Dynamic material flow analysis to support sustainable built environment development

Hu, M.

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

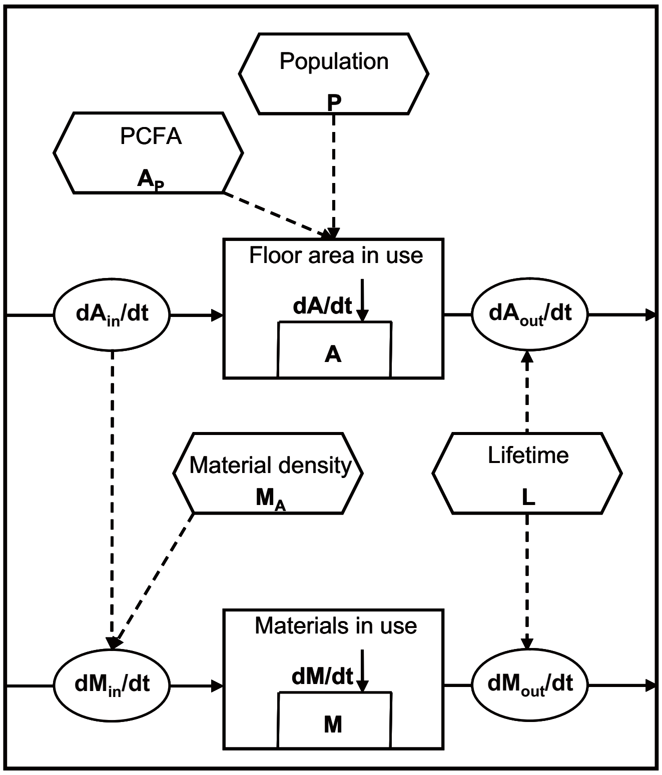

Figure 2.1 Conceptual outline of the stock dynamics model. PCFA = per capita floor area. Rectangles represent processes, ovals depict flows, and hexagons illustrate determinants or drivers. Dashed lines represent influences between variables: A = floor area stock; M = materials stock; dA/dt = net stock 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 20^{th} 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.

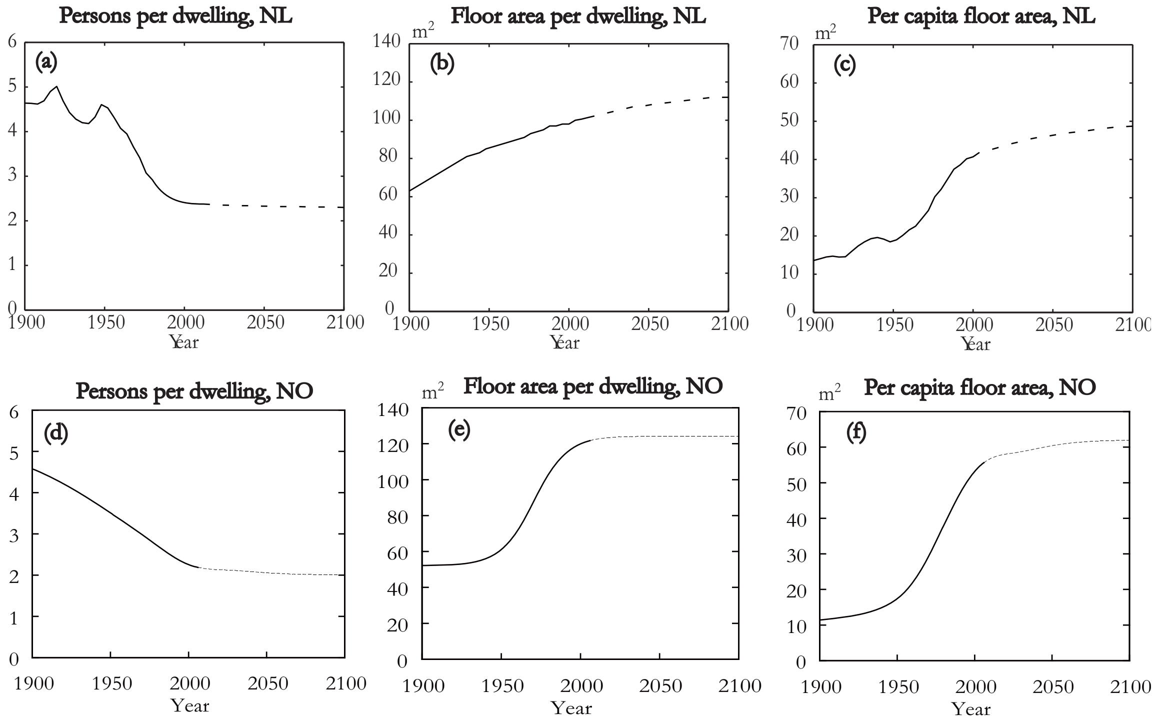

Figure 2.2 Historical figures and future projections (medium scenario) for persons per dwelling, floor area per dwelling and per capita floor area in the Netherlands and Norway. NL = the Netherlands; NO = Norway. *Source*: Müller (2006); Bergsdal et al (2007a).

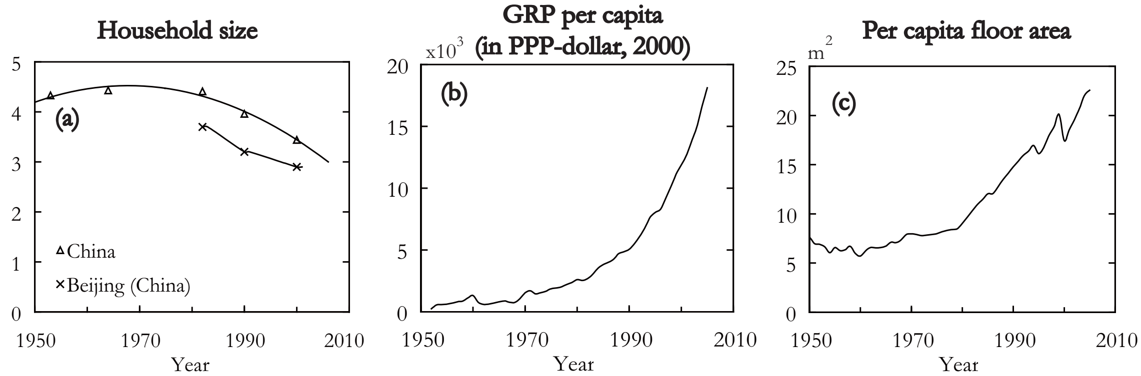

Figure 2.3 Historical figures of household size in Beijing (and all of China), gross regional product (GRP) per capita, and per capita floor area in Beijing. PPP = purchasing power parity. *Source*: BMBS (1999, 2000 – 2007); NBSC (2005); UNCDB (2008).

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).

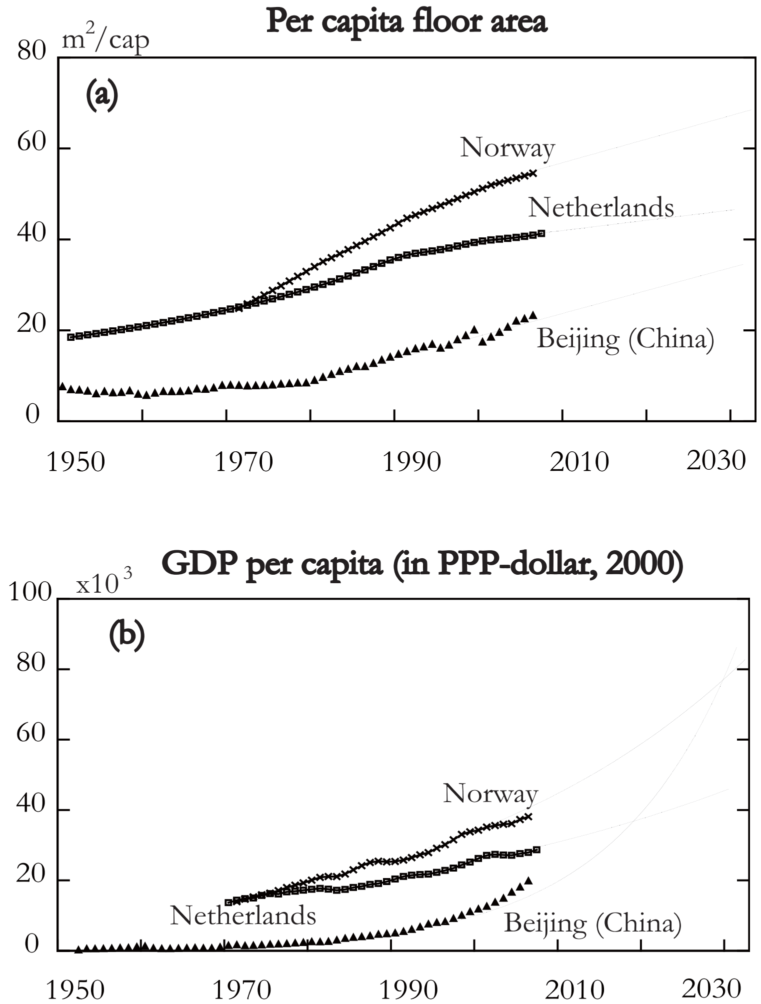

Figure 2.4 Historical figures of per capita floor area and gross domestic product (GDP) per capita in the Netherlands; Norway; and Beijing, China. m^2/cap = square meters per capita; PPP = purchasing power parity. *Source*: Müller (2006); Bergsdal et al (2007a); Eurostat (2009); UNCDB (2008); BMBS (1999,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

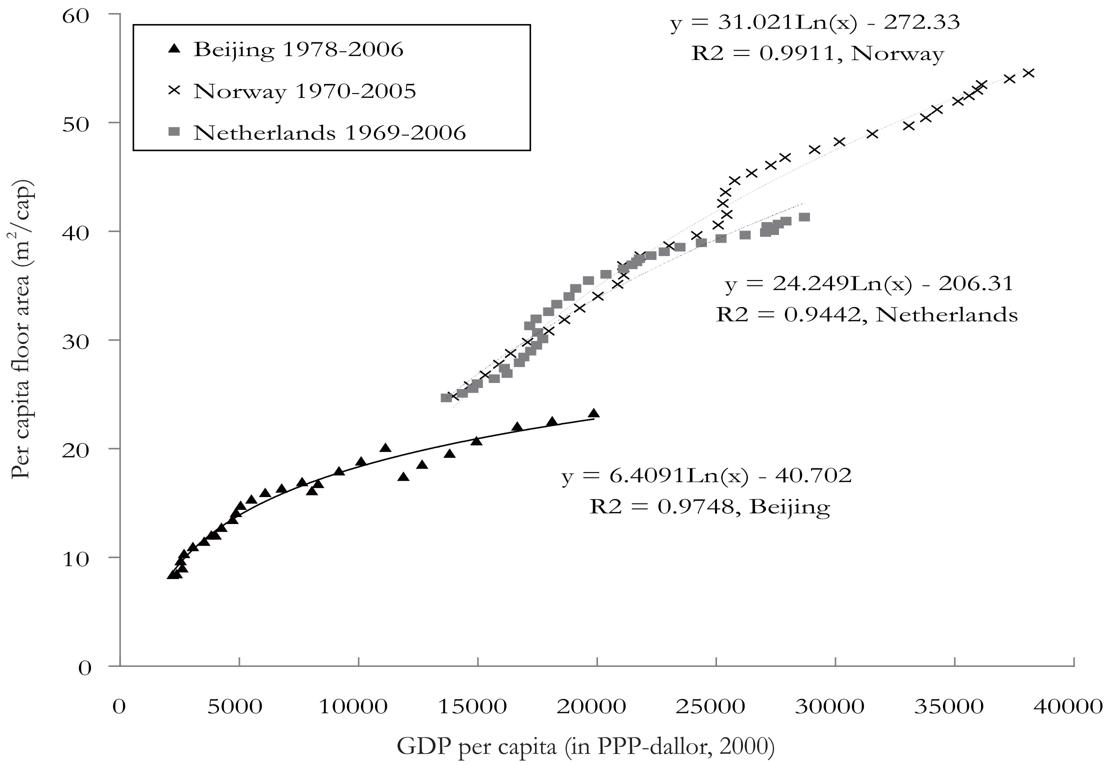

Figure 2.5 Historical regression of per capita floor area to gross domestic product (GDP) per capita in the Netherlands; Norway; and Beijing, China. PPP = purchasing power parity. *Source*: Müller (2006); Bergsdal et al (2007a); Eurostat (2009); UNCDB (2008); BMBS (1999, 2000 – 2007); NBSC (2005).

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.

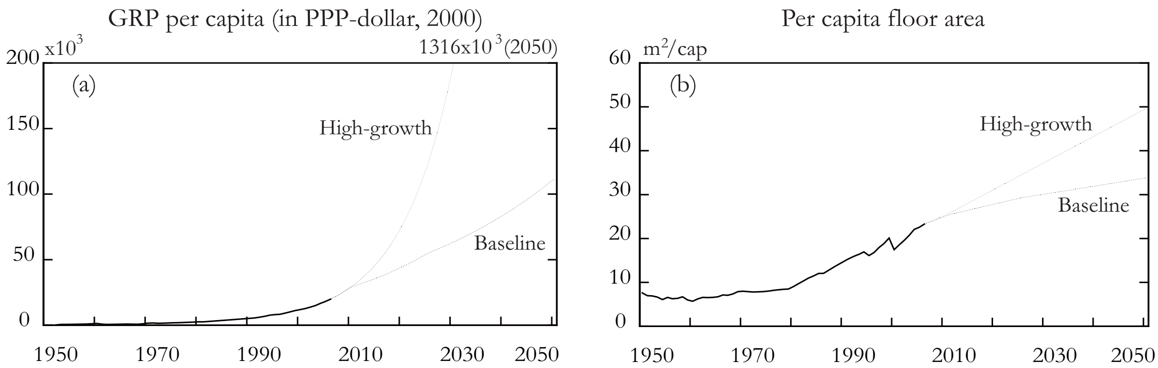

Figure 2.6 Historical figures and projections of gross regional product (GRP) per capita in Beijing and per capita floor area. PPP = purchasing power parity. *Source*: UNCDB (2008); BMBS (1999, 2000 – 2007); NBSC (2005).

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.

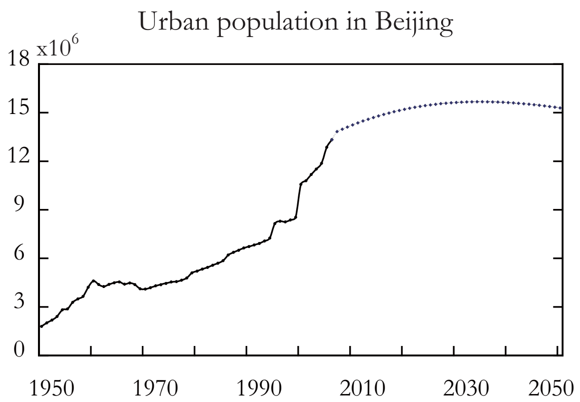

Figure 2.7 Historical figures and projection of urban population in Beijing. *Source*: BMBS (1999, 2000 – 2007).

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).

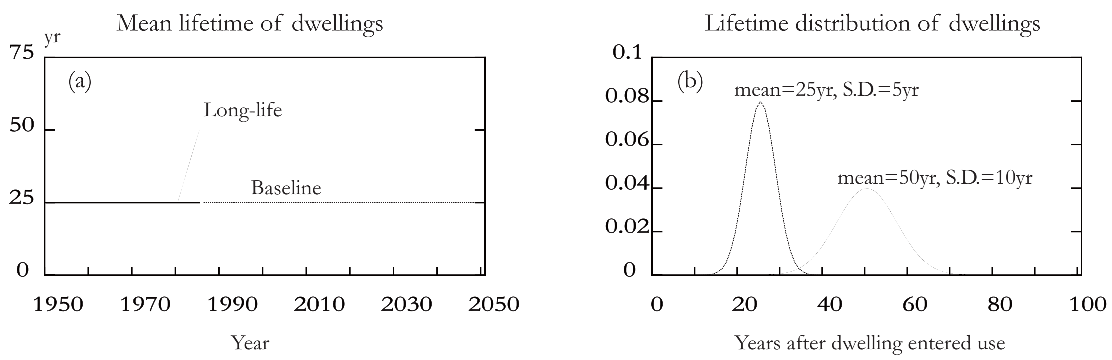

Figure 2.8 Estimations of the mean lifetime of dwellings (by year built) and lifetime distribution of dwellings (by years after dwelling entered use) in Beijing. S.D. = standard deviation.

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.

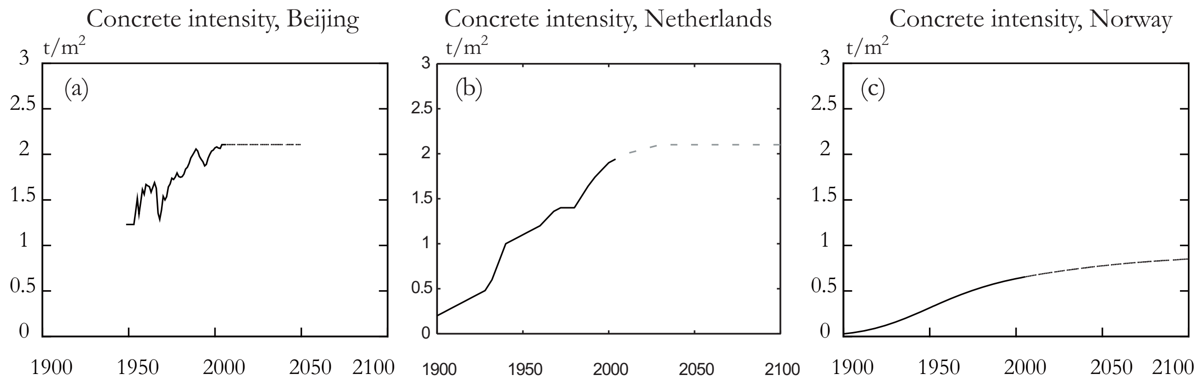

Figure 2.9 Historical figures and projections of the concrete intensity (tones per square meter floor area [t/m^2]) in housing construction in Beijing, China; the Netherlands (medium scenario); and Norway (medium scenario). One tonne (t) = 10^3 kilograms (kg, SI). *Source*: Liu and Hu (2006); BMBS (1999,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

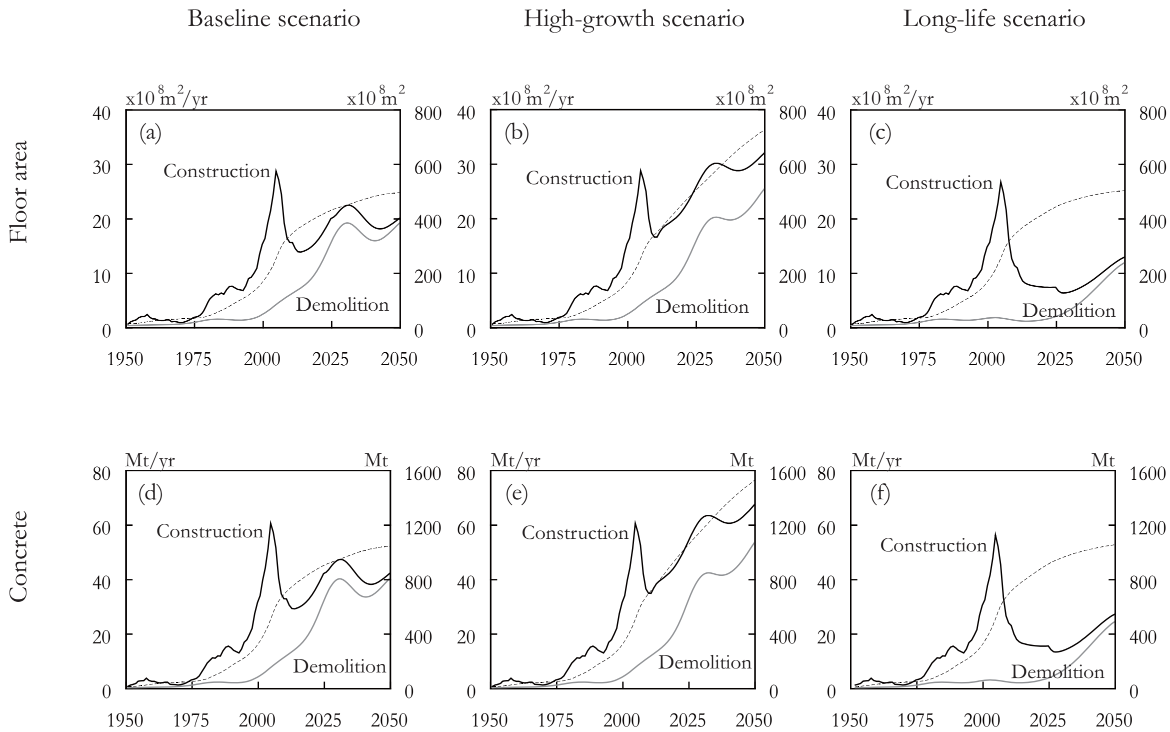

Figure 2.10 Housing floor area and concrete stock (dashed line), input flow (construction), and output flow (demolition) for the baseline, high-growth, and long-life scenarios. Stocks are measured on the right axis and flows on the left. Mt/yr = million metric tons per year.

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.