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

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Summary

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 million metric tons per year (megatonnes/year [Mt/yr]) of CDW are generated. This amount is expected to grow significantly when the first round of mass buildings erected in the 1990s starts to be demolished. In this study, a dynamic material flow analysis (MFA) is conducted for Beijing's urban housing system, with the demand for the stock of housing floor area taken 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 that PCFA has a strong correlation with the local gross domestic product (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 the lifetime of dwellings, are analyzed. The simulation results show that 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 CDW. From a systematic view, recycling is highly recommended for long-term sustainable CDW management.

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Introduction

Solid waste generated by the construction sector is classified as construction and demolition waste (CDW). In Beijing, three types of CDW are distinguished and monitored: excavated soil, demolition waste, and furnishings waste (Chen et al. 2004). Together, these three form a waste stream even larger than municipal solid waste. Records of the Beijing Solid Waste Administration Department (see table 1) show that the total CDW almost doubled from 1998 to 2004, whereas demolition waste more than tripled, to reach 2.8 million metric tons per year (megatonnes/year [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 a combination of socioeconomic and demographic changes and an aging building stock (Fatta et al. 2003; Poon et al. 2004a, 2004b; Müller 2006; Bergsdal et al. 2007a, 2007b).

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 possible optimal management strategies. The research questions are as follows:

- How will the amount of future waste concrete develop in Beijing's urban housing sector?
- If the trends found in the housing sector apply to the whole built environment, where the challenges and opportunities are for future CDW management in Beijing?
- Which strategies should be preferred, accordingly?

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

The latter approach is known as material flow analysis (MFA). Because it integrates the physical accounting into the socioeconomic dynamics analysis, this analysis respects physical laws and, at the same time, decreases the data demand for waste streams by using the relatively more easily accessible figures of inflow and stock. Depending on whether the residence time of materials is considered, this approach is further classified into dynamic MFA and static MFA. Static MFA is generally preferable because of its ease of calculation. For instance, demolition floor areas of buildings can be estimated by an assigned "replacement rate" (Yang and Hui 2008) or "reconstruction rate" (Baccini and Brunner 1991) of stocks. This calculation may lead to doubtful results, however, because the replacement rate cannot be obtained by trend extension. Voet and colleagues (2002) pointed out that when there has been a recent steep growth of long-life-span applications of goods, the present amount of waste generation is no indication at all of the future development of waste generation. Therefore, for long-life-span goods, such as buildings, researchers need to use dynamic MFA to project future waste flows.

Investigators have applied two main types of dynamic MFA models to estimate future waste streams. One is *flow dynamics* driven, as applied in work by Zeltner and colleagues (1999), Kleijn and colleagues (2000), Kohler and Hassler (2002), Voet and colleagues (2002), Elshkaki and colleagues (2004, 2005), Yang (2006), Bergsdal and colleagues (2007b), Bohne and colleagues (2007), Bradley and Kohler (2007), Hashimoto and colleagues (2007), Kohler and Yang (2007), and Yang and Kohler (2008). It assumes that the material stock is driven by its inflow and outflow; the inflow is predicted as a function of socioeconomic factors, whereas the outflow is determined by either a leaching or a delay process (Voet et al. 2002). The other type of

Table 1 Annual construction and demolition waste (CDW) generation in Beijing during 1998–2004

		Excavated soil		*Demolition waste*		*Furnishing waste*	
Year	*Total CDW*	*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.

dynamic MFA is *stock dynamics* driven, as applied in work by Binder and colleagues (2001), Johnstone (2001a, 2001b), Müller (2004, 2006), Bergsdal and colleagues (2007a), and Sartori and colleagues (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) or "stock expansion rate" (Johnstone 2001a, 2001b), or it can be defined as a function of the population and its lifestyle (e.g., Müller 2006). The outflow of materials, coupled with the obsolete service units, is determined by a delay process, whereas the inflow of materials, coupled with the new add-in service units, is introduced to maintain the stock in use. This approach, which uses 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). The current study uses a stock dynamics model to analyze the future concrete diffusion in Beijing's urban housing to generate insights for future CDW generation in Beijing.

In this article, we first introduce the stock dynamics MFA model and the calibration for the parameters. We then perform a comparison analysis for the per capita floor area (PCFA) in Beijing, the Netherlands, and Norway to project the future PCFA in Beijing. Then we conduct scenario analysis to check the impacts of high PCFA growth and a lengthening lifetime strategy on future waste generation. Finally, we make recommendations for CDW management in Beijing on the basis of the dynamic MFA study.

Methodology and Data

Stock Dynamics Model

The model presented herein represents an 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 and wood in Norwegian dwelling stock. Its main aspects are illustrated in figure 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 is represented by dA/dt and dM/dt. Input flows to stock are given by dA_{in}/dt and dM_{in}/dt, and output flows are represented correspondingly as dA_{out}/dt and dM_{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.

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

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

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

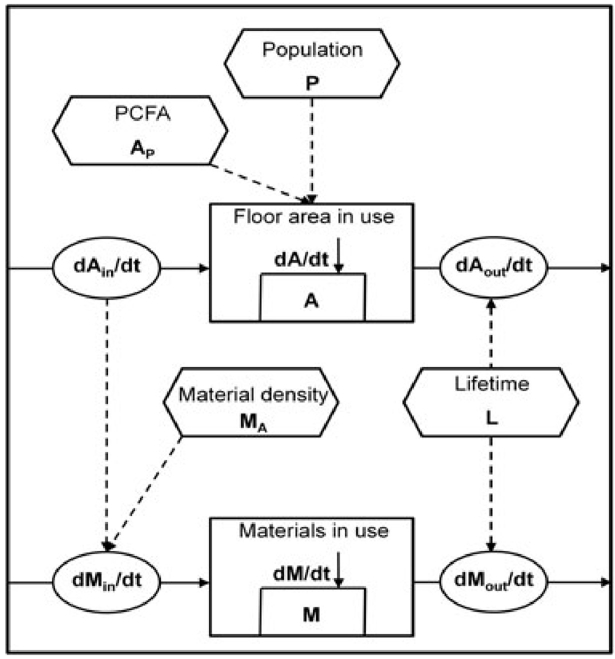

Figure 1 Conceptual outline of the stock dynamics model. Processes are represented by rectangles, flows by ovals, and drivers and determinants by hexagons. Dashed lines represent influences between variables: A = floor area stock; M = materials stock; dA/dt = net stock accumulation of floor area; dM/dt = net stock accumulation of materials; dA_{in}/dt = input flow of floor area; dM_{in}/dt = input flow of materials; dA_{out}/dt = output flow of floor area; dM_{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.

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

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

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

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

Equation (1) describes the driving forces of the model. The floor area of housing stock (here, PCFA) is driven by the population and its lifestyle, and it represents 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, which delays it by a certain service lifetime. Because dwellings may have different service lifetimes before they are demolished, a lifetime distribution $L(t, t')$ is used in equation (2); it represents the probability that the housing units entering service at time t' are going to be removed from the stock at 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) states that the future inflow of floor area is dependent on additional stock demand and outflow of floor area in the 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 a lifetime's delay $L(t, t')$. Equation (7) represents that the material stock in the housing system can be calculated according to the material inflow and outflow.

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 we discuss, gross domestic product (GDP) is also included in this study as an exploratory variable for PCFA. The calibration for each of the five modeling parameters and the data sources are described in this section.

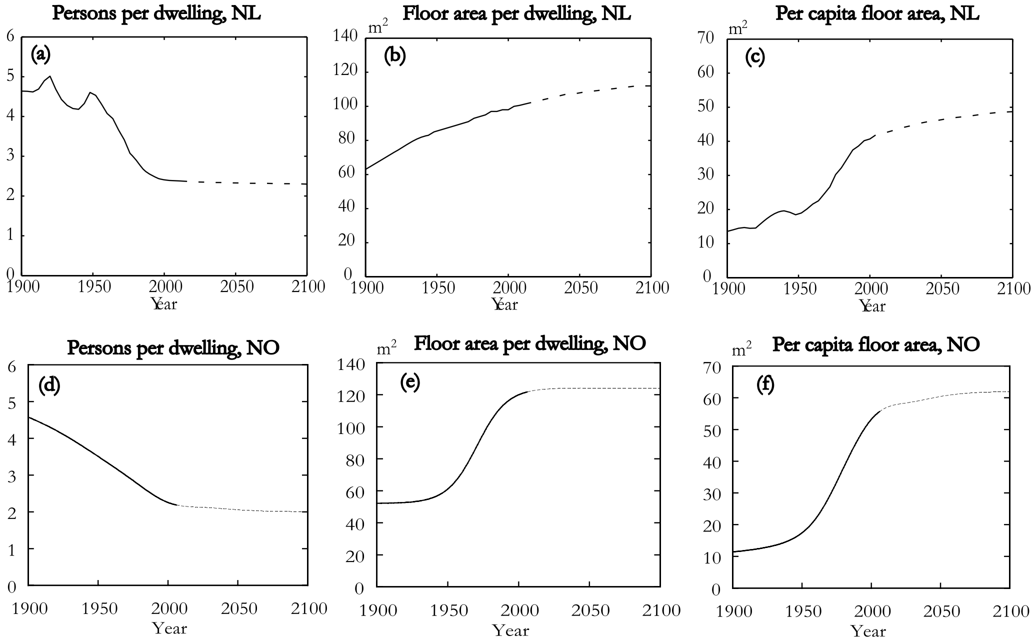

Figure 2 Historical figures and future projections (medium scenario) for persons per dwelling, floor area per dwelling, and per capita floor area in the Netherlands and Norway. NL = the Netherlands; NO = Norway. One square meter (m^2, SI) ≈ 10.76 square feet (ft^2). Source: Müller 2006; Bergsdal et al. 2007a

PCFA

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, whereas the latter, corresponding to the average number of persons per household or household size, indicates the social structure change of households. A significant decrease in 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 both countries during the 1950s and the 1990s (see figure 2). Toward the end of the 20th century, however, both variables showed a tendency toward flattening. If the current trends continue, we expect a saturated PCFA in both the Netherlands and Norway, as projected by Müller (2006) and Bergsdal and colleagues (2007a) in their medium scenarios.

In Beijing, the historical figures of PCFA are available from statistical yearbooks. In 1950, the PCFA occupied by an urban resident in Beijing was 7.6 square meters. This number fluctuated to reach 9 square meters by 1980 and then climbed at an accelerated speed to 23.3 square meters in 2005 (see figure 3c). 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 in the 1980s (see figure 3a). In contrast to the two European cases, however, no sign of flattening, either in the growth of PCFA or in the decrease of household size, can be deduced from the recent development of Beijing. The growth of PCFA has strongly coupled with that of gross regional

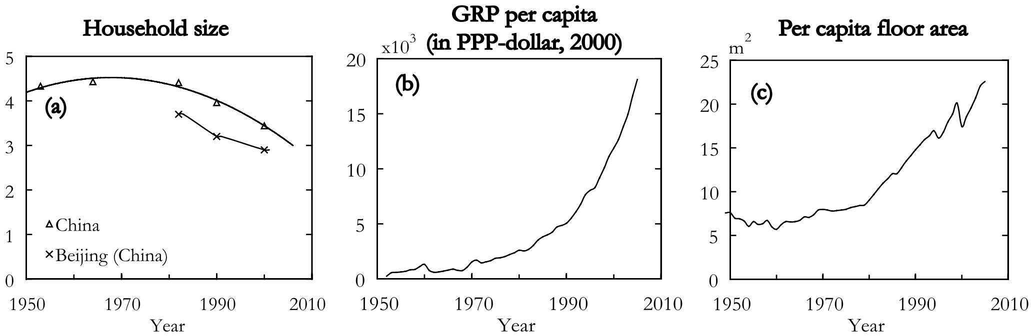

Figure 3 Historical figures of household size in Beijing (and all of China), gross regional product (GRP) per capita, and per capita floor area in Beijing. PPP = purchasing power parity. Source: BMBS 1999, 2000–2007; NBSC 2005; UNCDB 2008

product (GRP)[1] per capita in Beijing, especially for the last couple of decades (see figures 3b and 3c). 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, given the hypothesis that, in the course of development, as people become wealthier, they demand more living space. In this article, we conduct a comparison analysis 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 are available from 1952 to 2006 (BMBS 1999, 2000–2007; NBSC 2005). We extracted the historical figures of PCFA for the Netherlands and Norway from Müller (2006) and Bergsdal and colleagues (2007a), respectively. The GDP per capita is available for the Netherlands from 1969 to 2006 and for Norway from 1970 to 2005 from Eurostat (2009). For the purpose of comparison, we converted the data series of GRP per capita in Beijing into the constant market price in 2000 in Chinese currency (RMB), whereas we extracted the data series of GDP per capita for the Netherlands and Norway from Eurostat at a constant market price (in euros) that refers to 2000. We then converted the data into current international dollars in 2000, with purchasing power parity estimated by the World Bank, for international comparison (UNCDB 2008). The historical figures since 1950 and the extension of current trends to 2030 for PCFA and GDP per capita are illustrated for the three regions in figure 4, which shows the following:

1. All three regions have experienced a rapid increase in both PCFA and GDP per capita during the last 2 to 3 decades.
2. Either PCFA or GDP per capita of Beijing was and is still far behind that of the two European countries.
3. Beijing has had the highest GRP growth rate of the three 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 5, which shows the following:

1. In all the cases, the PCFA and the local GDP per capita are strongly related, which suggests that, to a certain extent, it is sound to forecast the future PCFA according to the projection of GDP per capita.
2. 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 that the wealthier people are, the more affluent living space they demand.
3. The growth curves of PCFA per unit GDP per capita for the Netherlands and Norway are much closer and more toward the upper

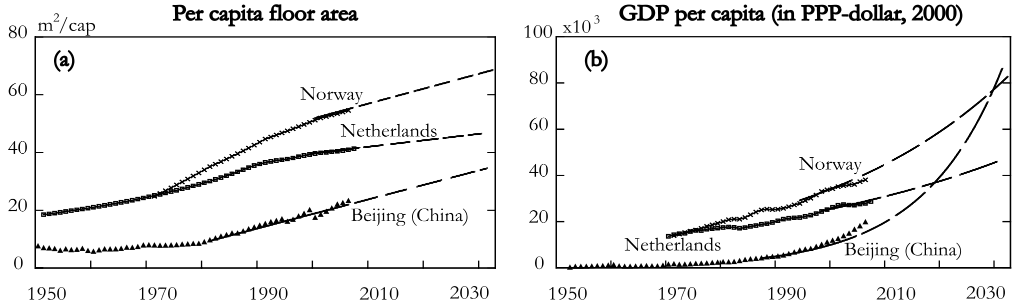

Figure 4 Historical figures of per capita floor area and gross domestic product (GDP) per capita in the Netherlands; Norway; and Beijing, China. m^2/cap = square meters per capita; PPP = purchasing power parity. Source: Müller 2006; Bergsdal et al. 2007a; Eurostat 2009; UNCDB 2008; BMBS 1999, 2000–2007; NBSC 2005

right corner than the growth curve for Beijing. This indicates that, when compared with the two European countries, housing development in Beijing is slower than the city's GDP growth.

Two possibilities can be considered to explain the slower PCFA development in Beijing. One is from the demand side—that is, Beijing residents may not need as much living space as Europeans. The other possibility is from the 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 to the two European countries when they

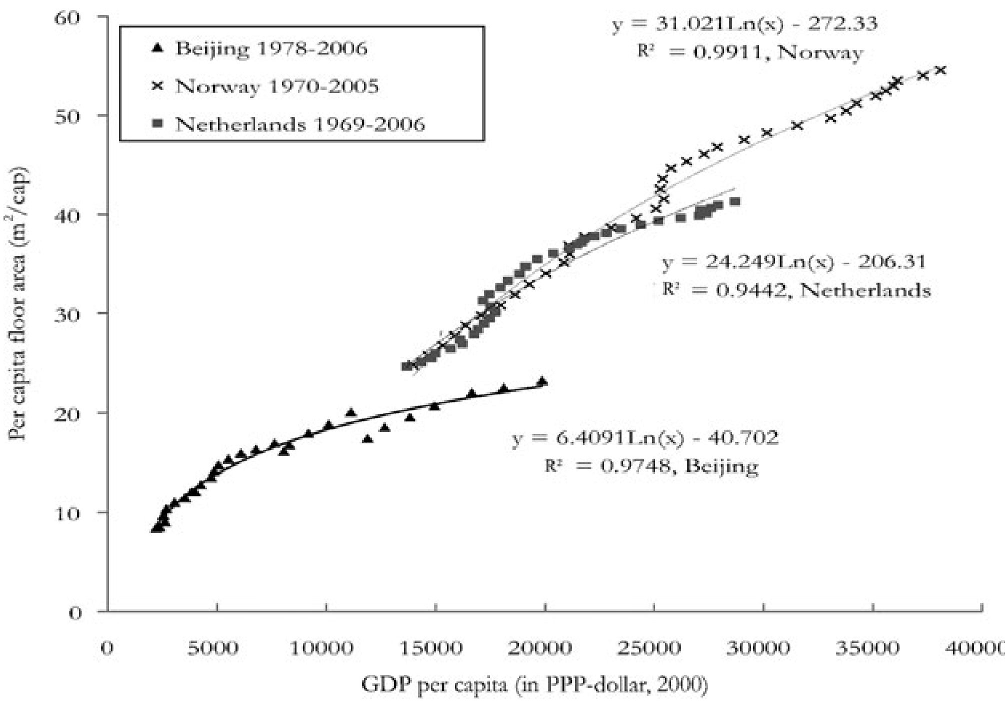

Figure 5 Historical regression of per capita floor area to gross domestic product (GDP) per capita in the Netherlands; Norway; and Beijing, China. PPP = purchasing power parity. Source: Müller 2006; Bergsdal et al 2007a; Eurostat 2009; UNCDB 2008; BMBS 1999, 2000–2007; NBSC 2005

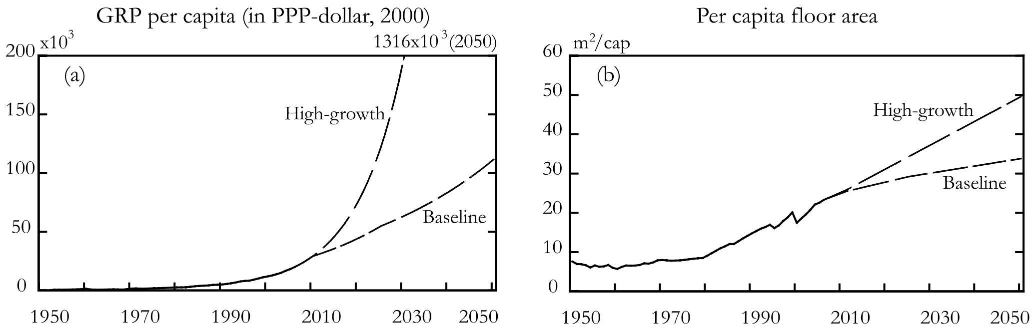

Figure 6 Historical figures and projections of gross regional product (GRP) per capita in Beijing and per capita floor area. PPP = purchasing power parity. Source: UNCDB 2008; BMBS 1999, 2000–2007; NBSC 2005

existed at a similar economic stage (see figures 2a, 2d, and 3a). From the supply point of 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. It may also mean, however, that other physical conditions in Beijing have constrained the growth of the PCFA. This argument sounds reasonable, because Beijing is an overcrowded metropolis, and it is unfair to compare the housing condition there with the two national cases. Such reasoning is out of the scope of this study, however. Nevertheless, the comparison analysis among 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, and 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 that particular area.

Therefore, the PCFA—GRP relation, based on the historical regression for the development of Beijing from 1978 to 2006 (see figure 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: the *baseline* scenario and the *high-growth* scenario. The baseline scenario adopts the GDP projection from Guest and McDonald (2007). These authors projected per capita GDP growth in China overall through 2100, with annual growth rates of 4.3% for 2000–2025, 2.9% for 2025–2050, and 2.6% for 2050–2100. We borrow this projection for Beijing for the period from 2011 to 2050, whereas we interpolate the figures for GRP per capita during 2007 and 2010 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. We do not intend this example to represent reality but instead use it 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 6. The baseline scenario projects that PCFA in Beijing will gradually increase to 34 square meters, whereas the high-growth scenario shows that in an extreme situation the number might reach 50 by 2050.

Population

Besides PCFA, population is another parameter determining the demand for stock of housing floor areas. In Beijing, historical data on the urban population are available for all years (BMBS 1999, 2000–2007). These data show that the population has increased by about 6.5 times in the last 58 years, which indicates that urban population growth was the most important factor for

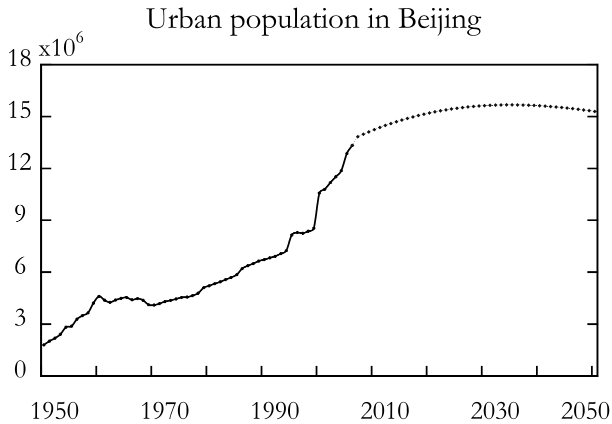

Figure 7 Historical figures and projection of urban population in Beijing. Source: BMBS 1999, 2000–2007.

the housing floor area expansion in Beijing for the past period. No future projection for Beijing's urban population has been found. The number of registered permanent residents has been forecast by the Beijing Population Research Institute (Ma 2000) from 2000 through 2050, however. The research shows that population development in Beijing is and will be mainly driven by immigration from outside the city during the next half century. Because it is already crowded, Beijing aims to keep its urban population within 18 million through 2020 (BMG 2005), by residence registration system. Compared with the goal, the medium scenario is recognized as most realistic; it 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 scenarios forecast a peak level 12% lower or 10% higher than the medium scenario, at 2020 and 2047, respectively. All of the scenarios show saturation of the population in Beijing in the next 4 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 population growth. We use the medium scenario result for registered permanent residents by Ma (2000) as the base to forecast the future urban population. In 2007, the urban population was 1.16 times the number of registered permanent residents 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 7.

Lifetime

The lifetime parameter, which determines the delay of demolition flow compared with the peak of construction, is the most important but poorly understood factor. No profound research has been conducted for the lifetime distribution of dwellings in Beijing. It is generally acknowledged, however, that the service lifetimes of buildings in China are rather short. Although the design lifetime is 50 years, the real lifetime of buildings is often observed to be much less, because of the low level of construction quality 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, which resulted 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 this study for the estimation of service lifetimes of dwellings. The short lifetime understanding is embodied in the baseline scenario, which assumes a mean lifetime of 25 years, with a standard deviation of 5 years. In the future, however, the housing lifetime in Beijing may increase, as the recently constructed

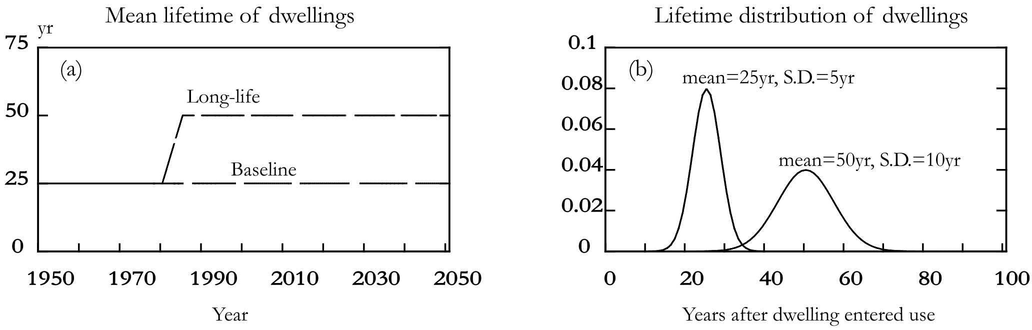

Figure 8 Estimations of the mean lifetime of dwellings (by year built) and lifetime distribution of dwellings (by years after dwelling entered use) in Beijing. S.D. = standard deviation.

residential buildings are mainly large apartment blocks built to a higher standard. The long-life scenario reflects the assumption 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, whereas 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 standard deviations of 20% of the mean values. The estimations of the mean lifetimes of dwellings in Beijing are illustrated in figure 8a, and the lifetime distributions for both scenarios are presented in figure 8b.

Material Density

The material density parameter links the subsystems of floor areas and materials. For the purpose of comparison, this study focuses only on concrete, as it is the common material 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. A project of the Chinese Academy of Sciences (Liu and Hu 2006), however, 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 (see table 2). We use this information to derive the concrete intensity for Beijing's residential buildings.

Concrete is a composite material made up of cement, water, gravel, and sand. The concrete intensity for each type of structure can be computed from the cement density (see table 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). One can calculate the average concrete intensity in Beijing's dwelling by weighting according to the floor area distribution of the building structures in the yearly new completed floor areas.

Table 2 Material composition of three main structures of residential buildings in Beijing

Structure	*Cement*	*Steel*	*Sand*	*Gravel*	*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

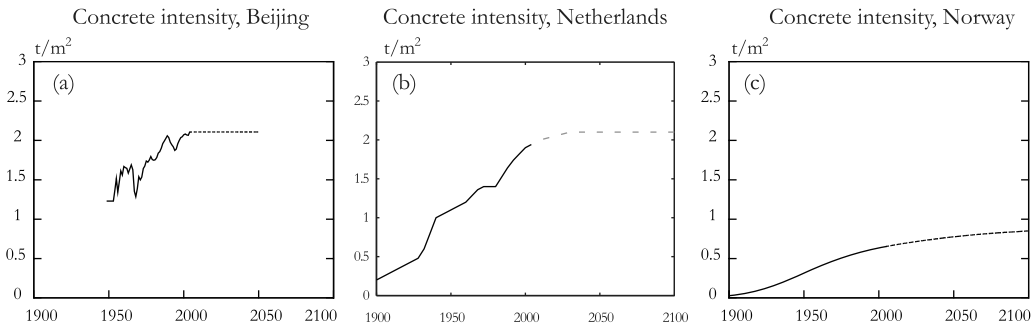

Figure 9 Historical figures and projections of the concrete intensity (tonnes per square meter floor area [t/m^2]) in housing construction in Beijing, China; the Netherlands (medium scenario); and Norway (medium scenario). One tonne (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons. Source: Liu and Hu 2006; BMBS 1999, 2000–2007; Müller 2006; Bergsdal et al. 2007a

The annual completed residential floor areas are classified in Beijing statistical yearbooks only by the number of stories, however, and not by the structure of the building. We assume that all dwellings of three stories or fewer are made with a brick—concrete structure, those of four to eight-stories are made with a concrete frame structure, and higher dwellings are made with a shearing-force structure. The weighted average concrete intensity in Beijing housing construction is calculated for 1949 to 2006. Because 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 through 2050.

The historical and projected concrete intensities used in housing construction in Beijing, the Netherlands, and Norway are illustrated in figure 9 for the purpose of comparison. The figure shows that in the last couple of decades, all three places have been increasing their use of concrete in dwellings. Beijing and the Netherlands have a similar concrete intensity, about 1.5 to 2 tonnes per square meter floor area, whereas Norway holds a much lower level, around 0.5 to 0.7 tonnes per square meter floor area. This is understandable, because large amounts of wood are used in dwelling construction in Norway, and therefore less concrete is needed to form a single square meter of floor area. The older historical figures of the concrete intensity in Beijing may be overestimated because they are based on recent sampled data.

Scenario Analysis

We investigate three scenarios mentioned in the previous section to understand how the future housing stock and related concrete flows in Beijing will develop (1) if current trends continue, (2) if future PCFA grows to a high extreme, or (3) if the lifetime of dwellings is prolonged. The baseline scenario assumes that future per capita GRP in Beijing will grow at the rate that economists have projected for China and that residential buildings in Beijing will continue to have a short lifetime. Calibrations for the parameters are presented in figures 6 (PCFA), 7 (population), 8 (lifetime), and 9a (concrete intensity). The high-growth scenario assumes that future per capita GRP in Beijing will develop at an annual growth rate of 10% through 2050 (see figure 6). The long-life scenario assumes that the future service lifetime of the dwellings in Beijing will be increased to 50 years (see figure 8). Other parameters for the high-growth and long-life scenarios have the same values as in the baseline scenario. Scenario results for both floor areas and amount of concrete are presented in figure 10 and summarized in table 3.

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

1. The stock of housing floor area in Beijing has grown explosively over the last couple of decades and will keep expanding, although at an expected slower rate.

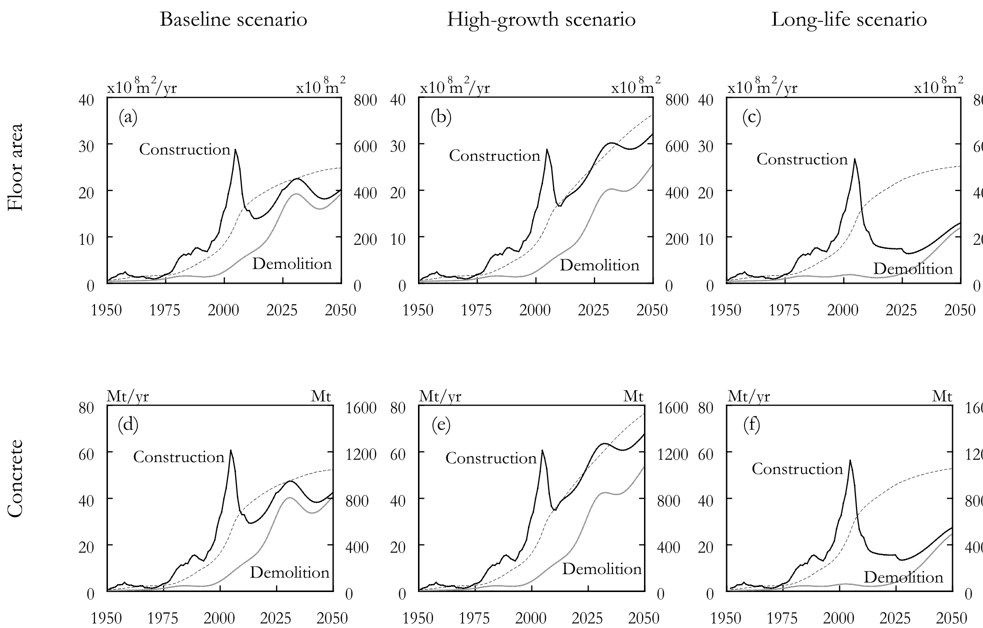

Figure 10 Housing floor area and concrete stock (dashed line), input flow (construction), and output flow (demolition) for the baseline, high-growth, and long-life scenarios. Stocks are measured on the right axis and flows on the left. Mt/yr = million metric tons per year.

2. Statistical data until 2006 show that residential construction in Beijing starts to fall after a peak in 2005. This change may be explained partly as the effects of preparation for the 2008 Olympic games in Beijing. Nevertheless, all the scenarios suggest that the oscillation in construction activity is unavoidable, because of the slowing down of the expansion of the dwelling stock around 2006.
3. 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 because 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. If we assume a continued short dwelling lifetime, Beijing will meet the first demolition peak at about 2030 and enter the second rise at about 2040. Greater PCFA growth will make the second rise even more extreme. If the dwelling lifetime can be prolonged, however, intensive demolition pressure can be postponed or even reduced altogether.

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

1. Due to high construction activity, the annual concrete use in Beijing housing surged to nearly 60 Mt/yr in about 2005. Except if we assume an extreme PCFA growth, such high demand is unlikely to happen again, at least until 2050.
2. So far, the concrete demolition waste flow is negligible compared with the concrete demand. All scenarios show a dramatic increase of concrete waste, however, in the long run up to a level that is comparable to the new inflow. This equilibrium will not 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.

Table 3 Simulation results and input parameters for floor areas and concrete in housing in Beijing

Stocks/flows		*Baseline*			*High growth*		*Long life*	
	Unit of measure	*2005*	*2030*	*2050*	*2030*	*2050*	*2030*	*2050*
	A (m^2)	*2.77E+08*	4.51E+08	4.97E+08	5.61E+08	7.26E+08	4.67E+08	5.04E+08
	%	*100*	163	179	203	262	168	182
Floor area	dA_{in}/dt (m^2/yr)	*2.72E+07*	2.25E+07	2.02E+07	3.00E+07	3.22E+07	6.70E+06	1.30E+07
	%	*100*	83	74	110	118	25	48
	dA_{out}/dt (m^2/yr)	*4.60E+06*	1.92E+07	1.93E+07	2.01E+07	2.56E+07	3.52E+06	1.20E+07
	%	*100*	418	419	436	555	76	260
	M (t)	*5.59E+11*	9.49E+11	1.05E+12	1.18E+12	1.53E+12	9.66E+11	1.06E+12
	%	*100*	170	187	211	274	173	189
Concrete	dM_{in}/dt (t/yr)	*5.74E+10*	4.74E+10	4.25E+10	6.31E+10	6.77E+10	1.41E+10	2.74E+10
	%	*100*	83	74	110	118	25	48
	dM_{out}/dt (t/yr)	*8.49E+09*	4.03E+10	4.07E+10	4.20E+10	5.39E+10	6.94E+09	2.47E+10
	%	*100*	474	479	495	635	82	291
Input parameters		*Baseline*			*High growth*		*Long life*	
	Unit of measure	*2005*	*2030*	*2050*	*2030*	*2050*	*2030*	*2050*
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)	*1.29E+07*	1.56E+07	1.53E+07	1.56E+07	1.53E+07	1.56E+07	1.53E+07
	%	*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

Note: Concrete is measured in metric tons (t) for stock and metric tons per year (t/yr) for input and output flows. Population is measured in capita (cap). A = floor area stock; dA_{in}/dt = input flow of floor area; dA_{out}/dt = output flow of floor area; M = materials stock; dM_{in}/dt = input flow of materials; dM_{out}/dt = output flow of materials; S.D. = standard deviation. Italics indicate data for the reference year 2005.

3. The concrete outflow will probably reach a first peak at more than 40 Mt/yr around 2030. An extreme PCFA growth will raise a second wave of waste of more than 50 Mt/yr by 2050. If the lifetime of residential buildings can be doubled, the peak of waste concrete can be delayed.
4. 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 about 2050. An extreme PCFA growth will bring the number even 50% higher, to about 1.5 billion tonnes at 2050.

Table 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. We have chosen the baseline value of each item in 2005 as a current base to evaluate the volume change in all scenarios. Input parameters for the simulation are listed in the bottom of the table.

Strategic Suggestions for Construction and Demolition Waste 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 that CDW generation in the near future strongly depends on the lifetime of the buildings, whereas 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 focused on prolonging the service life of the buildings whenever it is possible. Nonetheless, all the scenarios suggest that the dramatic rise of CDW generation will arrive sooner or later. Because this large amount of waste output is unavoidable, recycling should be emphasized to limit the pressure on landfills.

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 in construction in Beijing during the 1990s. If the lifetime of the buildings can be doubled, the rise of the waste peak will be pushed to the next half of the century. Therefore, for mid-term waste minimization, the most important strategy is to prolong the lifetime of the buildings. The first tool is to ensure a reasonable service lifetime for the new construction through the improvement of construction techniques and better urban planning. The second tool is to enhance the existing building stock management by, for instance, regular renovation.

Recycling Strategy

The dynamic MFA for Beijing housing shows that a dramatic rise of CDW generation is unavoidable, especially under the assumption of 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.

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, which indicates that other social, economic, or physical factors are also important as driving forces for PCFA. The investigation of the stock dynamics of construction materials leads to a number of recommendations for strategic CDW management:

1. The service lifetime of buildings in Beijing is presently very short. If this situation continues, demolition waste will rise dramatically over the next 50 years. If the PCFA keeps up its present high growth rate, this will make the situation even worse, with more than six times the current level of concrete demolition waste to deal with by 2050.
2. Lengthening the lifetime of buildings is crucial for keeping the consequences of this rapid growth in check. We recommend renovation activities and high building quality standards to realize this, wherever possible.
3. For existing buildings, however, the question is whether their quality is sufficient to actually realize a significantly longer life span. Future demolition waste depends in a large part on past construction; therefore, to some extent, the rise in demolition waste may not be prevented and must instead 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 life span.
4. Putting more effort into the recycling of CDW 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.

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Note

1. Similar to GDP, which is defined as the market value of all final goods and services produced within the borders of a nation in a year, GRP is a measure of the size of a metropolitan area's economy. In this article, the term *GDP* refers to only a nation or to both nations (i.e., the Netherlands, Norway) and an area (i.e., Beijing), whereas *GRP* refers to only an area (i.e., Beijing).

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