The effect will be particularly strong for the small new cities or towns built up in a very short time in the rapid urbanization progress.

The sensitivity analysis for rural housing floor area stock shows that:

- For demolition activity, there is no impact of stock scenarios for the next couple of decades, but in the long run the impacts will be larger.

- The construction activity strongly depends on future demand of floor area stock. For the saturation and shrinking stock scenarios, strong oscillations will occur due to the delayed demand for replacement, while in the growing stock scenario the oscillation is damped because the new construction has to meet not only the demand for replacement but also that for increasing stock.

The sensitivity analysis for rural housing lifetime shows that:

- The shorter lifetime of the buildings is the higher the construction and demolition activity level is. For the constantly short lifetime scenario (20 years), the demolition level might climb to be more than double of the peak estimated by the medium scenario and stay at the high level through the 21st century. However, the constantly short lifetime scenario seems not being supported by historic construction figures (Figure 6d) which show a general declining trend since late 1980s. Instead, the statistic data seem support a middle path between the medium and high lifetime scenarios.
- If the extremely short lifespan of existing rural housing 15 years (as estimated by some Chinese experts) would increase slowly to 75 years by 2100, the demolition demand in Chinese rural housing may be right on the peak now. The peak value can be more than double of the medium scenario results. However, available data do not allow us to judge how high the real demolition level in Chinese countryside is. Though, the increasing 'hollow villages'[16] in recent years indicate that there are growing number of Chinese rural houses abandoned. Both gradually-increasing-lifetime and medium scenarios suggest that the current high demolition demand in Chinese rural housing is to decrease over the next few decades.
- Driven by the estimated higher replacement demand, gradually-increasing-lifetime scenario projects a higher current construction demand than medium scenario but a similar reduction trend in a long run. The gradually increasing scenario seems to have captured the two rural construction peaks in the

[16] In the countryside, 'hollow villages' have become increasingly common. As peasants' incomes increase, they build new and larger houses, often on the outskirts of the villages encroaching on nearby farmland, rather than renovate their existing homes. As villagers move to their new houses on the outskirts, the village becomes 'hollow' as the old parts of the village become increasingly empty of people (Lin 2007 pp.1848).

history, but it overestimated the construction level even more seriously, indicating a probable underestimation of dwelling lifespan.

- If an extremely short lifetime would not be the case for the newly constructed rural houses, how many people would like to live in the countryside seems more relevant for projecting Chinese future demand in rural residential construction.

3.5 Discussions

Limitations of the model

The model used in this study is a simplified physical accounting causal model with limitations, and with uncertainties only partially covered by scenario analysis. When interpreting its results, several items should be aware of. Firstly, this model is suitable for projecting long-term trend, but not precise for short-term dynamics. As shown in the validation that the model correctly reflects the general long-term trend but overestimates the recent new construction level in urban areas. One reason for this overestimation could be attributed to the model neglects the rural-urban land transition in China's urbanization. It is because during such land transition, the people become urban do not really move, thus do not lead to additional demand for urban housing construction. Adjusted results show that the model overestimates the recent peak value in urban housing construction by nearly 20%. However, the pattern of oscillation in construction demand holds, even after this adjustment. Secondly, the analysis results of the model are not rigid predictions; they are feasible scenarios - the logic consequences of the potential paths of the future population's demand for housing floor area and the lifespan of dwellings. The model states that if the Chinese urban dwellings completed from the 1980s will last longer than 30 years, China's demand for new housing construction will soon enter a downward trend. But it cannot answer whether the lifespan of Chinese urban dwellings has been or will be prolonged. A better understanding of the lifespan of existing buildings and further observations of the evolution trend of this parameter will increase the precision of this model projection. Nevertheless, the wide variance of lifespan scenarios investigated in this study seems to indicate the robustness of the results.

Implications of the oscillation

The oscillation in urban housing construction has at least two impacts: less construction material demand and less construction activities. The impact of less material demand is applausive. From a resource reservation point of view, the decreasing material demand implies that urbanization in China should not raise the problem of material scarcity in housing construction. However, the impact of less construction activities can be problematic. First of all, if the oscillation phenomenon would apply to the whole construction sector, a large scale layoff and a potential unemployment problem might be foreseen. At the second, less new construction implies less effective of the current design-focused building regulations on achieving a high performance building stock in China. Thirdly, residential construction is one of the biggest steel users in China. The expected construction reduction may affect the steel industry significantly. In the second stage of our study (Hu et al. 2010b), the potential impacts on steel industry and the measures to meditate the negative consequences are investigated.

Options to dampen the oscillation

The expected oscillation in construction demand may affect the stability of the construction industry, and its upper stream material suppliers. According to this study, there are basically two types of strategies to mitigate the oscillation. One is to encourage high floor area demand in the future. This option may delay the problem and lead to high construction material input, but do not diminish the oscillation. Also, the macro-control policy of Chinese government on housing production structure and second home purchase does not support the high floor area scenario. This option may not be realistic. Another choice is to continue the current short lifespan situation of the buildings. This option may dampen the oscillation in construction, at the expense of significantly increasing demolition waste and resource demand. But it also offers the chance to replace some poorly performing buildings and provides the possibility to recycle secondary resources from demolition for replacing primary resource use. Would this be a feasible option for China to progress a sustainable construction sector? Further researches are indicated to explore the trade-offs between recycling and durability. The model presented in this study provides a framework for the future investigations.

3.6 Conclusions

This study is a first attempt to analyze the long-term dynamics of the Chinese housing stocks using a vintage approach for urban and rural dwelling inventories. By using population, per capita floor area, and dwelling lifetime as the main drivers, this approach allows for a simultaneous forecast of both construction and demolition rates. Several scenarios are generated and compared with a base medium scenario for a better understanding of the future projections. The main findings are:

- In the urban housing system, almost all scenarios show a declining construction activity for the coming decade, except if the average dwelling lifetime is below ca. 30 years and the demand for replacement will kick-in to counter the declining demand for stock expansion.
- In the rural housing system, demand for new construction has already been decreasing since the last decade. The levels of future construction activity will largely depend on the urbanization pace, if the extremely short lifetime ca. 20 years in the future will not be the case, as the current statistic data suggest.
- Demolition activity depends largely on lifetime assumption of existing buildings. The general trend is that, demolition level will rise in cities sooner or later over the 21st century, while it has probably already reached the top in the countryside. A high but decreasing demolition level may be expected in Chinese countryside for the next few decades. Given the significant magnitude of current rural demolition level, it seems worthwhile to have a more detailed review of the potential for recycling the scraps from Chinese rural housing stock.
- The lifetime distribution of dwellings is one of the most influential factors, determining future construction and demolition levels. Better understanding of the lifetime expectancy of Chinese housing stocks will improve the projection power of this model.

Reference to Chapter 3

Beijing Municipal Chorography Compiling Council (BMCCC) 1999. Volumes: Architecture chorography, Beijing chorography (in Chinese)

Bergsdal, H. et al. 2007a. Dynamic material flow analysis for Norway's dwelling stock. Building Research & Information, 35(5):557 – 570.

Bergsdal, H. et al. 2007b. Projection of construction and demolition waste in Norway. Journal of Industrial Ecology 11(3):27 – 39.

Brattebø, H., et al. 2009. Exploring built environment stock metabolism and sustainability by systems analysis approaches. Building Research & Information 37(5):569 – 582.

Center for Development Studies at the State Council 1991. China Economic Yearbook. Economic Management Press, Beijing.

Chan, K.W. and Y. Hu 2003. Urbanization in China in the 1990s: new definition, different series, and revised trends. The China Review 3(2):49–71.

Eurostat (European statistics) 2009. available on line at : http://epp.eurostat.ec.europa.eu/. Accessed on May 2009.

Fernández, J.E. 2007. Resource consumption of new urban construction in China. Jurnal of Industrial Ecology 11(2):99 – 115.

Garnaut, R. and L. Song 2006. China's resources demand at the turning point. In: Garnaut, R. and Song, L. (eds.) The Turning Point in China's Economic Development, Asia Pacific Press, Canberra, pp. 276–293.

Guan, K., K. Feng and S.X. Zeng 2001. Urban housing reform and development in China. Building Research & Information 29(4):286–292.

Guest, R.S. and I.M McDonald. 2007. Global GDP shares in the 21st century – An equilibrium approach. Economic Modelling 24: 859 – 877.

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

Ho, Ping-Ti 1959. Studies on the Population of China, 1368-1953, Cambridge, Massachusetts: Harvard University Press.

Hu, M., E. van der Voet and G. Huppes. 2010a. Dynamic material flow analysis for strategic construction and demolition waste management in Beijing. Journal of Industrial Ecology 14(3). doi: 10.1111/j.1530-9290.2010.00245.x

Hu, M., S. Pauliuk, T. Wang, G. Huppes, E. van der Voet and D.B. Müller. 2010b. Iron and steel in Chinese residential buildings: a dynamic analysis. Resources, Conservation & Recycling 54(9):591–600. doi: 10.1016/j.resconrec.2009.10.016.

Huang, Y.Q. 2004. The road to homeownership: a longitudinal analysis of tenure transition in urban China (1949-94). International Journal of Urban and Regional Research 28:74–795.

Huang, W. 2006. The speech on the meeting of 'Building New Countryside of the Socialist Society', 21 March, Beijing, Ministry of Construction of China, Beijing (in Chinese, available on line: http://www.cin.gov.cn/ldjh/jsld/200612/t20061225_37469.htm)

Kohler, N. and Yang, W. 2007. Long-term management of building stock. Building Research & Information 35(4):351 – 362.

Komatsu, Y., Y. Kato and T. Yashiro 1994. Survey on the life of buildings in Japan. In: CIB W70 Symposium, Tokyo. Vol. 1. p. 111 – 118. available at http://www.f.waseda.jp/ykom/CIB94.pdf.

Lan, X. 2008. Decoding China's Urbanization, Beijing Review. available on line: http://www.bjreview.com/print/txt/2008-07/05/content_132142.htm.

Liu, S., X. Li and M. Zhang 2003. Interim Report, Scenario Analysis on Urbanization and Rural-urban Migration in China, International Institute for Applied Systems Analysis, Laxenburg, Austria. Available on line: http://www.iiasa.ac.at/Admin/PUB/Documents/IR-03-036.pdf.

Logan, J.R., Y. Fang and Z. Zhang 2010. The winners in China's urban housing reform. Housing Studies 25(1):101–117.

Ministry of Construction of People's Republic of China (MCC) 2005. Code for Design of Civil Buildings (GB50352-2005), China Planning Press, Beijing.

McKinley, T. and L. Wang 1992. Housing and wealth in rural China. China Economic Review 3(2):195–211.

Müller, D.B. et al. 2004. Long-term coordination of timber production and consumption using a dynamic material and energy flow analysis. Journal of Industrial Ecology 8(3):65–87.

Müller, D.B. 2006. Stock dynamics for forecasting material flows – case study for housing in the Netherlands. Ecological Economics 59:142 – 156.

National Bureau of Statistics of China (NBSC) 2005. Statistical Compendium of China 1949 – 2004, China Statistical Press, Beijing.

NBSC. 1980 – 2008. China Statistical Yearbook 1980 …2008, China Statistical Press, Beijing.

Qu, T. 2003. Enhance rural housing planning and promote urbanization construction. Shanghai Rural Economy 9:26-27 (in Chinese).

Sartori, I. et al. 2008. Toward modeling of construction, renovation and demolition activities: Norway's dwelling stock, 1900 – 2100. Building Research & Information 36(5): 412 – 425.

Shaw, V.N. 1997. Urban housing reform in China. Habitat Intl. Vol. 21, No. 2, pp. 199-212.

Shen, L. et al. 2005. Urbanization, sustainability and the utilization of energy and mineral resources in China. Cities 22(4):287-302.

Song, C.H. 2005. Whole life and highgrade quality-stick to the implement housing performance certification. Housing Science 290(8):287-302.

Song, Y. and C. Ding eds. 2007. Urbanization in China: Critical issues in an era of rapid growth, ISBN 978-1-55844-175-0, Lincoln Institute of Land Policy, Cambridge.

United Nations Population Division (UNPD). 2003. World Population in 2300, Draft of 9 December 2003, United Nations, New York.

UNPD. 2006. World Population Prospects: The 2006 Revision, United Nations, New York (available in http://esa.un.org/unpp).

UNPD. 2007. World Urbanization Prospects: The 2007 Revision, United Nations, New York (available in http://esa.un.org/unup).

University of Utrecht, http://www.library.uu.nl/wesp/populstat/Asia/chinac.htm.

Yang, H. and J. Hui 2008. Forecasting housing supply and demand in China for next five years. Shanghai Real Estate July 2008: 26-30 (in Chinese).

Yang, W. and N. Kohler 2008. Simulation of the evolution of the Chinese building and infrastructure stock. Building Research & Information 36(1):1-19.

Ye, M. 2003. Problems and strategies of China's rural housing industrialization. Information of China Construction 12:31-33 (in Chinese).

Wang, Y. and A. Murie 1999. Housing Policy and Practice in China, Macmillan Press, New York.

World Bank. 2008. UN Common Database. http://unstats.un.org/

Wu, C. 1989. Forty years of housing construction in Beijing. City Planning 5:13 – 17.

Zhang, X.Q. 1997. Chinese housing policy 1949-1978: the development of a welfare system. Planning Perspectives 12(4):433 – 455.

Zhao, Z. 2003. Dualistic system of rural and urban housing in China. Urban Planning, 5:73-76 (in Chinese).

Zhou, Y. and L. Ma 2003. China's urbanization levels: reconstructing a baseline from the Fifth Population Census, The China Quarterly, 173, p.176 – 196.

Zhu, X.D. et al. 2000. Housing and economic development in Suzhou, China: a new approach to deal with the inseparable issues. Joint Center for Housing Studies W00-4. Harvard University.

Appendices to Chapter 3

Appendix A: Calculation of internal migration flow

The net internal migration is calculated from the mass balance on the processes with population stocks. As illustrated in Figure 3.1, the balance equations for urban and rural population stocks are given in equations (A1) and (A2).

$$\frac{dP_r}{dt} = (i_r - e_r) + (b_r - d_r) - (m_u - m_r) \qquad (A1)$$

$$\frac{dP_u}{dt} = (i_u - e_u) + (b_u - d_u) + (m_u - m_r) \qquad (A2)$$

The net internal rural-urban migration flow (m_u-m_r) can be obtained when the net migration flow (i_r-e_r) or (i_u-e_u) and natural population growth (b_r-d_r) or (b_u-d_u) are known. However, the net migration and natural population growth are not specified for rural and urban areas in China. The equations have to be converted to adopt the readily available national data. The balance equation for the nation is resulted by adding (A1) and (A2) together as shown in equation (A3), where P (=P_r+P_u) is total national population, *i* (=i_r+ i_u) and *e* (=e_r+ e_u) represents total immigration and emigration, and *b* (=b_r+ b_u) and *d* (=d_r+ d_u) denote natural population change from birth and death at year t in China.

$$\frac{dP}{dt} = (i - e) + (b - d) \qquad (A3)$$

In China, on national level, the net migration rate (=(*i*-*e*)/P) as well as birth rate (=*b*/P), death rate (=*d*/P) and natural population growth rate (=(*b*-*d*)/P) are available in time series in Nation Statistic Yearbooks (NBSC, 2005, 2007). China's future net migration rate, birth and death rate by 2050 can be found in the projections of United Nation Population Division (UNPD, 2006). The historical figures and UNPD projection show that the net migration flow through China's border is significantly smaller than the natural population change, less than 1% of natural population growth in most early years and around 5% in last 5 years. The net migration flows (*i*-*e*), (i_r-e_r) and (i_r-e_r) are neglected and equations (A1), (A2) and (A3) are simplified as:

$$\frac{dP_r}{dt} \approx (b_r - d_r) - (M_u - M_r) \qquad (A1')$$

$$\frac{dP_u}{dt} \approx (b_u - d_u) + (M_u - M_r) \tag{A2'}$$

$$\frac{dP}{dt} \approx (b - d) \tag{A3'}$$

Assume both rural and urban regions have a natural population growth rate as the national one. According to the definition of urbanization rate *u* as u=P_u/P, the net internal rural-urban migration flow (m_u-m_r) can be obtained by equation (A4) or (A5), based on the change of rural or urban population stock.

$$(M_u - M_r) \approx (b - d)(1 - u) - \frac{d(P \cdot (1 - u))}{dt} \tag{A4}$$

$$(M_u - M_r) \approx \frac{d(P \cdot u)}{dt} - (b - d)u \tag{A5}$$

Where $u = \frac{P_u}{P}$, $(i - e) \approx 0, (i_r - e_r) \approx 0, (i_u - e_u) \approx 0$ and $\frac{b - d}{P} \approx \frac{b_r - d_r}{P_r} \approx \frac{b_u - d_u}{P_u}$.

Fed with historical figures of *b*, *d*, *u*, P from NBSC for period between1949 and 2007 and the forecasting data from UNPD's medium scenario, the results of (m_u-m_r) calculated from (A4) and (A5) are slightly different (less than 1%). The net internal rural-urban migration in China is calculated as the average of the results from the two equations and is illustrated in Figure A.1.

Figure A.1a illustrates the development of China's population and its rural and urban components. The national population after 2007 is quoted from UNPD's medium projection, which shows China's population will peak by 2030. Matching with the urbanization rate in medium scenario of the study, the urban population in China which is fast increasing recently will overtake the rural one at about 2010 and will reach the saturation point around 2040. While the rural population in China which starts shrink since 1995 will keep declining in the first half of the 21^{st} century. The Figure A.1 (b) shows China has experienced the biggest internal migration period since 1996 with a yearly migration number more than 15 million for a decade. After a drop during 2004 and 2006, the number dramatically jumps to near 29 million at in 2007. While the combination result of the total national population growth and the urbanization trend foresee a steadily decrease till the end of 2050 and around 300 million people in China will shift their lifestyle from rural to urban by that time.

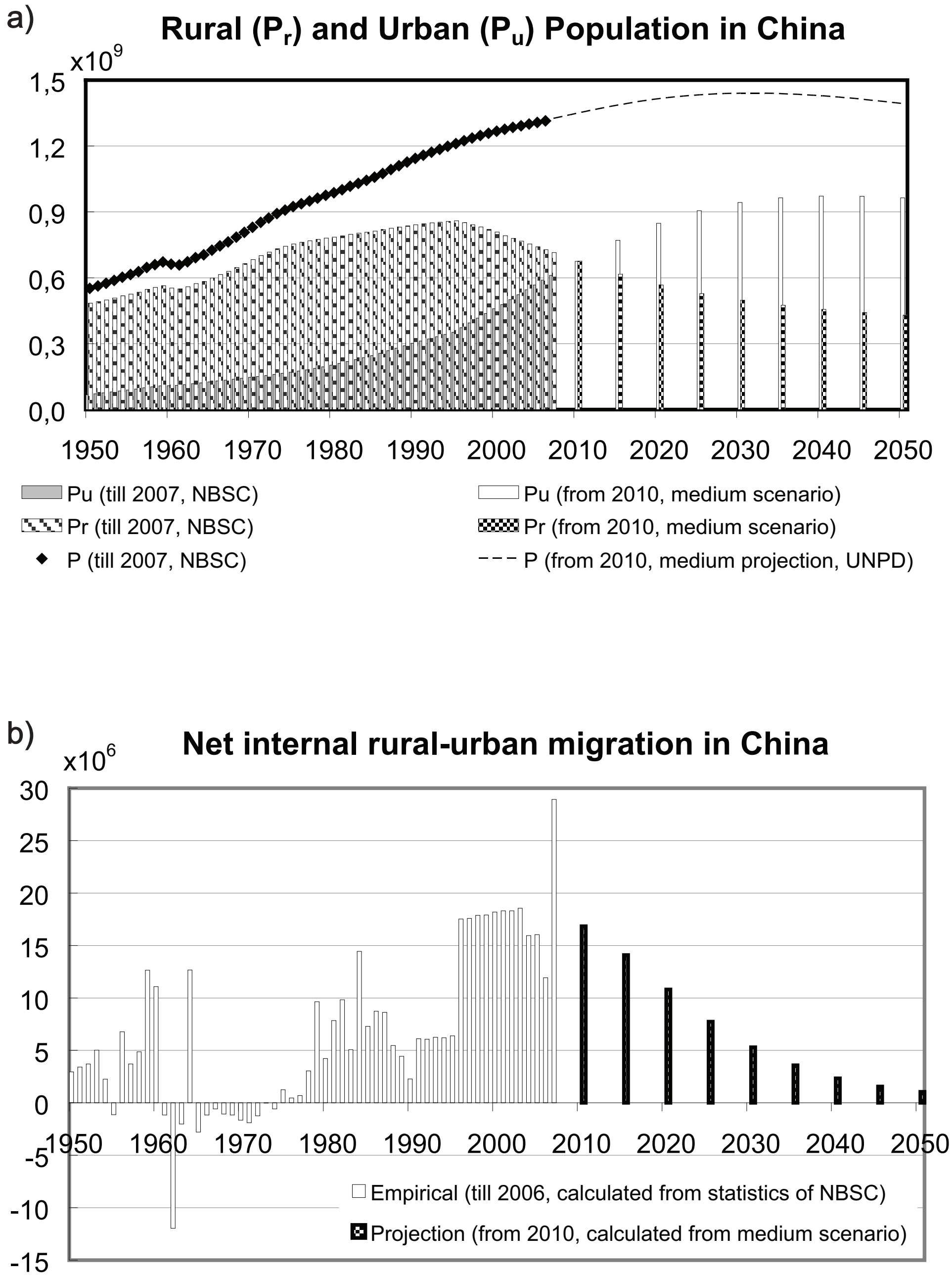


Figure A.1 Population components and net internal rural-urban migration in medium scenario. Data before 2006 are historical figures derived from National Bureau of Statistics of China (NBSC 1984-2007, 2005); forecasting data of China's national population is quoted from United Nations Population Division (UNPD 2006); future urbanization rate is the medium variant of the study with a saturation level at 70%.

Appendix B: Stock dynamics model for housing floor area

The generic stock dynamics model developed by Müller is applies for rural and urban housing stock individually. The central equations are given as following:

$$A_r(t) = P_r(t) \cdot A_{rc}(t) = P(t) \cdot (1 - u(t)) \cdot A_{rc}(t) \tag{B1}$$

$$A_u(t) = P_u(t) \cdot A_{uc}(t) = P(t) \cdot u(t) \cdot A_{uc}(t) \tag{B2}$$

$$\frac{dA_{r,out}(t)}{dt} = \int_{t_0}^{t} L_r(t,t') \cdot \frac{A_{r,in}(t)}{dt} dt' \tag{B3}$$

$$\frac{dA_{u,out}(t)}{dt} = \int_{t_0}^{t} L_u(t,t') \cdot \frac{A_{u,in}(t)}{dt} dt' \tag{B4}$$

$$L_r(t,t') = \frac{1}{\sigma_r \sqrt{2\pi}} \cdot e^{-\frac{(t-t'-\tau_r)^2}{2\sigma_r^2}} \tag{B5}$$

$$L_u(t,t') = \frac{1}{\sigma_u \sqrt{2\pi}} \cdot e^{-\frac{(t-t'-\tau_u)^2}{2\sigma_u^2}} \tag{B6}$$

$$\frac{dA_{r,in}(t)}{dt} = \frac{dA_r(t)}{dt} + \frac{dA_{r,out}(t)}{dt} \tag{B7}$$

$$\frac{dA_{u,in}(t)}{dt} = \frac{dA_u(t)}{dt} + \frac{dA_{u,out}(t)}{dt} \tag{B8}$$

Equations (B1) and (B2) indicate the urban and rural housing stocks are determined by the size of national population, the level of urbanization and per capita housing demand in either region. Equations (B3) and (B4) illustrate the outflow from the housing stock is determined by the past inflow, with a delay of the service life of the houses. Equations (B5) and (B6) assume the lifetime of rural and urban houses follows normal distribution function. Equations (B7) and (B8) forecast the future rural and urban inflows of housing stock by balancing the rural and urban housing processes respectively.

Appendix C: Various forecasts for urbanization rate in China

Various forecasts for the future urbanization trend in China and the variants adopted in the study are illustrated in Figure C.1. Precious forecasts are all projected only by 2050, where the data in China Energy Strategy (2000-2050) and those from the Center of China Population Information Research (Shen et al. 2005) are available for 10-year steps, while the UNPD's urbanization prospects are available for 5-year steps.

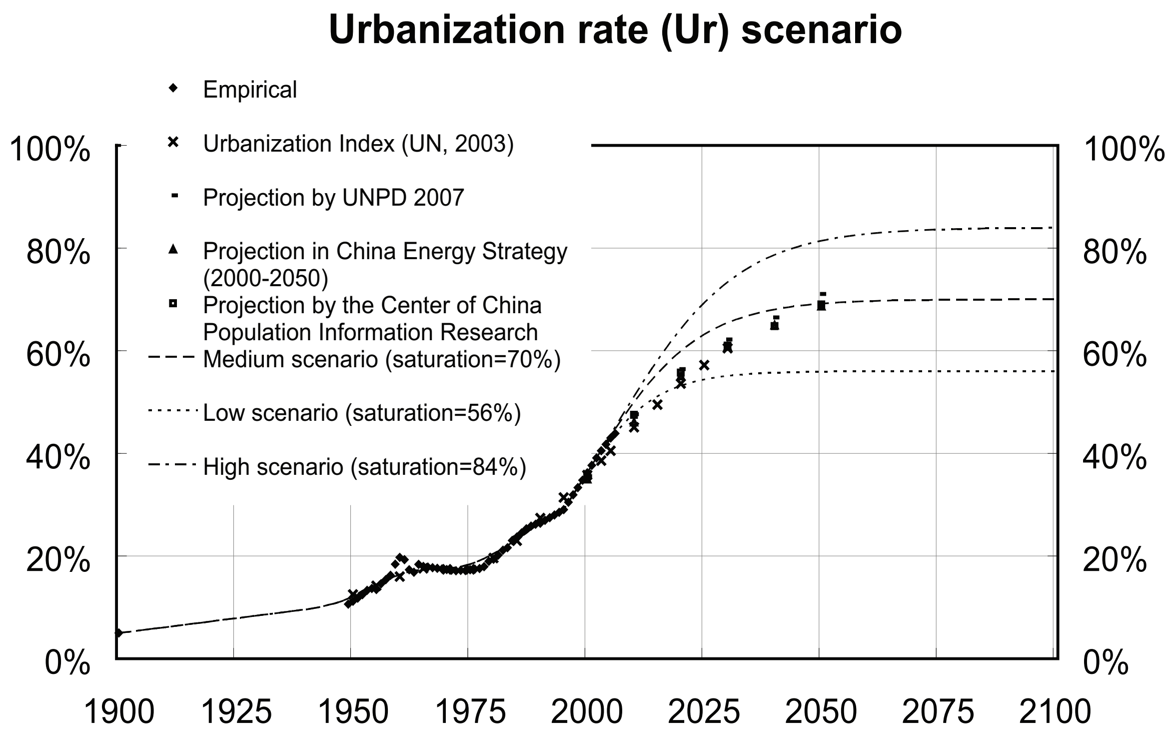


Figure C.1. Various forecasts for urbanization rate in China. Empirical data until 2006 are derived from National Bureau of Statistics of China (NBSC 1980-2007, 2005).

Appendix D: Urban per capita floor area as function of GDP per capita

The parameter per capita floor area represents people's living standard. Based on the hypothesis that the wealthier people are, the more affluent living space they demand, this parameter can be considered as a function of the socio-economic variables such as GDP. As illustrated in Figure D.1, previous housing case studies (Hu et al. 2010a; Bergsdal et al. 2007a; Müller 2006) show a strong logarithmic regression relationship has been found in all cases between the per capita floor area and the local GDP per capita. For the purpose of comparison, this study adopts a variant of per capita floor area as a function of per capita GDP. Historical figures of floor area and GDP are used to calibrate the regression formula. The future GDP growth quoted from World Economic Outlook Database for 2008 – 2013 and other economists' forecasts (Guest and McDonald 2007) are used for per capita floor area projection. The resulted urban per capita floor area as a function of per capita GDP is presented in Figure 3.2 (d) with other variants and the sensitivity analysis for the different projections are shown in Figure 3.5.

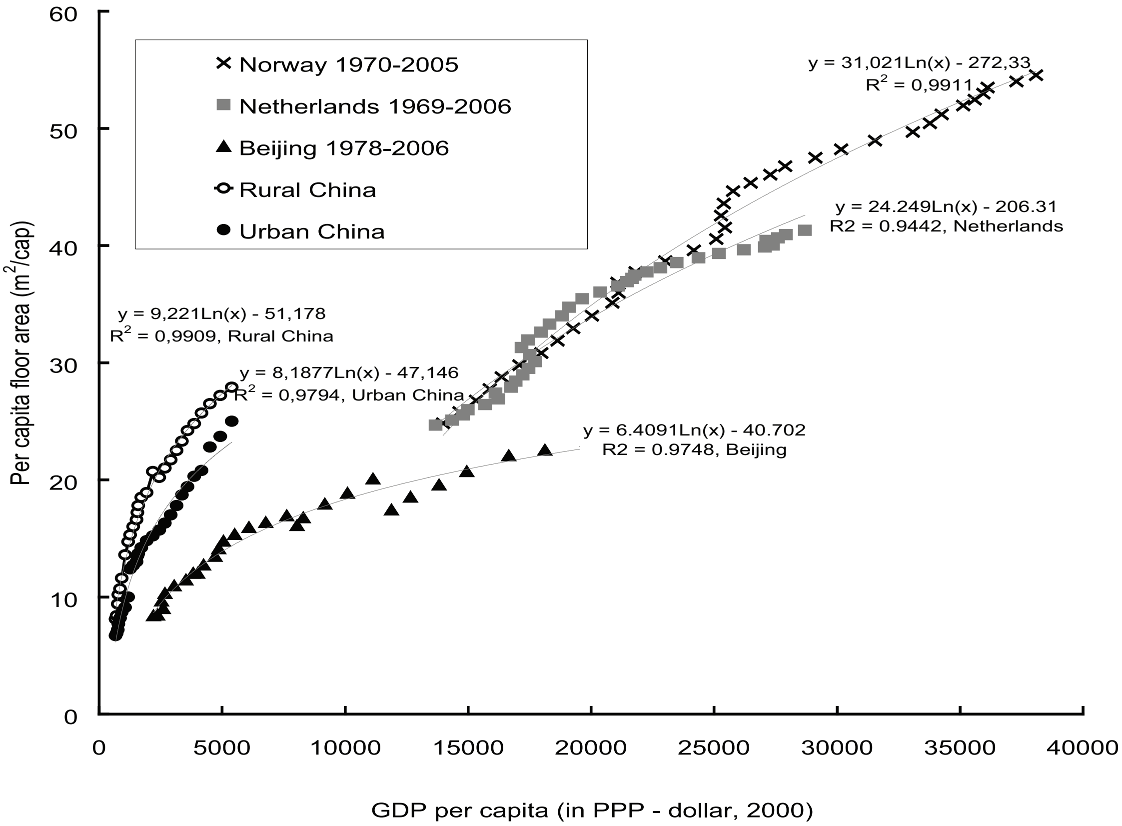


Figure D.1 Relation between floor area per capita and GDP per capita. Data sources: Bergsdal et al. (2007b), Müller (2006), NBSC (1984-2007, 2005), Eurostat (2009), World Bank (2008).

Chapter 4 Case III: Iron and Steel in Chinese Residential Buildings: a Dynamic Analysis [*]

Abstract

The rise of China to become world largest iron and steel producer and consumer since the late 1990s can be largely attributed to urbanization, with about 20% of China's steel output used by residential buildings, and about 50% for the construction sector as a whole. Previously, a dynamic material flow analysis (MFA) model was developed to analyze the dynamics of the rural and the urban housing systems in China. This model is expanded here to specifically analyze iron and steel demand and scrap availability from the housing sector. The evolution of China's housing stock and related steel is simulated from 1900 through 2100. For almost all scenarios, the simulation results indicate a strong drop in steel demand for new housing construction over the next decades, due to the expected lengthening of the – presently extremely short – life span of residential buildings. From an environmental as well as a resource conservation point of view, this is a reassuring conclusion. Calculations for the farther future indicate that the demand for steel will not just decrease but will rather oscillate: the longer the life spans of buildings, the stronger the oscillation. The downside of this development would be the overcapacities in steel production. A scenario with slightly lower life spans but a strong emphasis on secondary steel production might reduce the oscillation at moderate environmental costs.

Keywords: industrial ecology; dynamic material flow analysis; iron and steel; housing; China.

---

[*] Reprinted from "Hu, M., S. Pauliuk, T. Wang, G. Huppes, E. van der Voet and D.B. Müller. 2010. Iron and steel in Chinese residential buildings: a dynamic analysis. Resources, Conservation & Recycling 54(9): 591–600". This is the author's version of the work. It is posted here by permission of Elsevier for personal use, not for redistribution. The definitive version was published in Resource, Conservation and Recycling, Volume 54, Issue 9, July 2010. doi: 10.1016/j.resconrec.2009.10.016.

4.1 Introduction

The sharp increase in material demand in China has grown the country the largest iron and steel consumer as well as the largest producer in the world. China's annual use of iron per capita has risen from 90kg/year in 2000 to 370kg/year in 2008, while the world's per capita iron use increased in the same period from 130kg/year to 190kg/year (CISA 2008; WSA 2008, 2009). Along with that, production volume in China has more than tripled, from 129 to 500 Mt (million metric tons) between 2000 and 2008, which now accounts for 38% of world crude steel production (Price et al. 2002; WSA 2009). China has very limited domestic scrap supply (Lu 2002) and limited quantity and quality of iron ore. For this reason, China's steel production mainly relies on virgin minerals, which are largely imported (Wang et al. 2007). How China's demand will develop in the future will inevitable exert an influence on the global raw material market. Moreover, the extraction and production of iron and steel impose considerable energy and environmental consequences, which is especially true for the iron ore based[17] production in China. Therefore, it is important to understand the development mechanism of steel demand and scrap supply in China, and its economic and environmental implications.

The recent rise of steel demand in China can be largely attributed to the unprecedented urbanization in the country. In 2004, apparent steel consumption in China was 286 Mt/year, half of which is used in the construction industry while residential buildings account for 19% (Figure 4.1). A short-term forecast for China's future steel demand has been made by the Development Research Center of the State Council of China (DRCSCC), which indicates that steel demand in China will further increase by 50% from 2005 to 2010 (DRCSCC 2005).

[17] Primary steel is produced by basic oxygen furnace (BOF), whose scrap input is rather small, typically 10 – 25% (Price et al. 2002). Secondary steel is produced in an electric arc furnace (EAF) using scrap. In 2002, 84.5% of Chinese steel production is primary steel using mainly iron ore, while only 15.42% is secondary steel using scrap (Wang 2004).

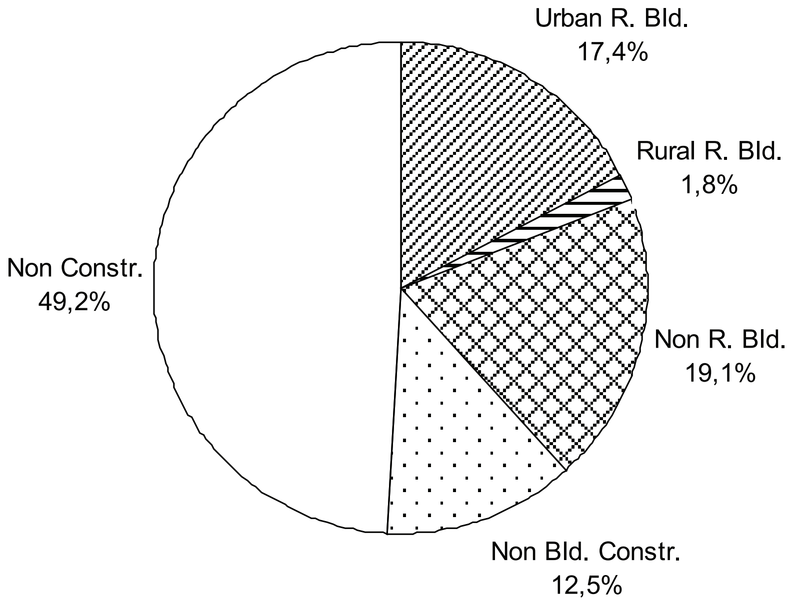


Figure 4.1 Apparent steel consumption in China 2004. Non Constr. = Non construction; Non Bld. Constr. = Non building construction; Non R. Bld. = Non residential building; Rural R. Bld. = Rural residential building; Urban R. Bld. = Urban residential building. *Source*: DRCSCC (2005).

An effort for long-term projection has been done by Yang and Kohler (2008) for the mass input and output of China's building and infrastructure systems. This research analyses the historical evolution of the Chinese building and infrastructure stock from 1978 to 2005 and estimates the future mass input and output through 2050. It provides valuable information about China's building stock. However, this model neglects the ageing of the building stock and assumes that the demolition rate is proportional to the total stock, and is therefore limited in its capacity to forecast long-term changes in construction and demolition activities and their related material flows.

A generic dynamic MFA model for simultaneously determining resource demand and waste generation through estimations of the population, its lifestyle, technology, and product lifetime has been proposed by Müller (2004, 2006). This model uses stock dynamics approach that tracks all vintage classes (year by year) individually and computes the demolition activities based on the estimates of probability distribution functions for the lifetimes of all vintage classes, and therefore provides a better framework to analyze the material diffusion in long lifespan goods, such as residential buildings. Based on the approach, Hu and colleagues (2010) developed a dynamic MFA model to simulate the evolution of the floor area stocks in China's urban and rural housing systems from 1900 through 2100. This model is expanded in this study to specifically cover China's iron and steel demand for residential construction and the scrap availability from housing demolition. Through the dynamic MFA for steel in China's housing stock, this study aims to answer the following questions: (a) how the housing related steel demand in China will likely develop in the future; (b) what the implications of such development are for the steel industry and how the potentially negative impacts on the industry could be mitigated; and (c) what the environmental consequences are for various options for mitigating the impacts.

4.2 Methods

4.2.1 System definition

The model presented in Figure 4.2 represents a material flow analysis (MFA) for the floor area and selected construction material (steel) in China's residential building stock. The system is divided into two sub-systems reflecting the rural and urban housing stocks. The two sub-systems are linked through migration flows from rural to urban areas (m_u) and vice versa (m_r). Each sub-system involves three types of processes, illustrated with rectangles: population within the region (P), housing floor area of the region (A) and related material (M). All the processes have a state variable (P_r, A_r, M_r for rural area or P_u, A_u, M_u for urban area) and a derivative, which is the net stock accumulation (dP_r/dt, dA_r/dt, dM_r/dt or dP_u/dt, dA_u/dt, dM_u/dt). Each population process has three pairs of input and output flows which are denoted respectively as: *b* and *d* for annual inflow and outflow of population led by birth and death, *i* and *e* for annual immigration and emigration crossing China's border, and m_u and m_r for internal migration flows from rural to urban and vice versa. The integrated effect of these flows on the share of people living in rural and urban can be indicated by the urbanization rate. In this study, the urbanization rate (u) and the total national population (P) are used as determinants for China's rural (P_r) and urban (P_u) population. Each housing floor area process has an input ($dA_{r,\ in}$ or $dA_{u,in}$) and an output flow ($dA_{r,out}$ or $dA_{u,out}$), represented with straight-line arrows and ovals. Housing floor area stock is shaped by population (P_r or P_u) and per capita floor area

(A_{rc} or A_{uc}); output flow is the delay of past input, determined by building lifetime function ($L_r \sim N(\tau_r, \sigma_r)$ or $L_u \sim N(\tau_u, \sigma_u)$); and the future input flow is formed to maintain the demanded size of in-use housing floor area stock. Input flow of material ($dM_{r,in}$ or $dM_{u,in}$) is coupled with floor area through the material intensity (M_{ra} or M_{ua}), and the output flow of material ($dM_{r,out}$ or $dM_{u,out}$) is determined by delaying the input.

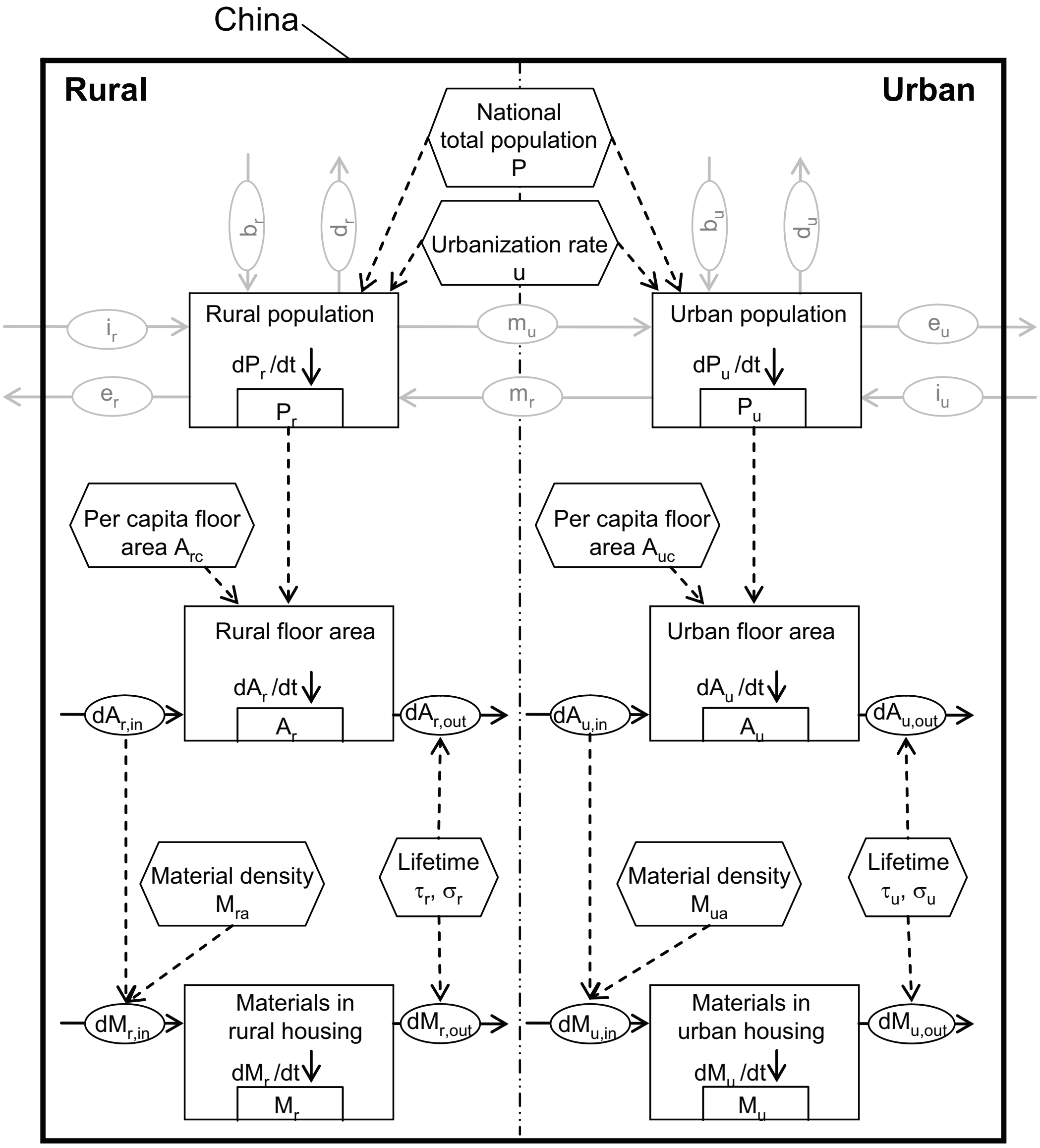


Figure 4.2 Conceptual outline of the stock dynamics model. Rectangles represent processes, ovals depict flows, hexagons illustrate determinants or drivers and dashed lines represent influences between variables.

The underlying equations are given in Appendix and the eight external parameters for the model are listed as follows:

P	National total population
u	Urbanization rate = P_u/P
A_{rc}	Per capita floor area in rural region
A_{uc}	Per capita floor area in urban system
L_r	Lifetime distribution of rural housing ($L_r \sim N(\tau_r, \sigma_r)$)
L_u	Lifetime distribution of urban housing ($L_u \sim N(\tau_u, \sigma_u)$)
M_{ra}	Material intensity per unit floor area in rural region
M_{ua}	Material intensity per unit floor area in urban system

4.2.2 Model parameter quantification

Steel intensity

Very few data are available for the steel intensity in different dwelling vintages. Little iron and steel was used in Chinese housing construction before 1950s when concrete structure became popular in urban residential construction. Typical Chinese dwellings at the beginning of 20th century were one or two-floor buildings built from local materials such as clay, bricks, wood, bamboo et al. A recent survey estimates the average steel intensity in China's urban residential construction in 2004 to be 36.5 kg/m^2 (DRCSCC 2005). Due to the promotion of steel structures, the same study expects the steel intensity in urban residential construction to further increase to 41.3 kg/m^2 by 2010 (DRCSCC, 2005; illustrated as dots in Figure 4.3 (b), however, the trend for the longer term is less clear. From one side, the steel intensity may continue to rise if China's high steel production capacity will lead to low cost construction steel, or if the increase of high residential buildings will employ more high steel content structures in residential construction. From another side, technical innovation may minimize the steel use in concrete structure, which is dominant in China's urban residential buildings. For instance, the steel content in concrete may be substituted by glass fiber, if the technical development will drop the cost of glass fiber to be competitive, or when developments in the steel market will cause the steel prices to rise significantly. We therefore assume that the steel intensity in China's residential construction follows a (double) logistic curve with initial level zero, with the measured level of 2004, and with different assumed saturation levels. Three potential future paths are investigated, representing trends of increasing, decreasing, and stabilizing steel intensity (Figure 4.3 (b)).

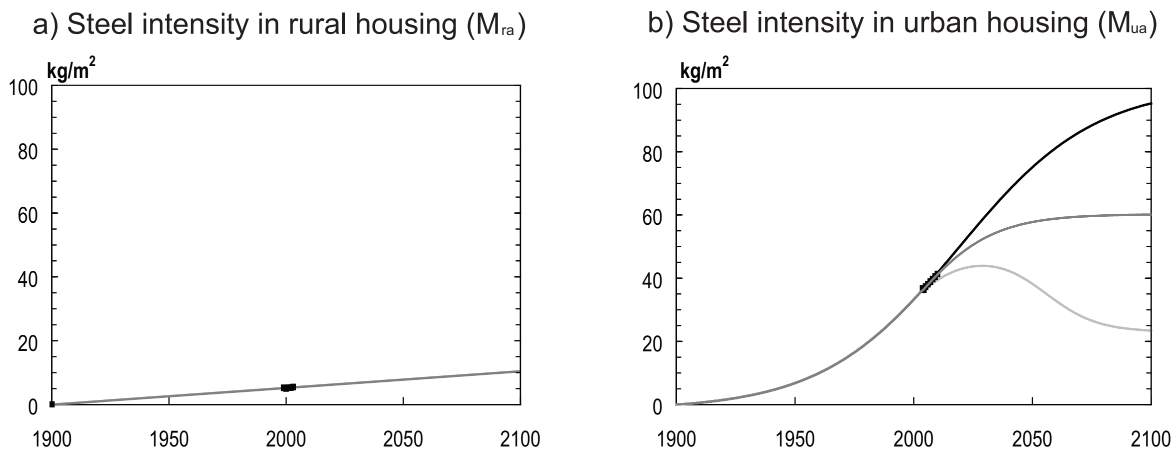


Figure 4.3 Assumptions of steel intensity in rural housing construction (one path), and in urban housing construction with a low (light grey), medium (dark grey) and high (black) variant from 2005 until 2100. Dots are figures quoted from DRCSCC (2005).

The variance for steel intensity in urban housing construction is based on a survey for 100 residential buildings in Beijing (Liu and Hu 2006). The survey shows the shearing-force structure dwellings have the highest steel intensity as 97.1 kg/m^2, while the brick-concrete structure dwellings have the lowest value as 23.4 kg/m^2. We assume that by 2100, for increasing path, due to the increase of high dwellings and the promotion of steel intensive structure in residential construction, the average steel intensity in China's urban residential construction will approach the observed high value 97.1 kg/m^2 of shearing-force structure; while for decreasing path, due to technical innovation, for instance, high density concrete or glass fiber, the average steel intensity in China's urban residential construction will decline to the observed low value 23.4 kg/m^2 of brick-concrete structure. The medium path is assumed as that, after a continuous rise till around 2050, the steel intensity in China's urban residential will stay at near 60kg/m^2, the middle point of the variance range, through 2100.

Very little steel has been used in China's rural housing. In China, rural residential construction is in a period of transition from brick-concrete to reinforce concrete structure. Since brick and other low steel buildings still account for a big share of the annual completed rural houses, instead of per unit floor area steel use, per rural capita purchased steel is used to estimate the steel demand in rural residential construction (DRCSCC 2005). Historical figures of per capita purchased steel can be found in DRCSCC report for 1999 to 2003. Assuming all the rural purchased steel was used in residential construction, the steel intensities for rural housing during 1999 - 2003 are obtained by dividing the rural purchased steel with the completed rural housing floor area at corresponding year, as around 5.0 - 5.5kg/m^2 (dots in Figure 4.3 (a)). This assumption may lead to over-estimation, because a part of rural purchased steel might have ended up in public buildings or infrastructures. However, even with the high estimation, the steel intensity in rural residential construction consumption is still less than 15% of that in urban. Therefore, for the purpose of anticipating the residential steel demand in the future, we focus mainly on the urban housing stock in China. Only one growth path is estimated for steel intensity in future rural housing, due to its relatively insignificant role. Steel intensity in rural residential construction is estimated to have increased linearly from 0 in 1900 to 5.0kg/m^2 in 2000 and will continue the growth rate to reach 10.4kg/m^2 in 2100.

Other parameters

For the other six external parameters: population (P), urbanization rate (u), per capital floor area in rural (A_{rc}) and urban (A_{uc}), lifetime distribution of rural housing (L_r) and urban housing (L_u), the same calibration as adopted in the early floor area stock dynamics model in Chapter 3 (see section 3.2.3) is used here. For each external parameter, a low, medium and high variant are estimated for the future period. In the early study presented in Chapter 3, the parameter of urban per capita floor area was estimated as a function of China's per capita GDP as a fourth variant for the purpose of comparison. This scenario is omitted in this study for housing related steel flows, because the path of future residential stock development resulted by the GDP driving urban per capita floor area is already covered by the variance between the lowest urban stock demand resulted by the low urban population and low per capita floor area scenario, and the highest stock demand resulted by high urban population and high per capita floor area scenario.

4.3 Results and discussion

4.3.1 Simulation results

Simulations are performed on the basis of the parameter variations discussed in the previous section. The base case scenario, for which the results are presented in this section, is constructed by applying the medium values for all input parameters. Figure 4.4 shows the results. The base case scenario results for floor area and steel in China's urban and rural housing systems at 2010, 2050 and 2100, representing the near, the medium distant and the far distant future, are listed in Table 4.1 with both absolute value and the percentage in the total national volume.

The results show that, in a distant future, the housing related steel demand and scrap supply will be clearly concentrated in urban system, though the levels of construction and demolition actives will be still comparable for both the rural and the urban housing systems. In 2050, more than 91% of residential steel demand and 87% of scrap from housing demolition are expected from urban dwellings, and the urban proportions will rise further through 2100. Both the steel demand and scrap supply from rural housing has right peaked in the past few years. The steel in rural in-use housing stock and the related input and output steel flows are expected to stay at the current low levels through 2100.

A strong oscillation in urban residential steel demand is indicated by the base case scenario. The results show that urban residential construction will reach a peak of 1.3 billion square meters per year around 2011, subsequently, declines for about 40 to 50 years to about a quarter of the peak of new construction. Coupled with that, the steel demand for urban residential construction is going to drop by a factor of 3.5, from 60Mt/yr in around 2017 to 17Mt/yr in around 2054. The oscillation is a consequence of the fast growth in the past: the build-up time of the housing stock (ca. 30 years), is shorter than the expected lifetime of the buildings. The first rise of new construction is caused by the growth in stock demand, and when the saturation of the stock occurs, the demand for new construction will be due to replacement only. Because of the long dwelling lifetime, the demand for replacement will kick-in only after 2050, and a period of low demand for new construction emerges, so the oscillation in residential steel demand occurs.

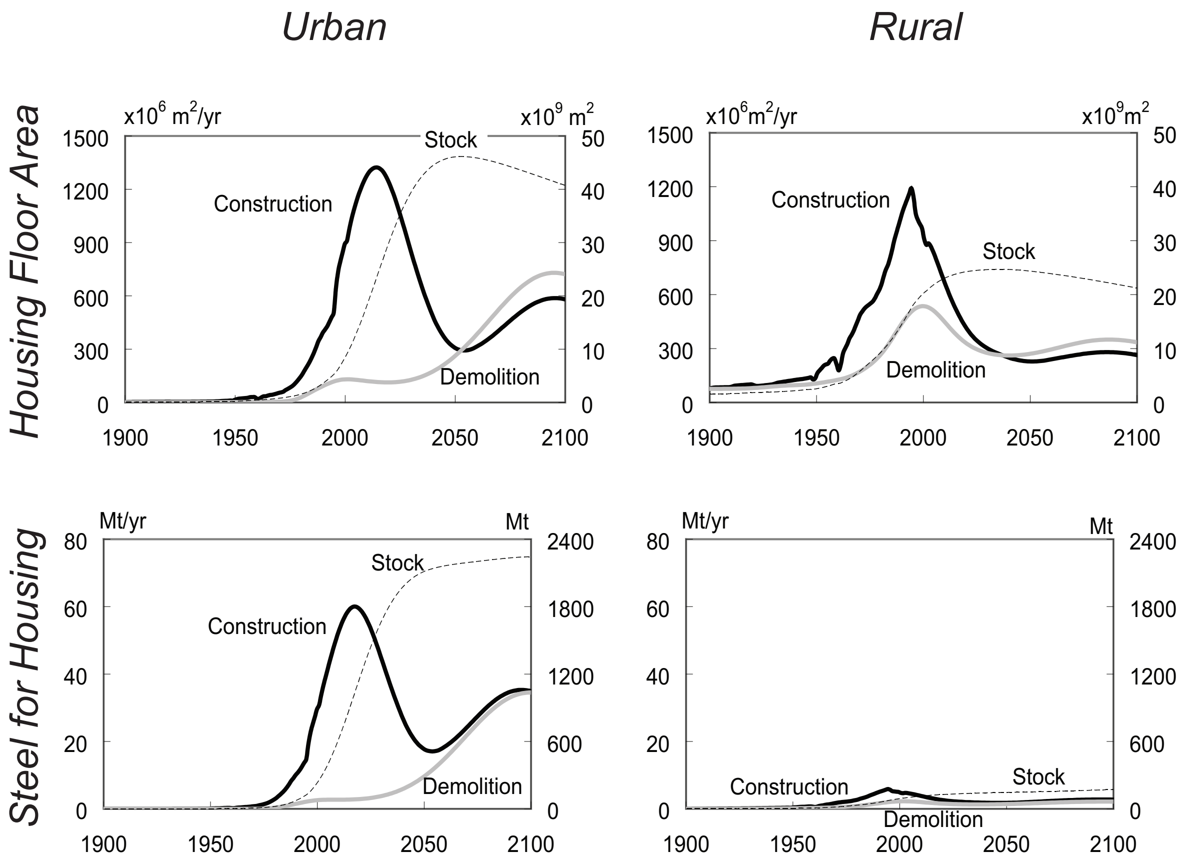


Figure 4.4 Simulation results for the medium variant. Stocks are measured on the right axis and flows on the left.

This period of low replacement also indicates that the volume of scrap from urban residential demolition will stay at current low level for a couple of decades. It means that, right now, steel stock in residential buildings is being built up which requires primary ore resources. Only approaching the second half of the 21st century, due to the oscillation in new construction and the kick-in of the replacement for dwellings erected during the first surge of construction, obsolete scrap will be possible to be a major resource for residential steel demand.

Table 4.1 Simulation results for floor area and steel in the urban and the rural housing systems in China in the years of 2010, 2050 and 2100. Up are absolute values and down are percentages of total national volumes.

	Stocks/flows	Urban			Rural		
		2010	2050	2100	2010	2050	2100
Floor area	A (m^2)	1.81e10	4.61e10	4.07e10	2.25e10	2.41e10	2.10e10
	(%)	45%	66%	66%	55%	34%	34%
	dA_{in}/dt (m^2/yr)	12.8e08	3.08e08	5.81e08	6.54e08	2.28e08	2.64e08
	(%)	66%	57%	69%	34%	43%	31%
	dA_{out}/dt (m^2/yr)	1.21e08	2.61e08	7.22e08	4.42e08	2.72e08	3.35e08
	(%)	21%	49%	68%	79%	51%	32%
Steel	M (Mt)	614	2110	2240	114	147	172
	(%)	84%	94%	93%	16%	6%	7%
	dM_{in}/dt (Mt/yr)	52.4	17.8	34.9	3.77	1.79	2.75
	(%)	93%	91%	93%	7%	9%	7%
	dM_{out}/dt (Mt/yr)	2.72	9.56	34.5	1.99	1.43	2.16
	(%)	58%	87%	94%	42%	13%	6%

4.3.2 Sensitivity analysis

The simulation results presented in the previous section are based on the medium variant for all parameter functions. As there are significant uncertainties regarding how these determinants will behave in the future, in this section, the effect of each determinant (floor area stock, steel intensity and dwelling lifetime) is tested individually for its low, medium, and high variants. The widespread of parameter assumptions is chosen to capture a large range of possible scenarios, as shown in Figure 4.5 and 4.6.

The results are illustrated only for steel input (construction) and scrap output (demolition) of urban residential buildings. Figure 4.5 shows the influences of the average dwelling lifetime (in column) and the steel intensity in residential construction (in row) for the medium housing floor area scenario (left-up corner; stabilizing dwelling stock). Figure 4.6 shows the impacts of housing floor area scenario (in column; shrinking, stabilizing and increasing dwelling stocks), when dwelling lifetime and steel intensity are both at their medium variants.

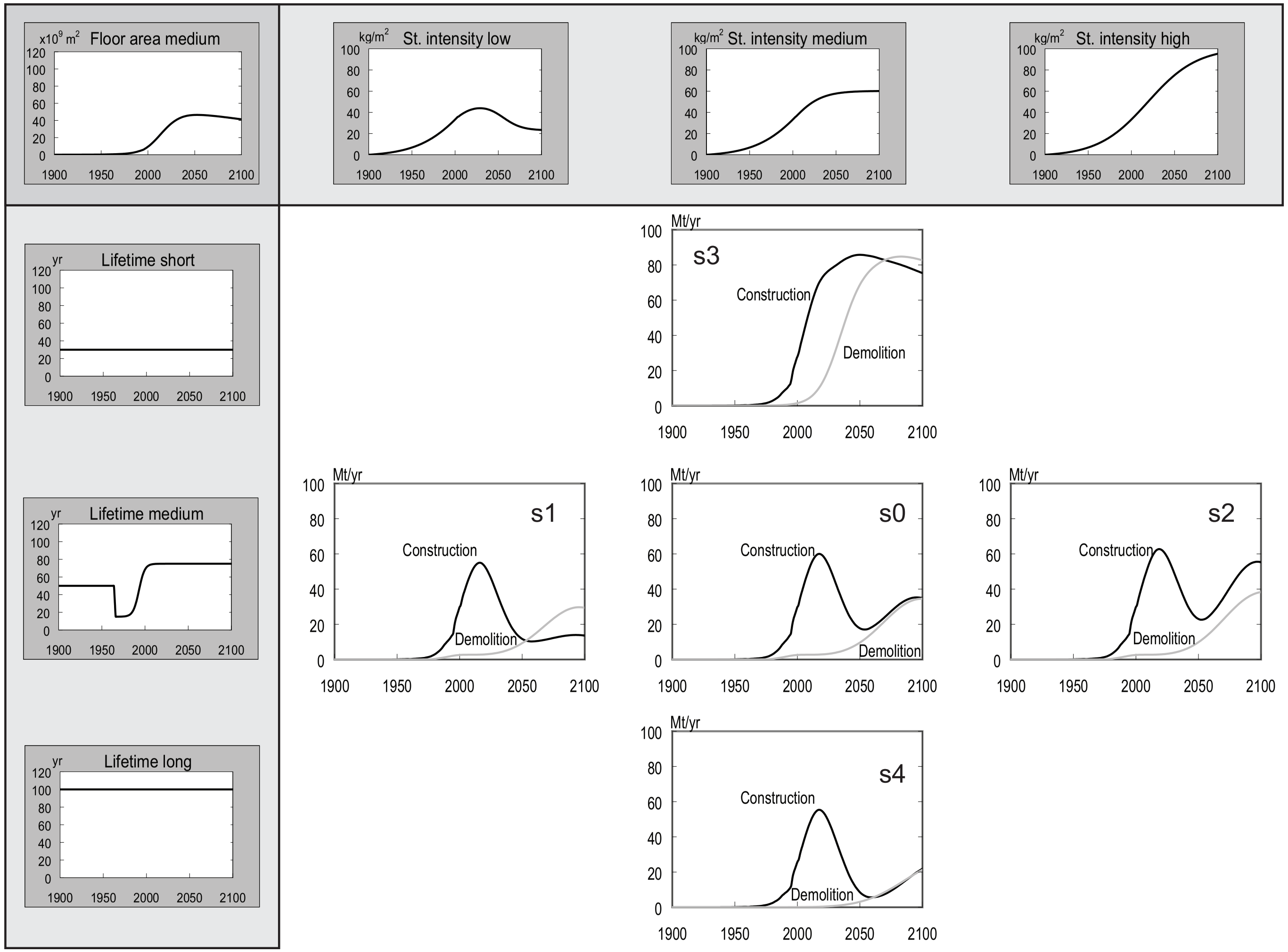


Figure 4.5 Sensitivity analysis for steel in urban housing system. Steel input (construction) and output (demolition) in Mt (million metric tons) per year, as influenced by steel intensity and lifetime variants, for a medium floor area scenario (stabilizing dwelling stock). s0 = Base case; s1 = Low steel intensity; s2 = High steel intensity; s3 = Short lifetime; s4 = Long lifetime.

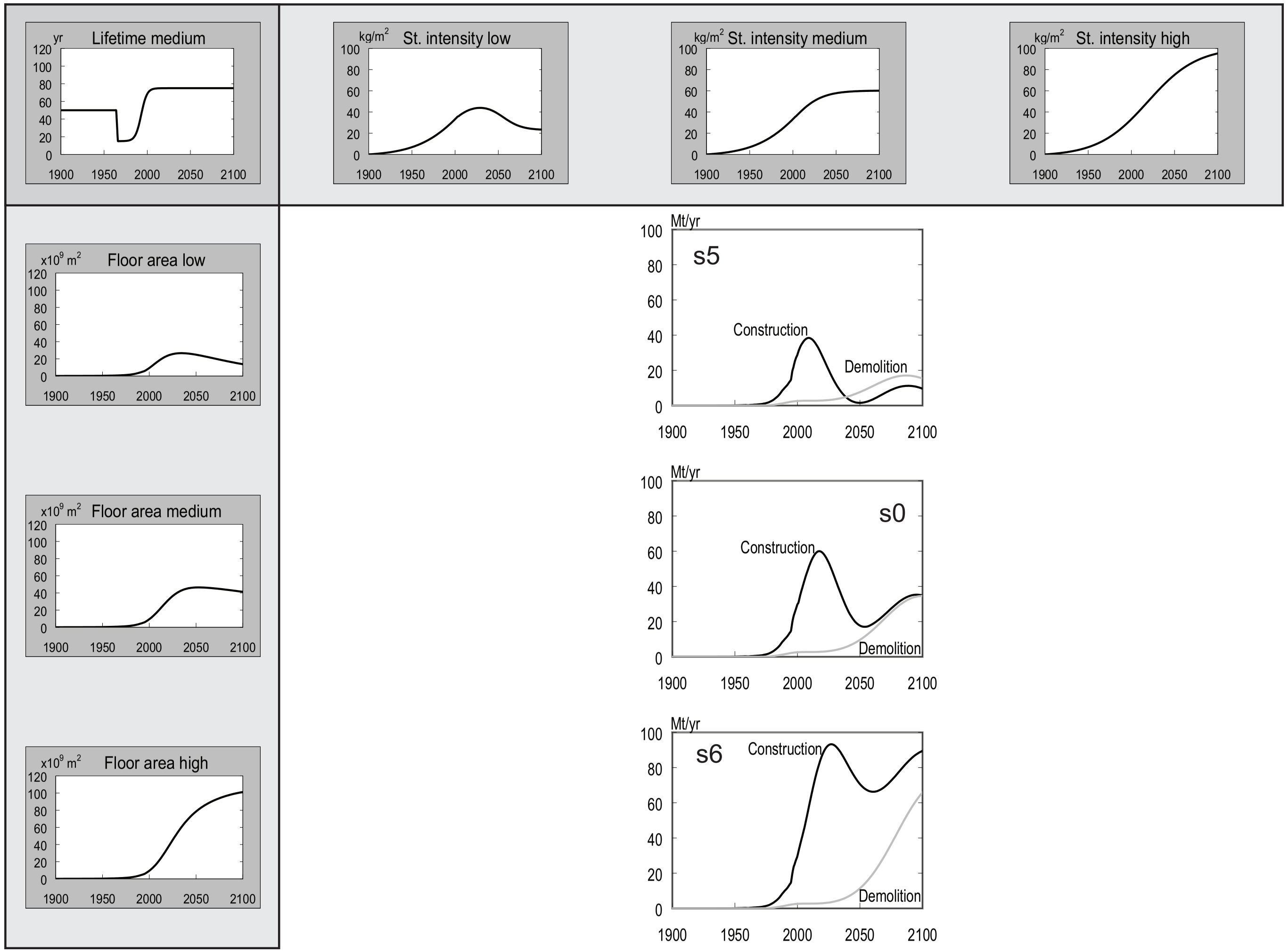


Figure 4.6 Sensitivity analysis for steel in urban housing system. Steel input (construction) and output (demolition) in Mt (million metric tons) per year, as influenced by floor area scenarios (shrinking, stabilizing and increasing dwelling stocks) at medium steel intensity and lifetime. s0 = Base case; s5 = Low floor area; s6 = High floor area.

The sensitivity analysis for steel in urban housing construction shows that an oscillation in new construction can be expected to occur. The oscillation seems to be there independent of variations in the floor area and steel intensity within the projection period. The life span of the buildings however does make a difference: in the low lifetime scenario, when the lifetime is assumed to be 30 years, the oscillation is not visible. Floor area and steel intensity do have some influence on the magnitude of the oscillation: the larger the future housing floor area stock and the steel intensity are, the less dramatic the oscillations will be.

Obsolete scrap generation from urban housing demolition is increasing in all scenarios. If the floor area saturates and the steel intensity in buildings remains on current levels, the volume of obsolete scrap from dwellings will eventually reach a level that is potentially sufficient to cover steel demand for residential construction entirely from secondary source and achieve a closed system (circular economy) for iron. In the low steel intensity scenario, substitute materials may lead to a lower demand for steel, so the supply of secondary steel will be even higher than the demand.

Compared to previous forecasts, this dynamic MFA study detects a dramatic change in trends of residential steel demand, which is likely to happen very soon. Forecasts of DRCSCC (2005) foresee a continuous increase of residential steel demand till 2010, while projection of Yang and Kohler (2008) expects a relatively stable input mass flow into China's buildings stock through 2050. The new finding of this study demonstrates the fail of trend expansion in forecasting material flows associated with long lifespan applications. It also illustrates the crucial role of life span and stock aging information in projections.

4.3.3 Implications for steel industry

Oscillation indicated by the dynamic MFA in residential steel demand implies the potentially serious overcapacity in China's steel production. The effect may exert to the global market when China will probably export its surplus steel at a more competitive price.

The dynamic MFA in residential sector shows that oscillation occurs if the build-up time of the housing stock is shorter than the expected lifetime of the buildings. Considering the similar fast growth in Chinese non-residential buildings and infrastructures for the last two to three decades, we suspect that the oscillation would occur also in non-residential sector, and might be more severe in infrastructure construction due to the expected longer life span. If that would be the case, significant shrink in construction steel demand is expected in China for the decades to come.

China's rise to be world's largest steel producer is driven largely by its growing construction demand, which accounts for half of its annual steel output (Figure 4.1). The probably decreasing construction demand implicates that China is likely to produce lots of surplus steel with its high production capacity. It means that Chinese construction steel producers may have to seek market in automobile or machinery sectors. However, this change will require a shift of production capacity from long products (normally used in construction) to flat products (normally used in automobile or machinery). Otherwise, Chinese steel industry will have to increase export at more competitive price, which will in turn lead to global overcapacity in the future.

Lifetime of buildings and infrastructures is most influential in steel demand projections. For the purpose of stabilizing steel demand, policies which may lead to higher replacement rate are more effective than those inducing higher steel intensity or bigger service size in residential buildings.

Lifetime is the most influential factor. With very short lifetimes, the oscillation in construction steel demand can be almost not visible, while steel demand is much higher (Figure 4.5). However, the lifetime parameter depends not only on the quality of houses and city infrastructures but also on cultural, economic, institutional and political factors, and so is still few understood. Therefore, better understanding on lifetimes of residential and non-residential buildings and infrastructures is essential for anticipating China's future construction steel demand.

Reducing service lifetime is the most effective measure on mitigating the oscillation, though it is ridiculous to shorten dwelling lifetime for stabilizing steel demand. However, policies, such as those which suggest replacing low efficient buildings according to certain energy standards may indeed result to shorter dwelling lifetime. As illustrated in Figure 4.5, such policies will be more effective to create a stable steel demand than those promoting steel intensive structures or encouraging a more affluent dwelling size.

Short lifetime anticipates the strong and early rise of scrap, implying the need to expand China's secondary steel production capacity.

While mitigating the oscillation in steel demand, short dwelling lifetime will also lead to strong and early rise of scrap (Figure 4.5). The current Chinese steel production is mainly based on iron ore. A choice should be made to increase the scrap based steel production in China, so as to absorb the scrap locally, instead of mass scrap exporting combined with mass ore importing, for a more self-sufficient iron economy as well as a greener steel production in China. However, such a strategy would require an expansion of secondary steel production capacities and thereby further exacerbate the overcapacity problem.

4.3.4 Environmental consequences

The major environmental impacts of steel consumption for housing construction are on resource depletion and global climate change. The former can be assessed by the accumulated net steel use (Figure 4.7), while the later can be assessed by the net CO_2-equivalent emission (Figure 4.8) for the investigated period (2001 – 2100). The calculation is made for two extreme recycling situations, representing no recycling or 100% recycling of the obsolete scrap from housing demolition, for urban residential buildings.

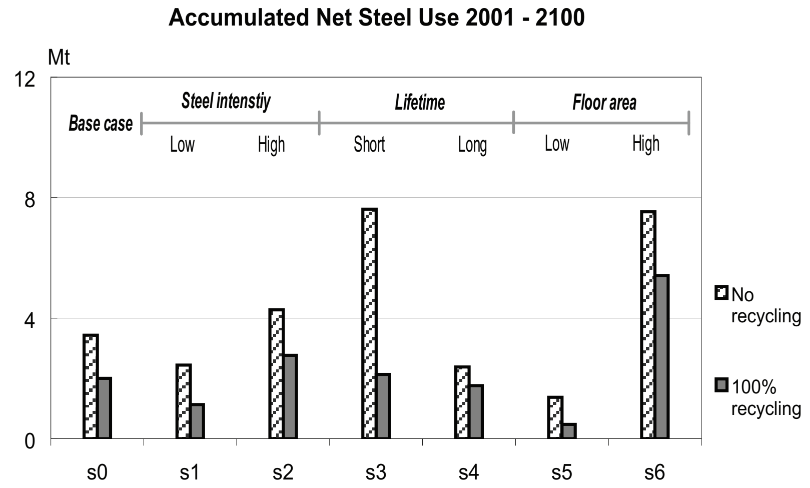


Figure 4.7 Accumulated net residential steel use for no recycling (slope stripe) and 100% recycling (solid) of scrap from 2001 to 2100 in Mt (million metric tons). s0 = Base case; s1 = Low steel intensity; s2 = High steel intensity; s3 = Short lifetime; s4 = Long lifetime; s5 = Low floor area; s6 = High floor area.

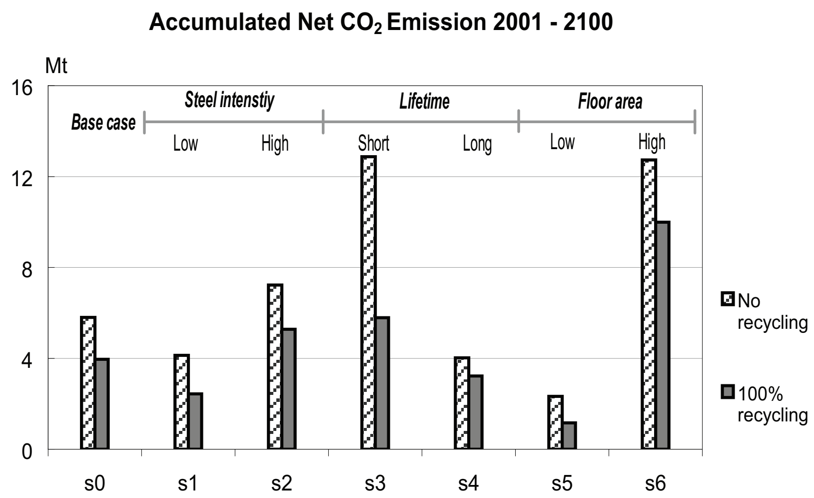


Figure 4.8 Accumulated net CO2 emission of residential steel production for no recycling (slope stripe) and 100% recycling (solid) of scrap from 2001 to 2100 in Mt (million metric tons). s0 = Base case; s1 = Low steel intensity; s2 = High steel intensity; s3 = Short lifetime; s4 = Long lifetime; s5 = Low floor area; s6 = High floor area.

Net steel use

For no recycling situation, all the steel demanded for new housing construction has to be supplied from outside the urban housing system. The net steel use is assumed to be the same as the accumulated residential steel input during 2001 to 2100. For 100% recycling situation, the scrap from housing demolition is assumed to be completely used to produce secondary steel to supply the steel demand for new housing construction. The net steel use is then assumed to be the gap between the accumulated scrap generation and the accumulated residential steel input for the period (2001 – 2100). The results are presented in Figure 4.7.

Net CO_2 emission

All the steel input for new housing construction is assumed to be primary steel, produced by *iron ore based process* (Sintering/Coking/electric arc furnace (EAF)/Continuous casting/Rolling). While all the scrap released from housing demolition is assumed to be used to produce secondary steel by *scrap based process* (Sintering/Coking/blast furnace (BF)/basic oxygen furnace (BOF)/Continuous casting/Rolling). The CO_2 emission factors for both processes are derived from those of Japanese iron and steel industry in 1999 (MITI 2000; Gielen and Moriguchi 2002), adjusted with energy intensity of the best practice of Chinese steel enterprises in 2007 (MMI 2008), with consideration of the high emission level due to China's coal based electricity generation. The resulted factors are, for iron ore based process 1,690 kg CO_2 per ton primary steel production, and for scrap based process 399 kg CO_2 per ton secondary steel production. These factors are used here as the emission levels of Chinese steel production through 2100, though they may be both decreasing due to the continuous technical improvement. However, the significant savings of CO_2 emission from replacing iron ore based production with scrap based production will be always the case.

The net CO_2 emission in 100% recycling situation is calculated by subtracting the production emission of the primary steel demanded for new housing construction with the emission savings due to replacing the primary steel production with secondary steel production using all the scrap liberated from housing demolition. For no recycling situation, the net CO_2 equals to the emission led by producing primary steel for new housing construction. The results are presented in Figure 4.8.

The results show that, from environmental point of view, floor area stock is the most sensitive factor; high growth in residential floor area has the strongest impact on both resource depletion and global climate change, no matter recycling scrap or not.

Shortening lifetime is most effective to adjust the oscillation in residential steel demand. The environmental impacts of short lifetime strategies depend largely on the recycling scheme. The shorter the lifetime is, the better scrap recycling requires. For maximum recycling, shortening dwelling lifetime may cause no resource depletion and moderate rise of CO_2 emissions. Because although a short lifetime demands big amount of steel to provide the same size of dwelling stock, it at the same time releases big amount of scrap, which provides the potential to circulate the steel within the residential sector instead claims from outside. Since steel production from scrap causes less CO_2 emissions than from ore, in the case of proper recycling, the CO_2 emissions in short lifetime scenario will increase much slower than its steel demand.

4.4 Conclusions and outlook

The model calculations indicate that a highly oscillating demand for steel is to be expected in China for the coming century. The longer life span of buildings or the lower floor area stock is, the stronger the oscillation will be. Opposite to most projections, this study shows a significant reduction in steel demand over the coming decades from China's residential sector, which currently accounts for 20% of the country's steel consumption. The use of a dynamic MFA model enables to include stock ageing, which is not present in other forecasts, and which seems to be of primary importance. The expected reduction in steel demand has obvious benefits both from an environmental point of view and from a resource conservation point of view. In the long run, the longer the life span is the lower the CO_2-emissions related to construction activities, and the lower the use of potentially scarce resources. However, the expected oscillation has negative consequences as well for the stability of the steel producing industry, in China or even worldwide. The model calculations indicate that shortening the life span of the buildings is the most effective way to avoid the oscillation – but at obvious costs of higher CO_2-emissions and resource use. These could be reduced to some extent by a strong emphasis on using secondary materials. Further research is indicated to explore the consequences of various options. To what extent can the demand for steel in construction be met by secondary materials, and what are limiting factors? What are trade-offs between recycling and durability? How can we stabilize markets with the least possible environmental and resource impacts? What can be the role of new construction materials or new building designs to replace steel? Such questions should be answered to indicate how China can progress on the road towards a sustainable construction sector.

Reference to Chapter 4

Bergsdal, H., H. Brattebø, R.A. Bohne, D.B. Müller. 2007. Dynamic material flow analysis for Norway's dwelling stock. Building Research & Information 35(5):557-570.

China Iron and Steel Association (CISA). 2008. China Steel Yearbook, Beijing, China (in Chinese).

Davis, J., R. Geyer, J. Ley, J. He, R. Clift, A. Kwan, M. Sansom, T. Jackson. 2007. Time-dependent material flow analysis of iron and steel in the UK - Part 2. Scrap generation and recycling. Resources, Conservation and Recycling 51:118-140.

Development Research Center of the State Council of China (DRCSCC). 2005. Forecast Report of the Steel Consumption of China 2005–2010. Beijing, China (in Chinese).

Fernández, J.E. 2007. Resource consumption of new urban construction in China. Journal of Industrial Ecology 11(2):99-115.

Garnaut, R. and L. Song. 2006. China's resources demand at the turning point. In: R. Garnaut (ed.), The turning point in China's economic development, Asia Pacific Press, Canberra, pp. 276-293.

Gielen D and Moriguchi Y. 2002. CO_2 in the iron and steel industry: an analysis of Japanese emission reduction potentials. Energy Policy, 30:849-863.

Hu, M., H. Bergsdal, D.B. Müller. 2010. Dynamics of urban and rural housing stocks in China. Building Research & Information 38(3):1–17. doi:10.1080/09613211003729988.

Liu, T. and D. Hu. 2006. Environmental Impact of Residential Building Construction in Beijing. Journal of Graduate School of the Chinese Academy of Sciences 23(2):231-241.

Lu, Z.W. 2002. Iron-flow analysis for the life cycle of steel products: a study on the source index for iron emission. Acta Metall Sinica 38(1):58-68 (in Chinese).

Müller, D.B. et al. 2004. Long-term coordination of timber production and consumption using a dynamic material and energy flow analysis. Journal of Industrial Ecology 8(3).

Müller, D.B. 2006. Stock dynamics for forecasting material flows – case study for housing in the Netherlands. Ecological Economics 59:142-156.

Müller DB, Wang T, Duval B and Graedel TE. 2006. Exploring the engine of anthropogenic iron cycles, Proceedings of the National Academy of Sciences of the United States of America. 103(44):16111-16116.

Ministry of International Trade and Industry (MITI). 2000. Yearbook of iron and steel statistics 1999. Research and Statistics Department Minister's Secretariat, Tokyo.

Ministry of Metallurgical Industry (MMI). 2008. Yearbook of iron and steel industry of China, Beijing.

National Bureau of Statistics of China (NBSC). 2005. Statistical Compendium of China 1949 – 2004. China Statistical Press, Beijing.

National Bureau of Statistics of China (NBSC). 1980 – 2007. China Statistical Yearbook 1980 …2007. China Statistical Press, Beijing.

Price, L., J. Sinton, E. Worrell, D. Phylipsen, H. Xiulian, L. Ji. 2002. Energy use and carbon dioxide emissions from steel production in China. Energy 27:429-446.

Shen, L., S. Cheng, A.J. Gunson, H. Wan. 2005. Urbanization, sustainability and the utilization of energy and mineral resources in China. Cities 22(4): 287-302.

United Nations Population Division (UNPD). 2003. World Population in 2300, Draft of 9 December, United Nations, New York.

United Nations Population Division (UNPD). 2006. World Population Prospects: The 2006 Revision, United Nations, New York. Accessed at http://esa.un.org/unpp on July 2009.

United Nations Population Division (UNPD). 2007. World Urbanization Prospects: The 2007 Revision, United Nations, New York. Accessed at http://esa.un.org/unup on July 2009.

Wang, T., D.B. Müller, T.E. Graedel. 2007. Forging the anthropogenic iron. Environmental Science and Technology 41:5120-5129.

Wang, T., J. Mao, J. Johnson, B.K. Reck, T.E. Graedel. 2008. Anthropogenic metal cycles in China. Journal of Material Cycles and Waste Management 10:188-197.

Wang, Z. 2004. Mitigate resource supply tenseness by sensibly using scrap. Nonferrous Metal Recycling and Use 3:25-27(in Chinese).

World Steel Association (WSA). 2008. Steel Statistical Yearbook, WSA, Brussels, Belgium.

World Steel Association (WSA). 2009. Latest steel statistics. http://www.worldsteel.org/?action=lateststeellist, accessed on July 2009.

Yang, W. and N. Kohler. 2008. Simulation of the evolution of the Chinese building and infrastructure stock. Building Research & Information 36(1):1-19.

Appendix to Chapter 4

Stock dynamics model for steel in housing stock

The stock dynamics model for steel in China's rural and urban housing stock is formulated in following equations:

$$A_r(t) = P_r(t) \cdot A_{rc}(t) = P(t) \cdot (1 - u(t)) \cdot A_{rc}(t) \quad (1)$$

$$A_u(t) = P_u(t) \cdot A_{uc}(t) = P(t) \cdot u(t) \cdot A_{uc}(t) \quad (2)$$

$$\frac{dA_{r,out}(t)}{dt} = \int_{t_0}^{t} L_r(t,t') \cdot \frac{dA_{r,in}(t')}{dt} dt' \quad (3)$$

$$\frac{dA_{u,out}(t)}{dt} = \int_{t_0}^{t} L_u(t,t') \cdot \frac{dA_{u,in}(t')}{dt} dt' \quad (3')$$

$$L_r(t,t') = \frac{1}{\sigma_r \sqrt{2\pi}} \cdot e^{-\frac{(t-t'-\tau_r)^2}{2\sigma_r^2}} \quad (4)$$

$$L_u(t,t') = \frac{1}{\sigma_u \sqrt{2\pi}} \cdot e^{-\frac{(t-t'-\tau_u)^2}{2\sigma_u^2}} \quad (4')$$

$$\frac{dA_{r,in}(t)}{dt} = \frac{dA_r(t)}{dt} + \frac{dA_{r,out}(t)}{dt} \quad (5)$$

$$\frac{dA_{u,in}(t)}{dt} = \frac{dA_u(t)}{dt} + \frac{dA_{u,out}(t)}{dt} \quad (5')$$

$$\frac{dM_{r,in}(t)}{dt} = \frac{dA_{r,in}(t)}{dt} \cdot M_{ra}(t) \quad (6)$$

$$\frac{dM_{u,in}(t)}{dt} = \frac{dA_{u,in}(t)}{dt} \cdot M_{ua}(t) \quad (6')$$

$$\frac{dM_{r,out}(t)}{dt} = \int_{t_0}^{t} L_r(t,t') \cdot \frac{dM_{r,in}(t')}{dt} dt' \quad (7)$$

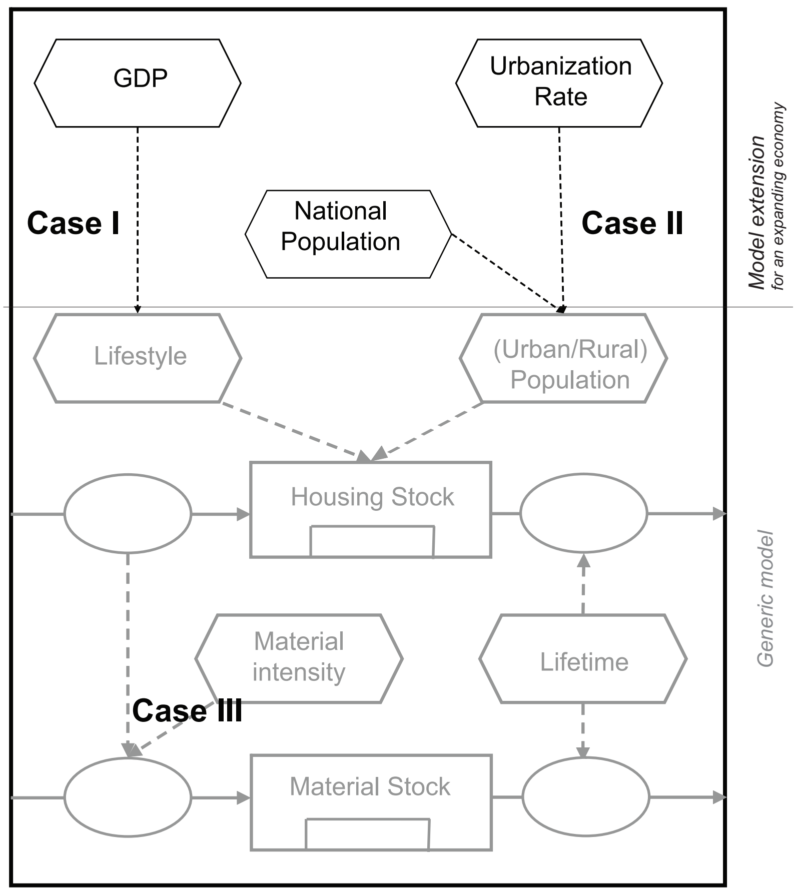
$$\frac{dM_{u,out}(t)}{dt} = \int_{t_0}^{t} L_u(t,t') \cdot \frac{dM_{u,in}(t')}{dt} dt' \tag{7'}$$

$$\frac{dM_r(t)}{dt} = \frac{dM_{r,in}(t)}{dt} - \frac{dM_{r,out}(t)}{dt} \tag{8}$$

$$\frac{dM_u(t)}{dt} = \frac{dM_{u,in}(t)}{dt} - \frac{dM_{u,out}(t)}{dt} \tag{8'}$$

Equations (1) and (2) indicate the urban and rural housing stocks are determined by the size of national population, the level of urbanization and per capita housing demand in either region. Equations (3) and (3') illustrate the outflow from the housing stock is determined by the past inflow, with a delay of the service life of the houses. Equations (4) and (4') assume the lifetime of rural and urban houses follows normal distribution function. Equations (5) and (5') forecast the future rural and urban inflows of housing stock by balance the rural and urban housing processes respectively. Equations (6) and (6') forecast link the service system of rural and urban housing floor area to the related material system with the material density parameters $M_{ra}(t)$ and $M_{ua}(t)$. Corresponding to equations (3) and (3'), equations (7) and (7') represent that the rural and urban material outflows are determined by previous inflows after delaying a lifetime $L_r(t, t')$ or $L_u(t, t')$. Equation (8) and (8') represent that the material stocks in the rural and urban housing systems can be calculated according to the material inflows and outflows.

Chapter 5 Discussion, Conclusions and Recommendations



5.1 Introduction

This thesis has developed and applied dynamic material flow analysis models for exploring the long-term dynamics of Chinese urban and rural residential housing stocks. The models extend the currently available dynamic MFA models by including general socio-economic and specific urbanization driving factors in China. Using scenario analysis, the patterns of building life time and age structure, material demand and waste generation related to Chinese residential building stocks are simulated and the critical parameters affecting the environmental performance are identified.

This concluding chapter develops the discussion of the three hypotheses and four research questions that were raised in Chapter 1 and investigated through three case studies (Case I ~ Case III) that were presented from Chapters 2 to 4. Major insight that has been obtained during the case studies is summarized and listed in section Conclusions. Future efforts for using dynamic material flow analysis to support sustainable built environment development are recommended at the end.

5.2 Discussion and evaluation of the case studies

5.2.1 Hypotheses

The case studies carried out are based on three hypotheses, for supporting sustainable construction strategies in rapidly urbanizing developing regions, which are:

(1) 'metabolism metaphor' is useful;

(2) dynamic material flow analysis is essential;

(3) stock dynamics driving dynamic MFA is suitable.

Regarding Hypothesis (1), the investigation for the material metabolism of Chinese housing stocks seems to indicate the potential of using 'metabolism metaphor' for integrating the social, economic and environmental concerns, such as layoff of construction workers, overcapacity of steel production and demolition waste pressures, into one framework to support sustainable construction strategies.

With regard to Hypothesis (2), the dynamic material analyses for Chinese housing stocks indicate that a highly oscillating demand for housing construction is to be expected for the coming decades. The longer the lifespan of buildings is, the stronger the oscillation will be. The use of dynamic MFA models enables to include stock ageing, which seems to be of primary importance for anticipating the long-term development of construction demand.

In relation to Hypothesis (3), the generic stock dynamics model has been extended to include GDP, an indicator of economic growth/income rise, and urbanization rate, an indicator of urbanization process, as two of the drivers for the long-term evolution of housing stocks in China. A strong correlation between per capita floor area (PCFA) and local per capita GDP has been identified in the study on construction and demolition waste in Beijing (Chapter 2). The historical correlation can be used to estimate future PCFA development based on GDP projections. The study on dynamics of urban and rural housing stocks in China (Chapter 3) uses this approach to construct a GDP driven scenario for investigating the urban housing stock dynamics in China, which gives a modest PCFA growth till 2100. However, due to the uncertainty of the correlation function and the GDP projection for the distant future, this scenario is used only as a reference for the medium scenario and a much wider variance has been used to investigate the effect of floor area stock pattern on future construction and demolition. The studies on floor area dynamics and iron and steel cycles in Chinese urban and rural housing stocks use urbanization rate, dividing Chinese national population in rural and urban, to derive the housing floor area stocks in the two systems. These studies show that it is feasible to explore the built environment metabolism in an expanding economy based on an extended stock dynamics model.

Though, one should be aware that the stock dynamics model used in this thesis is a simplified physical accounting causal model with limitations, and with uncertainties only partially covered by scenario analysis. The suitability of the model depends also on how well the limitations and uncertainties are considered, when applying the modeling results for developing sustainable construction strategies.

5.2.2 Limitations of stock dynamics model and its uncertainties

Firstly, the stock dynamics model is not precise for short-term dynamics. It assumes the demand for in-use housing floor area stock is determined by the population and its living standard represented. It is a reasonable assumption for projecting long-term trends, but is not suitable to capture the detailed short-term fluctuations, because in the short term housing demand is also determined by business cycles and more specific development as in financial markets as for mortgages, tax facilities etc.

Secondly, the results of the model are not rigid predictions; they are possible scenarios. The stock dynamics model gives the logic consequences of the potential paths of the future population's demand for housing floor area and the lifespan of dwellings. The model can say that if the Chinese urban dwellings completed after 1980s will last longer than 30 years, since the owners would not allow their home being demolished at least before they reach their rental period for the land where they standing (ca. 70 years), China's demand for new housing construction will probably soon enter a downward trend. But the model does not answer whether the lifespan of Chinese urban dwellings has been or will be prolonged. The lifespan is determined exogenously.

Thirdly, quantification of the variables involves uncertainty. For instance, in the case studies, historical per capita floor area is not available in China before 1949 and there is especially scarce lifespan information of the buildings. However, the sensitivity analysis following each case study shows that the most critical factor is the lifespan of the Chinese urban dwellings built in the last three decades which cover the most of the standing cohort in urban areas. Better understanding of the lifespan of the specific cohort of buildings and further observations of the evolution trend of the lifespan of the newly completed dwellings in China will increase the precision of this model projection. Nevertheless, the wide variance of lifespan scenarios that were investigated in the cases studies seems to indicate the robustness of the results.

5.2.3 Evaluation of the case studies

Four research questions that were raised at beginning of the thesis, considering the sustainability challenges due to material mobilization of the built environment development. What are:

Q1. Trends for inflows (in construction)

Q2. Trends for outflows (in demolition)

Q3. Environmental impacts

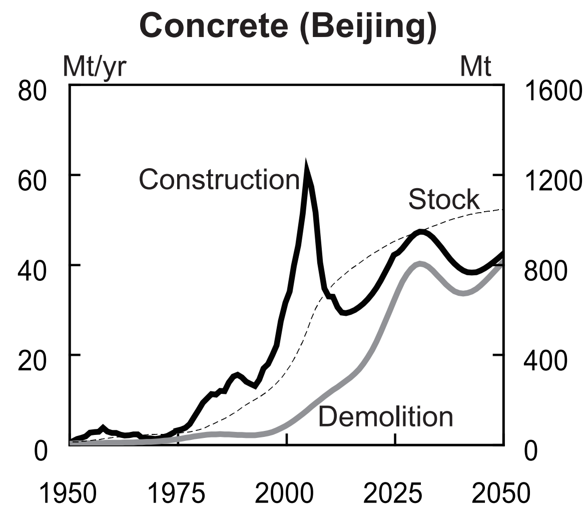
Q4. Implications for industries

With the support of the developed stock dynamics dynamic MFA models, these questions have been investigated through three case studies that are presented from Chapter 2 to 4, as indicated in Table 1.1.

Overview of research questions addressed in each chapter of this thesis*

	Research questions			
	Q1	*Q2*	*Q3*	*Q4*
Chapter 2 (Case I)	●	●		
Chapter 3 (Case II)	●	●		●
Chapter 4 (Case III)	●	●	●	●

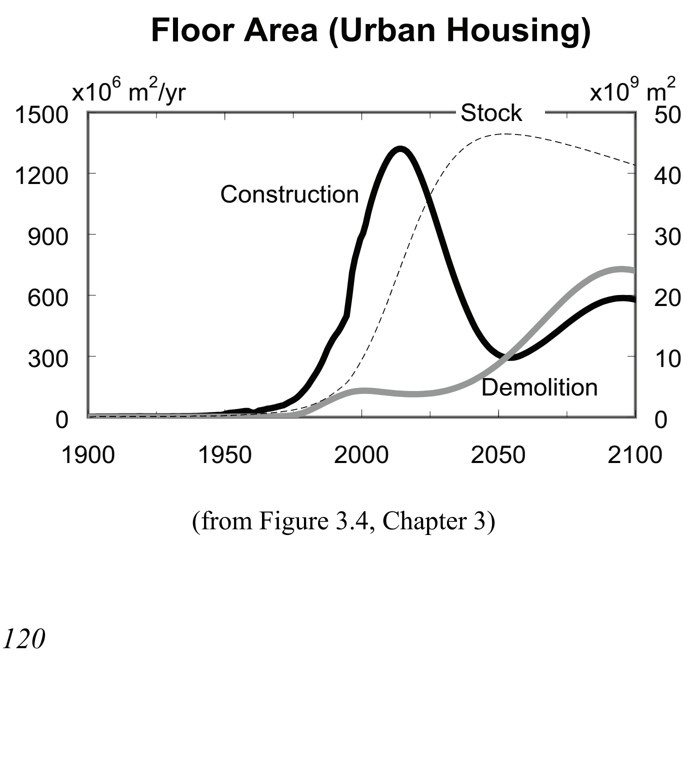
* Reproduction of Table 1.1, Chapter 1.



(from Figure 2.10, Chapter 2)

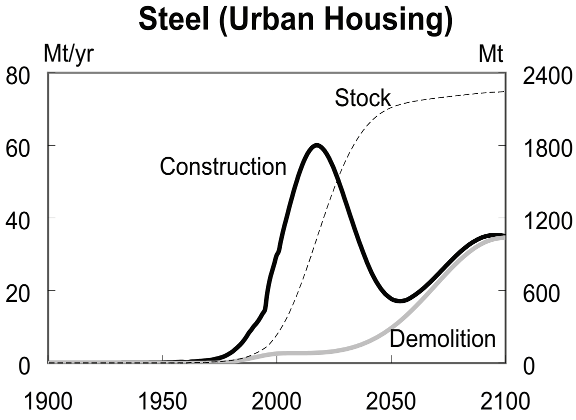
Case I (Chapter 2) develops a GDP driving dynamic MFA model for examining the concrete diffusion in Beijing's urban housing system. It answers the questions *Q1* and *Q2*. Regarding '*Trends for inflows*', it states that the concrete demand for new residential construction in Beijing is probably to drop over the next decade, even with an extremely high GDP growth. With regard to '*Trends for outflows*', it states that, in the coming decades, the demolition activities and related concrete debris in Beijing will rise, unavoidably. If the current short lifespan of buildings (ca. 25 years) continues, Beijing will face a dramatic rise of demolition concrete through 2050. Doubling the lifespan can push the significant rise to a more distant future but cannot avoid it. The amount of concrete released from demolition will almost catch the level of construction demand by 2050. Hence developing concrete recycling techniques have an increasing potential to close this material loop in Beijing's residential construction.

Case II (Chapter 3) develops a two-sub-systems dynamic MFA model for including the driving force of urbanization in the investigation of floor area dynamics in Chinese urban and rural housing stocks. It provides a base for answering the questions *Q1*, *Q2* and *Q4*. Regarding '*Trends for inflow*', it indicates a strong oscillation in the demand for urban housing construction over the coming decades. This study gives an early alarm for the changing trends of China's demand for housing construction. Even in view of the ongoing urbanization, China's present trend of high residential construction may not continue. The turning point of the downtrend may well be right now. The downturn of residential construction has already been observed in China's statistical yearbook released afterwards (though in 2008, reduced Chinese growth may have played a role for this drop as well). This study identified that the critical factor for the oscillation phenomenon is the lifespan of dwellings. Whether the lifespan of Chinese urban dwellings has been increased significantly after the 1980s' housing privatization reform is critical for anticipating China's housing stock dynamics in the next couple of decades. As to '*Trends for outflow*', this study indicates that the current development trends of housing demolition may not change dramatically in both rural and urban areas for a couple of decades. With regard to '*Implication for industry*', this study states that the dramatic reduction (from 1.3 billion to 0.3 billion square meters) in annual residential construction demand for the coming decades may imply a significant problem for the building industry and its



(from Figure 3.4, Chapter 3)

upstream suppliers.



(from Figure 4.4, Chapter 4)

Case III (Chapter 4) extends the two-sub-systems floor area dynamic MFA model developed in Case II to investigate the dynamics of iron and steel cycles in Chinese residential stocks. It addresses all the four questions proposed at the beginning of the thesis. With regard to question *Q1* '*Trends for inflow*', it states that the oscillation phenomenon identified at the floor area level happens also at the material level for residential iron and steel demand. The longer lifespan of buildings and the lower the floor area stock is, the stronger the proportional oscillation will be. Opposite to most projections, this study indicates a significant reduction in steel demand over the coming decades from China's residential sector, which currently accounts for 20% of the country's steel consumption. The use of dynamic MFA enables to include stock ageing, which is not present in other forecasts, and which seems to be of primary importance. As to question *Q2* '*Trends for outflow*', the scrap becoming available from residential demolition is likely to rise significantly after ca. 2040. However, though all scrap can be recycled, it is still unlikely to supply the new construction demand to a substantial degree for the next couple of decades. Regarding question *Q3* '*Environmental impacts*', the study shows that 'floor area stock' is the most influential factor for the accumulated environment performance of China's urban housing stock in the 21st century. Increasing demand for housing floor area will lead to a significant increase in resource use and energy demand, here focused on the production of residential steel. This holds even for the 100% recycling scrap scenario. Nevertheless, increasing scrap recycling can decrease the accumulated net CO_2-emissions and resource use to some extent for all the scenarios. The shorter lifespan the dwellings have the more critical of recycling strategy will be to minimize the environmental costs. With regard to question *Q4* '*Implications for industry*', if the current steel production would continue, the oscillation of steel demand in Chinese residential construction indicates that there might be serious overcapacity in China's steel industry and its upstream supplier, especially iron ore mining. Given its substantial size, this is likely to exert a substantial impact on the global markets involved. This study has high relevance for the steel industry and the building industry, and broader for society, by indicating structural development in demand. It provides a basis for the further exploration on the consequences of various policy options for China's building and construction development. Short term analysis can better be framed in the long term framework we developed. This would benefit both industry and society. One definite recommendation is that recycling of scrap from CDW waste must be organized.

5.3 Conclusions

5.3.1 Methodology

1. Stock dynamics model is suitable for investigating the long-term metabolism of the built environmental stocks, also for a developing economy in the process of ongoing urbanization. However, it is not precise for predicting short-term fluctuations.
2. The lifespan of buildings, determining the patterns of future demand for construction and demolition, is the most crucial factor for forecasting the long-term dynamics of the housing stock.
3. The in-use-stock of service units plays a prominent role in exploring the long-term metabolism of the built environment system. It allows for examining the building material stocks in a dynamic way, where annual stock quantities can be linked to annual demand for building service provided to the population, which in turn depends upon socio-economic and demographic parameters. Thus, it is useful to investigate the future metabolic patterns of the built environment development in a fast developing economy and a rapid urbanizing region.
4. The stock ageing mechanism is of primary importance for analyzing the long-term metabolism of a built environment system. For a recently expanded built environment stock, extrapolation of the 'demolition rate' or 'replacement rate' does not make a good indicator. Therefore it is problematic to estimate future demolition activity level based on historic demolition rate and future stock size. For long lifespan goods such as buildings, dynamic material flow analysis is required to project future material demand and waste flows.
5. For long-term projection, trend extrapolation in demand for new construction materials is not suitable. It is especially problematic to estimate the future material demand for a built environment system which has been or is being built up in a very short time, because the relatively long lifespan of built structures

may displace the rise of replacement demand and the drop in stock expansion demand. Thus structural oscillations in new construction and the related material demand occur.

6. Per capita floor area has a strong correlation with the local per capita GDP, which directly affects future construction demand. However, its effect on demolition waste generation will show only in the distant future, based on stock dynamics.
7. Although the material intensity per unit of floor area influences future material demand, it is unlikely to substantially alter the pattern of inflows. If oscillation occurs in new construction demand for housing floor area, a growing material intensity scenario may mitigate but cannot eliminate the oscillation in demand for construction materials. Also, the future material intensity is the least influential parameter for projecting future demolition waste generation.

5.3.2 Housing service units

8. While China's urbanization target will be reached in about 2050 and the national population will peak in about 2040, the stock expansion of urban housing floor area in China is slowing down and likely to reach the top by 2040.
9. The lifespan of the existing buildings has a considerable influence on future residential construction and replacement demand. If the existing dwellings in urban China have a very short lifespan (less than ca. 30 years), driven by the need for replacement, the demand for urban residential construction will stay at a high level through the 21st century, companied by a high demolition.
10. If the implementation of housing privatization reform from the 1980s has led to lengthening lifetime expectancy of Chinese urban dwellings, and if the urban dwellings completed since then have a lifespan longer than 30 years, China's demand for new urban residential construction will oscillate in the 21st century. The longer the lifespan of buildings is and the lower per capita living space is, the stronger the proportional oscillation in new construction demand will be.
11. The rural residential construction in China has started to shrink since a few years ago and will likely keep dropping in the coming decades and stay at a low level through all the 21st century.

5.3.3 Construction materials

12. Large amount of demolition concrete is expected to arrive over the next 50 years in Beijing city and similarly in other urban areas. Lengthening the service lifetime of dwellings can postpone the arrival of the peak of demolition concrete to mitigate its pressure for waste management in the near future. However, this mitigation might be offset by other solid wastes arising from renovation and refurbishment activities that are employed to realize the longevity of buildings. High per capita floor area will lead to a high level of demolition concrete in the more distant future.
13. The steel scrap from housing demolition will likely increase to almost reach the level of the steel demand for new construction by the end of 21st century. However, for the 21st century as a whole, both steel and concrete will keep accumulating in China's urban residential stocks.
14. The environmental impacts of the material use in Chinese urban residential construction could be reduced to some extent by a strong emphasis on producing secondary materials from demolition waste. The shorter the lifespan of the building is, the more critical the recycling of scrap will be.
15. Steel component in Chinese rural residential stock is very limited and is unlikely to increase significantly. Material analysis for iron and steel in China's rural and urban housing systems shows that one of the consequences of urbanization is the increased steel intensity life style. Projection for residential steel demand should focus on the urban system.
16. If the existing Chinese urban dwellings have an average lifespan longer than 30 years and if the future completed ones will have a lifespan around its land lease contract (70 years), the steel demand for Chinese residential construction will probably drop by a factor of 3.5 from ca. 2020 to ca. 2050. Such reduction may apply also for Chinese infrastructures, which usually have even longer service lifetimes.
17. China's becoming world largest steel producer and biggest consumer[18] since the late 1990s (Price et al. 2002) can be largely attributed to its rapid urbanization, with half of its domestic steel consumption ends in construction sector (DRCSCC 2005). The foreseen significant contraction in Chinese demand for construction steel may lead to a decrease in global steel consumption of up to 10%.

[18] China accounts for 38% of the world's crude steel production and 34.8% of the world's apparent steel consumption in 2008 (WSA 2010).

18. If the current level of Chinese steel production continues, a severe overcapacity may be expected. This might exert pressures to global markets in the next couple of decades, due to an increase of Chinese steel export at more competitive price.

5.4 Recommendations

5.4.1 Technical and policy recommendations

1. China's housing construction is likely to shrink, if the existing buildings can last more than 30 year. To cope with the challenge of the ageing housing stock and the change in construction demand, policy makers and building professions in the construction industry of China are advised to shift their focus from new construction to maintenance and refurbishment of existing buildings. This is also important for energy reason in the use phase during service life with increased heating and cooling requirements.
2. Given the demolition activities will continue to rise throughout the rest of the 21st century in China, efforts on extending the service lifetime of the buildings are recommended to reduce the demolition waste in the near future. While for a long-term strategy, increasing the recycling of demolition materials is highly recommended. One fundamental solution is to develop an information system to document the construction materials deposited in the built environment. This would offer a basis for planning the reuse, recycling and disposal of construction and demolition waste, and can be used as a map for future 'urban mining'.

5.4.2 Recommendations for the development and use of dynamic material flow analysis models to support construction strategies

3. The service lifetime is the most influential but least understood factor in dynamic material flow analysis models. Further research on factors determining lifetime of buildings, and other infrastructures are recommended.
4. The stock dynamic models developed in this thesis are based on top-down approaches and physical accounting. If used in combination with bottom-up approaches and other models, such as economic models of the housing market or decision models on demolition vs. maintenance and renovation their long-term projection power would increase. Hence it is worthwhile for future research to look into.

5. Case studies conducted in this thesis refer only to one of the subsystems of built environment, the housing system, which is more directly linked with the population and its living style. For the dynamics of other subsystems of the built environment such as non-residential buildings and urban infrastructures, similar stock dynamics will hold, but with different determining factor and time frame. Further research is recommended.
6. Compared to MFA, LCA is a better known tool in the construction professions. While LCA is useful to support decisions for individual built objects like a building, a bridge or a road, MFA has special strength on recommending policies on a regional or national scale (e.g. urban planning and building standards). How to standardize MFA studies and use them complementarily with LCA for supporting sustainable construction practices is recommended for future research.
7. The dynamic material flow analysis model focuses on systems understanding. How to translate this systems knowledge into action knowledge of individual actors related to sustainable built environment development is an important subject for future research.

Reference to Chapter 5

Development Research Center of the State Council of China (DRCSCC). 2005. Forecast Report of the Steel Consumption of China 2005–2010. Beijing, China (in Chinese).

Price, L., J. Sinton, E. Worrell, D. Phylipsen, H. Xiulian, L. Ji. 2002. Energy use and carbon dioxide emissions from steel production in China. Energy 27:429-446.

World Steel Association (WSA). 2010. Steel Statistical Yearbook 2009, Brussels.

Publications in this thesis

Chapter	Reference
2	Hu, M., E. van der Voet and G. Huppes. 2010. Dynamic material flow analysis for strategic construction and demolition waste management in Beijing. Journal of Industrial Ecology 14(3). doi: 10.1111/j.1530-9290.2010.00245.x
3	Hu, M., H. Bergsdal, E. van der Voet, G. Huppes and D.B. Müller. 2010. Dynamics of urban and rural housing stocks in China. Building Research & Information 38(3):1–17. doi: 10.1080/09613211003729988.
4	Hu, M., S. Pauliuk, T. Wang, G. Huppes, E. van der Voet and D.B. Müller. 2010. Iron and steel in Chinese residential buildings: a dynamic analysis. Resources, Conservation & Recycling 54(9):591–600. doi: 10.1016/j.resconrec.2009.10.016.

Samenvatting

In dit proefschrift wordt de ontwikkeling beschreven van een voorraad-gestuurd model voor dynamische materiaalstroomanalyse (*materials flow analysis*, MFA) dat kan worden gebruikt voor het analyseren van het langetermijn-metabolisme van de woningvoorraad in snel verstedelijkende opkomende regio's.

Inleiding

Veel van de duurzaamheidsproblemen die ontstaan door de huidige ontwikkelingen in de gebouwde omgeving hebben te maken met de grootscheepse mobilisering van materialen, die twee soorten problemen met zich meebrengt. Aan de instroomzijde gaat het hierbij om uitputting van de voorraden hulpbronnen en emissieproblemen als gevolg van de productie van bouwmaterialen, terwijl het aan de uitstroomzijde gaat om problemen met het bouw- en sloopafval (BSA). Met name de opkomende economieën zien zich geconfronteerd met ernstige problemen, aangezien naar verwachting bijna de gehele toename van de wereldbevolking in de volgende 50 jaar zal moeten worden opgenomen door de verstedelijkte gebieden in deze landen. Ondertussen is de theorievorming over de duurzame ontwikkeling van de gebouwde omgeving nog in ontwikkeling. Hoewel de concepten en doelstellingen nog niet voldoende zijn gedefinieerd, is er een duidelijke behoefte aan een langetermijn systeemvisie ter ondersteuning van de ontwikkeling van een duurzame gebouwde omgeving. Een dergelijke visie kan alleen worden ontwikkeld op basis van inzicht in het langetermijn-metabolisme van de voorraden in de gebouwde omgeving, door toepassing van dynamische materiaalstroomanalyse. Bij eerder onderzoek naar woningvooraden in ontwikkelde landen met behulp van dynamische materiaalstroomanalyse is reeds met succes gebruik gemaakt van een aanpak op basis van voorraaddynamiek, maar deze benadering is nog niet toegepast op opkomende landen, waar rekening moet worden gehouden met de gecombineerde effecten van zeer snelle economische ontwikkeling en urbanisatie.

Onderzoeksopzet

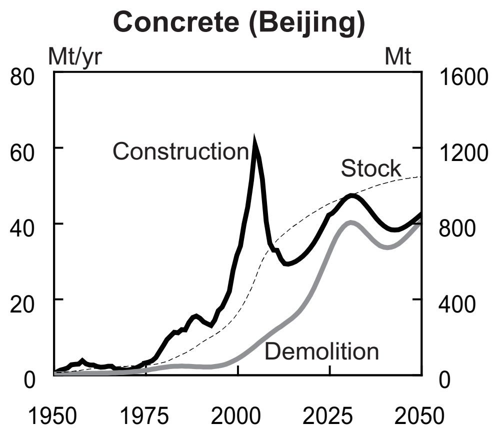
De toegevoegde waarde van het hier beschreven onderzoek ten opzichte van de bestaande benaderingen is gelegen in het gebruiken van algemene sociaal-economische en specifieke urbanisatie-gerelateerde factoren in China. Het onderzoek omvatte drie opeenvolgende stadia, in de vorm van drie case studies (Case I ~ Case III in Hoofdstuk 2 ~ 4) betreffende woningvoorraden in China, die elk reeds als afzonderlijk artikel zijn gepubliceerd. Daarnaast wordt in Hoofdstuk 1 een algemene inleiding gegeven, terwijl in Hoofdstuk 5 de resultaten worden besproken, conclusies worden getrokken en aanbevelingen worden gedaan voor het gebruik van dynamische MFA ter ondersteuning van de duurzame ontwikkeling van de gebouwde omgeving.

- In Case I (Hoofdstuk 2) zijn de langetermijn-gevolgen van de economische groei van Beijing op de vraag naar bouwmaterialen en de productie van sloopafval bestudeerd met behulp van een model voor voorraaddynamiek.
- In Case II (Hoofdstuk 3) zijn de langetermijn-gevolgen van de verstedelijking van China op de vraag naar woning-vloeroppervlakte in urbane en rurale gebieden onderzocht met behulp van een model voor vloeroppervlaktedynamiek in deze twee systemen.
- In Case III (Hoofdstuk 4) is ingegaan op de langetermijn-dynamiek van het in China voor woningbouw gebruikte ijzer en staal, in het licht van de voortgaande verstedelijking, door het twee-systemen model voor vloeroppervlakte uit te breiden tot het niveau van de materialen.

Case studies

De ontwikkelde modellen zijn gebruikt ter beantwoording van vier onderzoeksvragen: '*Welke tendensen kunnen worden onderscheiden voor wat betreft de instroom?*'; '*Welke tendensen kunnen worden onderscheiden voor wat betreft de uitstroom?*'; '*Wat zijn de milieueffecten?*' en '*Welke gevolgen hebben deze tendensen voor de industrie?*', dit alles in relatie tot de toekomstige ontwikkelingen in de woningvoorraden in China.

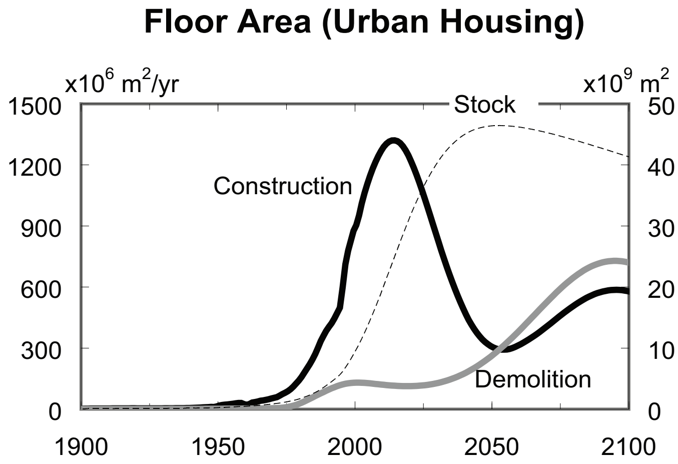
Case I: Dynamische materiaalstroomanalyse voor strategisch beheer van bouw- en sloopafval in Beijing



(ontleend aan Figuur 2.10, Hoofdstuk 2)

In dit onderzoek werd een dynamisch MFA-model op basis van het bruto binnenlands product (BBP) per hoofd van de bevolking ontwikkeld ter bestudering van de verspreiding van beton in het stedelijke woningbouwsysteem in Beijing. Uit vergelijkingen met andere landen werd een sterke correlatie afgeleid tussen de vloeroppervlakte per hoofd van de bevolking en het lokale BBP per hoofd van de bevolking. Op basis van de historische correlatie kan het model vervolgens het effect van een groei van het BBP op toekomstige veranderingen in de woningvoorraad voorspellen. Bij dit onderzoek lag de nadruk op inzicht in de 'tendensen voor wat betreft de uitstroom', aangezien het onderzoek was gericht op het ondersteunen van het beheer van bouw- en sloopafval (BSA). De resultaten van het model geven aan dat de hoeveelheid beton die vrijkomt uit de sloop van woningen in Beijing de komende 50 jaar zeer sterk zal toenemen. Verder geven de resultaten aan dat de hoeveelheid BSA die in de nabije toekomst zal worden gegenereerd, sterk afhangt van de levensduur van de gebouwen; een sterke groei van de vloeroppervlakte per hoofd van de bevolking als gevolg van voortdurende stijging van het BBP zal leiden tot een groei van de hoeveelheid BSA, met name op langere termijn. De strategie voor de middellange termijn zou derhalve gericht moeten zijn op het verlengen van de bruikbare levensduur van de gebouwen. Dit kan worden bereikt door renovatie en het stellen van hoge kwaliteitseisen aan nieuwbouw. Alle scenarioberekeningen geven echter aan dat een stijging van de geproduceerde hoeveelheid BSA onvermijdelijk is. Daarom dient de langetermijn-strategie vooral gericht te zijn op recycling, teneinde de druk op stortplaatsen en de vraag naar grondstoffen in de toekomst te beperken.

Case II: Dynamiek van woningvoorraden in urbane en rurale gebieden in China

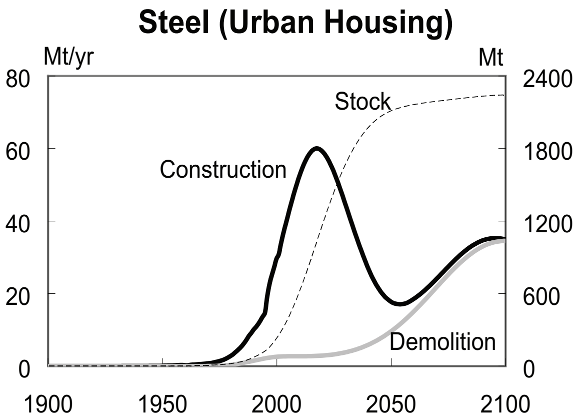


(ontleend aan Figuur 3.4, Hoofdstuk 3)

In dit onderzoek werd een dynamisch MFA-model voor twee systemen ontwikkeld, met inbegrip van de verstedelijking als drijvende kracht, ter bestudering van de vloeroppervlakte-dynamiek van de totale woningvoorraad in urbane zowel als rurale gebieden in China. Hierin wordt op basis van de mate van verstedelijking de Chinese bevolking onderverdeeld in rurale en urbane bevolking, om de woningvoorraad in termen van vloeroppervlakte voor de twee systemen afzonderlijk te kunnen afleiden. Het onderzoek richtte zich vooral op het verkrijgen van inzicht in de 'tendensen voor wat betreft de instroom'. De met het model verkregen resultaten duiden op aanzienlijke schommelingen in de vraag naar nieuwe woningbouw in de stedelijke gebieden in de komende decennia. De onderzoeksresultaten vormen een waarschuwing dat er veranderingen te verwachten zijn in de vraag naar woningbouw in China. Ondanks de voortgaande verstedelijking zal het huidige hoge volume van de woningbouw in de Chinese stedelijke gebieden niet blijvend zijn. Het keerpunt in de groei is wellicht al bereikt of zal in de nabije toekomst worden bereikt. Uit onze gevoeligheidsanalyse blijkt dat de schommeling in de nieuwbouw vooral afhangt van de levensduur van de gebouwen. Alleen voor het scenario dat uitgaat van een zeer korte levensduur (minder dan 30 jaar) levert de simulatie een minimale schommeling op. Beter inzicht in de levensduur van gebouwen is dan ook van essentieel belang om te kunnen anticiperen op de toekomstige dynamiek in de woningvoorraad.

Case III: IJzer en staal in Chinese woongebouwen: een dynamische analyse

In deze studie werd het dynamische twee-systemen MFA-model voor vloeroppervlakte dat was ontwikkeld voor het onderzoek naar de dynamiek van de Chinese woningvoorraad in urbane en rurale gebieden, uitgebreid ten behoeve van een analyse van veranderingen in de hoeveelheid ijzer en staal die worden gebruikt in de woningvoorraad in China. Daartoe werden de historische ontwikkelingen en de potentiële toekomstige ontwikkelingen in de staalintensiteit van de Chinese woningbouw bestudeerd. Bij dit onderzoek lag de nadruk op het verkrijgen van inzicht in de 'milieueffecten' en de 'gevolgen voor de industrie'. De met het model verkregen resultaten geven aan dat de schommelingen die waren gevonden op het niveau van woningbouw ook optreden op het niveau van materialen, voor wat betreft de vraag naar ijzer en staal voor woningbouw. Hoe langer de levensduur van de gebouwen en hoe lager de totaal beschikbare vloeroppervlakte, des te heviger zullen de relatieve schommelingen zijn. In tegenstelling tot de meeste ramingen blijkt uit onze resultaten dat de vraag naar staal vanuit de woningbouwsector in China, die nu nog goed is voor 20% van de nationale staalconsumptie, de komende decennia significant zal afnemen. Dankzij het gebruik van dynamische MFA is het mogelijk ook de veroudering van de bestaande woningvoorraad, die in de meer trendgerichte voorspellingen buiten beschouwing wordt gelaten, mee te nemen in de analyse. Dit is van primair belang. De verwachte daling in de vraag naar staal biedt uiteraard voordelen voor wat betreft zowel milieueffecten als het beperken van het grondstoffenverbruik. Op lange termijn geldt dat een langere levensduur van de gebouwen leidt tot minder CO_2-uitstoot als gevolg van bouwactiviteiten, en tot een lager verbruik van potentieel schaarse hulpbronnen. Als de Chinese staalproductie echter op het huidige niveau door zou gaan, zou de daling in de vraag naar staal voor de woningbouw leiden tot het ontstaan van een grote overcapaciteit in de Chinese staalindustrie. Gezien de omvang van deze industrie zou dit een substantiële invloed hebben op de desbetreffende wereldmarkt.



(ontleend aan Figuur 4.4, Hoofdstuk4)

Voornaamste conclusies

5. Modellen voor voorraaddynamiek vormen een geschikt middel voor het onderzoeken van het langetermijn-metabolisme van de gebouwde omgeving; dit geldt ook voor snel groeiende economieën in landen met een sterke tendens tot verstedelijking.
6. De levensduur van gebouwen, die bepalend is voor de toekomstige ontwikkeling van de vraag naar woningbouw en -sloop, is de meest cruciale factor bij het voorspellen van de langetermijn-dynamiek van het metabolisme van de woningvooraad.
7. De omvang van de sloopwerken in China zal in de loop van de 21ste eeuw onvermijdelijk toenemen. Voor wat betreft het terugdringen van de milieueffecten kan worden geconcludeerd dat het hergebruik van secundaire materialen uit bouw- en sloopafval des te crucialer zal zijn naarmate de levensduur van de gebouwen korter is.
8. In de loop van de komende decennia kan een daling van de vraag naar nieuwe woningbouw worden verwacht. Als de staalproductie op het huidige niveau wordt gehandhaafd, is te voorzien dat er een grote overcapaciteit zal ontstaan in de Chinese staalindustrie. Deze zal grote gevolgen hebben voor de wereldmarkt, in de vorm van een afname van de mondiale staalconsumptie met misschien wel 10%.

Aanbevelingen voor verder onderzoek

De volgende aspecten van dynamische materiaalstroomanalyse ter ondersteuning van strategieën voor duurzaam bouwen vormen interessante onderwerpen voor verder onderzoek:

- inzicht in de factoren die de levensduur van gebouwen bepalen;
- het combineren van dynamische MFA-modellen met economische modellen;
- het analyseren van de dynamiek van andere subsystemen van de gebouwde omgeving (zoals niet voor bewoning bestemde gebouwen en stedelijke infrastructuur);
- het gebruik van dynamische MFA in combinatie met LCA;
- het vertalen van de uit dynamische MFA verkregen systeemkennis naar praktische kennis die kan worden benut door de bouwsector.

Acknowledgement

I thank Ayman Elshkaki and Ruben Huele at Leiden University, Håvard Bergsda and Stefan Pauliuk at Norwegian University of Science and Technology for the discussion of modeling techniques and Tao Wang for the knowledge of iron and steel in China. I am grateful to Yong Wu at Ministry of Housing and Urban-Rural Development of the People's Republic of China and Huaping Liu at Tsinghua University, for supporting me in data collection for the case studies.

Curriculum Vitae

Personal

Name	Mingming Hu
Date of birth	20 May 1975
Place of birth	Sichuan, China

Education

B.Sc., Mechanical Engineering, Chongqing Jianzhu University, Chongqing, China, 1997
M.Sc., Mechanical Engineering, Chongqing Jianzhu University, Chongqing, China, 2000
Ph.D., Environmental Science, Leiden University (2010, expected)

Employment record

Lecturer, Chongqing University, Chongqing, China, 2000 – 2002
Government employee, Chongqing Construction Commission, Chongqing, China, 2002 – 2006
Researcher, Chongqing University, Chongqing, China, 2006 – present

Articles

Hu, M., E. van der Voet and G. Huppes. 2010. Dynamic material flow analysis for strategic construction and demolition waste management in Beijing. Journal of Industrial Ecology 14(3). doi: 10.1111/j.1530-9290.2010.00245.x

Hu, M., H. Bergsdal, E. van der Voet, G. Huppes. and D.B. Müller. 2010. Dynamics of urban and rural housing stocks in China. Building Research & Information 38(3):1–17. doi:10.1080/09613211003729988.

Hu, M., S. Pauliuk, T. Wang, G. Huppes, E. van der Voet and D.B. Müller. 2010. Iron and steel in Chinese residential buildings: a dynamic analysis. Resources, Conservation & Recycling 54(9):591–600. doi: 10.1016/j.resconrec.2009.10.016.

Report

Hu, M. Efficiency of screening operations for mixed construction and demolition waste sorting. Report for Kringbouw project: Automatic Sorting of Construction and Demolition Waste (CDW), Delft, 2007.

Presentations

Housing lifestyle and its long-term material consequence, In: European Network for Housing Research Conference, Dublin, Ireland, 2008.

Multi-regional dynamic material flow analysis for urban housing stock – case study for housing in Beijing, In: ConAccount Conference, Prague, Czech Republic, 2008.