



Universiteit
Leiden
The Netherlands

Dynamic material flow analysis to support sustainable built environment development

Hu, M.

Citation

Hu, M. (2010, May 18). *Dynamic material flow analysis to support sustainable built environment development*. Retrieved from <https://hdl.handle.net/1887/15545>

Version: Not Applicable (or Unknown)

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/15545>

Note: To cite this publication please use the final published version (if applicable).

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

Abstract

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

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

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

3.1 Introduction

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

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

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

3.2 Urbanization and housing in China

Since 1958, the Chinese government has used the household registration system, called Hukou, to control the movement of people between rural and urban areas. This division led, among others, to a detachment between the rural and the urban housing systems, which are largely different in housing supply, renovation and transferring. In cities, up until 1978 urban housing were allocated by Chinese government as part of social welfare for urban households (Zhu et al. 2000). During this period, around 75% urban households were in the public rental housing sector (Huang 2004). Since the rents were extremely low⁸, urban public housing was heavily subsidized and caused heavy financial burden on the state (Shaw 1997). Subsequently, insufficient state investment led to: (1) serious shortage of urban housing. Per capita living space in cities declined from 4.5m² in the 1950s to 3.6m² in 1978 (Center for Development Studies at the State Council 1991); (2) low-quality housing construction. Especially around 1966-1971⁹, when ‘building housing by laying dry mud’ was advocated from Beijing as a land-saving and high-speed measure, resulted in a generation of low quality, functional defect dwellings (BMCCC 1999; Wu 1989); (3) inappropriate maintenance. As a result, housing ages quickly (Shaw 1997).

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

⁹ During China’s Cultural Revolution period (1966-1976).

In the late 1970s, when China's economic reform started, previously suppressed housing problems initiated Chinese urban housing reform (Xu 1993; Lee 2000). This reform, aiming to marketisation and privatisation of urban housing production and consumption, then triggered a strong wave of real estate development in many major Chinese cities during the 1980s and 1990s (Zhu et al. 2000). By 2005 only 8% of Chinese urban housing units were public rentals and most newly constructed owner-occupied housing in the future will be in the private sector (Logan et al. 2010). With the move from 'welfare' housing to commodity housing, the provision of an adequate quantity and the quality of housing units in urban China began to be addressed successfully (Rapanos 2002). However, this process is also accompanied by speculative investment. To curb soaring housing prices, Chinese central government requires that 70% of new completed residential units be smaller than 90 m² since June 2006. From June 2009, the central government further tightened financing for the purchase of second home to cool Chinese property market. Nevertheless, one positive effect of housing privatisation seems undeniable, that is, the lifetime expectancy of recently completed urban dwellings has increased largely. This is because: firstly, higher construction quality may have been achieved due to the expansion of housing construction for sale at market prices; secondly, better caring of the dwellings may be taken due to the owner-occupied housing; thirdly, land lease contract may support the expectation of urban households for using their purchased home no less than 70 years¹⁰.

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

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

the 1980s¹¹. Between 1978 and 1988 rural per capita living space more than doubled, from about 8.1 square meters to 16.6 (NBSC 1999). The quality of rural housing also improved; many new houses were constructed of bricks, tiles, or reinforced concrete during the 1980s (McKinley and Wang 1992).

Following the economic reforms from 1978, the substantial rise in agricultural productivity has generated a large surplus rural labor force that needs to be transferred into non-farm sectors and possibly urban settlements. Responding to it, since 1984, Chinese government partially lifted the control over rural-urban migration¹² (Lin 2007). The massive rural-urban migration has then significantly raised the urbanization level in China (Zhang 2008), resulting in an expanding urban population and since 1995 a shrinking rural population (NBSC 2005; 1980-2008). It leads to, regarding resource management, two important challenges: the growth of the urban housing stock acting as a sink of raw materials and the shrinkage of the rural housing stock potentially becoming a source for secondary materials. In order to obtain a long-term vision of the challenges, this study aims to construct a robust physical base for future investigation on the relationship between urbanization in China and its material demand.

3.3 Method

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

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

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

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

3.3.1 System definition

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

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

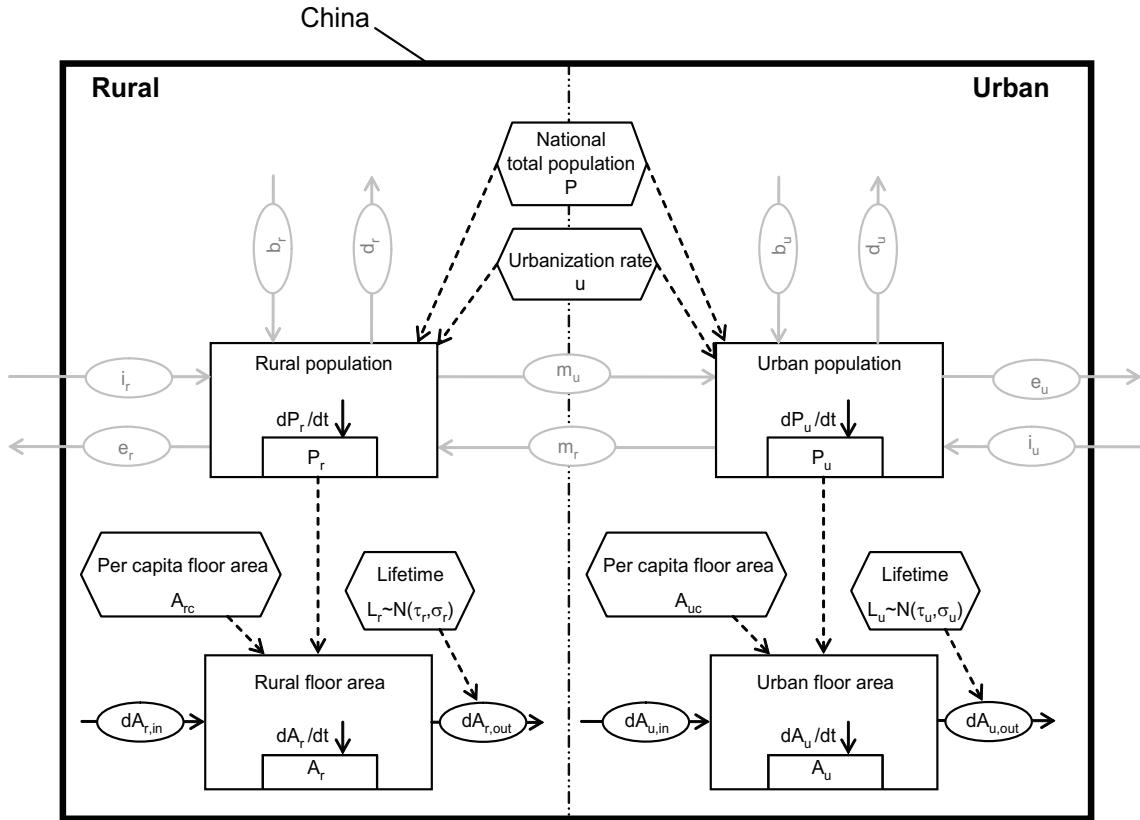


Figure 3.1 Conceptual outline of the stock dynamics model. Rectangles represent processes, ovals depict flows, hexagons illustrate determinants or drivers and dashed lines represent influences between variables. Light grey depicts background flows not appearing in modelling. b_r (b_u), d_r (d_u), i_r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

3.3.2 Mathematical model formulation

The generic stock dynamics model developed by Müller (2006) is applied to both the urban and rural housing sub-systems. The basic principle of the model is the law of mass conservation. Within either sub-system, the demand for dwelling stock in the region is driven by the corresponding population and living standard. Construction

activity is determined by how much floor area that has to be replaced because of demolition activity, plus any additional demand caused by increasing stock demand. Demolition activity is determined by the past construction activity with a delay of the service lifetime of the houses. A normal distribution function is assumed for the lifetime of all houses, though the mean and standard deviation of the function is estimated individually for rural and urban system. The underlying equations are given in Appendix B and the six external parameters for the model are listed as follows:

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

3.3.3 Calibration

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

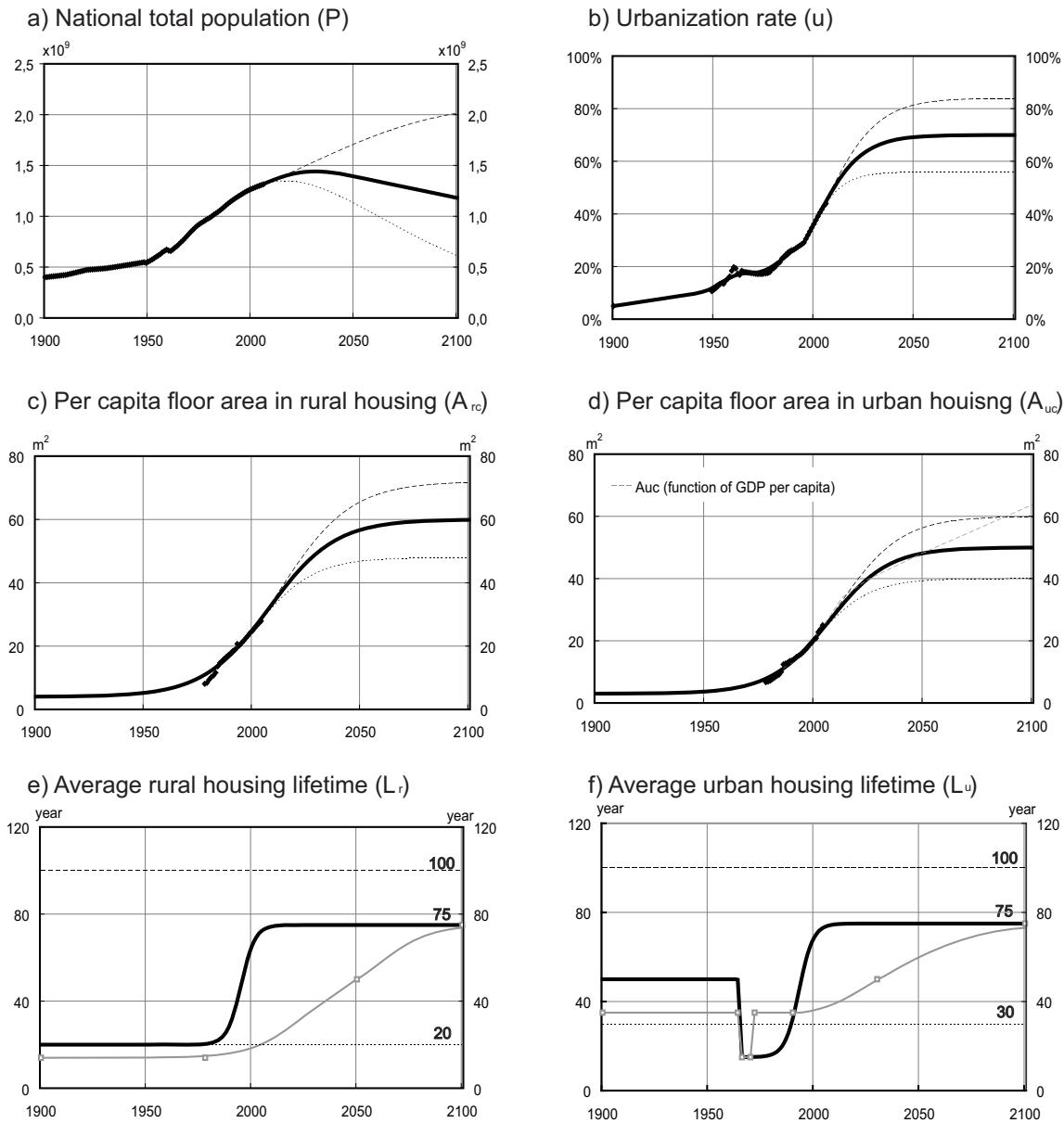


Figure 3.2 Calibration of input parameters, with historic data from 1900 until 2006 and estimation for variants low (dot line), medium (bold solid line), and high (dashed line) from 2006 until 2100. Dashed grey line represents GDP-driving-A_{uc} scenario and solid grey lines represent gradually-increasing-lifetime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

Historical data on total national population, urbanization rate¹³, and per capita floor area in rural and urban regions are collected from China Statistic Yearbooks (NBSC, 2005, 1980 – 2008) for 1949 to 2006. Total national population before 1949 is obtained from database of University of Utrecht (Ho 1959; <http://www.library.uu.nl/wesp/populstat/Asia/chinac.htm>). The population projections are quoted from the low, medium and high variants of China's population issued by the United Nations Population Division (UNPD 2003, 2006). The urbanization rate in 1900 is assumed as 5%, and the yearly data between 1900 and 1949 are inserted by linear interpolation. The future urbanization rate is assumed to saturate at a level of 70% for the medium variant, and 56% and 84% for low and high variants, respectively. Various previous forecasts for the future urbanization trend in China are illustrated in Appendix C for comparison. Data of per capita floor area in 1900 are assumed as 4 and 3 square meter per capita for residents in rural and urban areas respectively. In future, we assume, the figures will follow a logistic function to reach 60 m² (a level of US in the early 1990s (Guan et al. 2001)) and 50 m² (the current level of the Netherlands (Müller 2006)) in Chinese rural and urban areas by 2100, for the medium scenario. The high and low variants in 2100 are set as 20% higher and 20% lower than the medium value, which are 72 m² and 48 m² for rural area and 60 m² and 40 m² for urban area, respectively. Considering the rapid economic development in China and the hypothesis that the wealthier people are, the more affluent living space they demand, the GDP-driving-A_{uc} scenario is investigated for the purpose of comparison, in which urban per capita floor area is estimated as a function of China's per capita GDP (dashed grey line, Figure 3.2 (d)). The relation between per capita floor area and GDP per capita has been identified in Hu and colleagues (2010a) and is presented in Appendix D.

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

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

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

Given the improving quality of housing since 1978, for the medium scenario it was assumed that by around 2020 the lifetime of newly completed dwellings, in both urban and rural China, would increase to 75 years, with reference to land lease for urban commercial housing (70 years). The transition of lifetime expectancy from the historical low level to the future high level follows a double logistical function. Rural housing constructed before 1978 is estimated to have a short lifetime of 20 years¹⁴ (bold solid line, Figure 3.2 (e)). In cities, a lifespan of 50 years is estimated for dwellings built before 1966, and a lifespan of 15 year is assumed for the extremely bad quality cohort produced around 1966–1971 (bold solid line, Figure 3.2 (f)). However, these assumptions are uncertain, because the available data do not allow for an analysis of the historical evolution of the dwelling longevity. In addition, the question of how long existing buildings can last depends on current and future decisions on maintenance, etc. To analyze the sensitivity of the lifetime parameter, a variance of average lifetime is chosen, assuming the constant values of 100 and 20 years as the high and low variants for rural dwellings, and 100 and 30 years for urban dwellings. Furthermore, to understand how influential the development pattern of the lifetime is, the gradually-increasing-lifetime scenario is investigated. It assumes that, in the countryside, the lifetime of dwellings built before 1978 is 15 years (as estimated by Huang, 2006); it gradually increases to 50 years (as Chinese national standard, MCC 2005) by 2050 and finally reaches 75 years by 2100 (solid grey line, Figure 3.2 (e)). In cities, except for the 1966–1971 cohort with an extremely short lifetime as 15 years, dwellings completed before 1978 are estimated to have a

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

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

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

All the people shifting from rural pool to urban pool are considered as migration¹⁵ (see Figure A.1, Appendix A). The forecast of national population from UNPD's medium projection, predicts that China's population will saturate by 2030. Combining this with the urbanization rate in the medium scenario for population, the rapidly increasing urban population in China will overtake the rural one between 2010 and 2015, and will reach the saturation point around 2040. The rural population in China, which has already been shrinking since 1995, will keep declining in the first half of the 21st century. It indicates that China has experienced the biggest internal migration period since 1996 with a figure of over 15 million migrants per year over the period of a decade. The combined result of the total national population growth and the urbanization trend predicts a steady decrease of the internal migration till the end of 2050, and around 300 million people in China will by then have shifted their lifestyle from rural to urban.

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

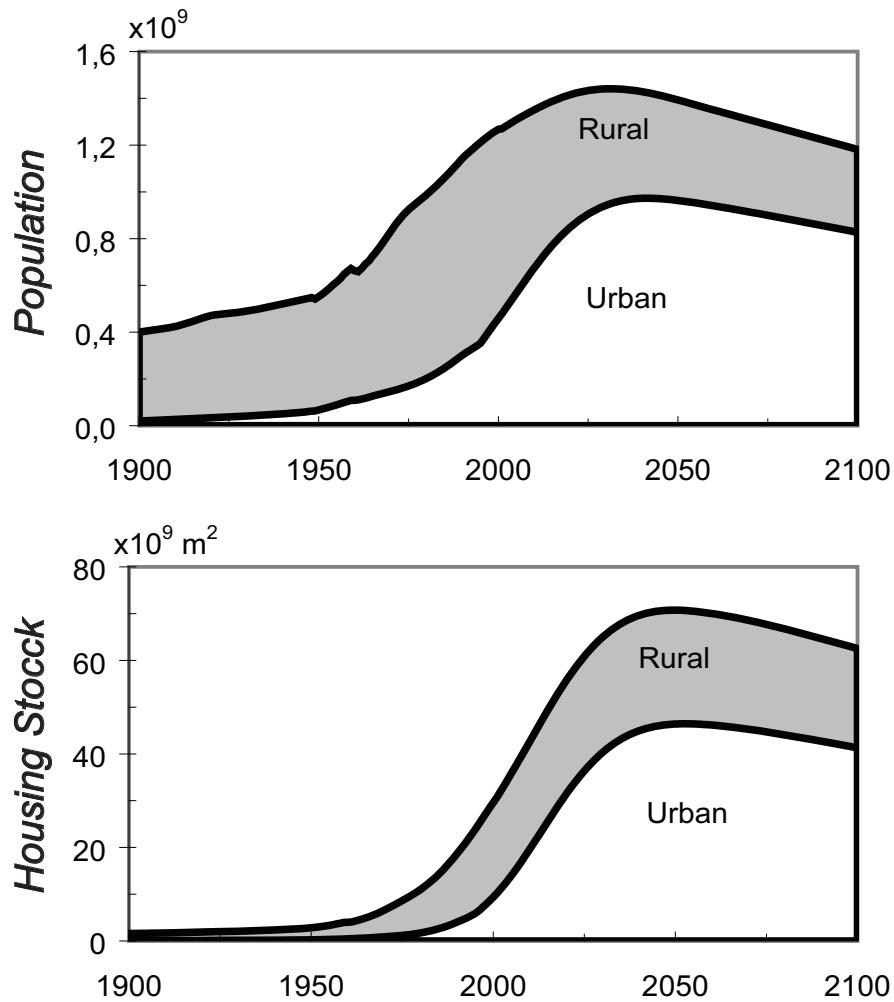


Figure 3.3 Population stocks and housing floor area stocks in rural (grey) and urban (white) China. All input parameters are set at medium values given in Figure 3.2.

3.3.4 Validation

The model was validated using historical data of newly completed residential buildings in rural and urban China, which are available in the statistical yearbook for 1984 until 2006 (see Figure 3.5 (c), (d) and Figure 3.6 (c), (d)). The validation shows that the medium scenario results fit with the climbing trend of urban housing construction. However, the modeling values tend to be higher than the statistical

values. This could indicate an underestimation of the lifetime or an inconsistency in the official statistics for population, housing stock, and construction activities. For urban area, a third reason may be the fraction of “urbanization” resulting from the transition of rural to urban areas. According to Yang and Hui (2008), during 2001 – 2006, about 18 – 20 million people has shifted from rural to urban stock annually, among which nearly 5 million/year are due to official designation of new cities without really moving and do not demand housing from urban stock. It means about 30% of annual rural-urban migration should be subtracted from urban population stock when calculating the demand for new urban housing construction. This factor has been considered in the study and the adjusted result for medium scenario is presented in Figure 3.5 (d) (dotted grey line). As the rural-urban migration is expected to decrease through 2050, its effect on overestimation also decreases over the time. This adjustment amends the overestimated peak construction demand. It, however, does not affect the projected pattern of oscillation in Chinese demand for urban housing construction.

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

3.4 Stocks and flows of housing in China

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

3.4.1 Medium scenario results

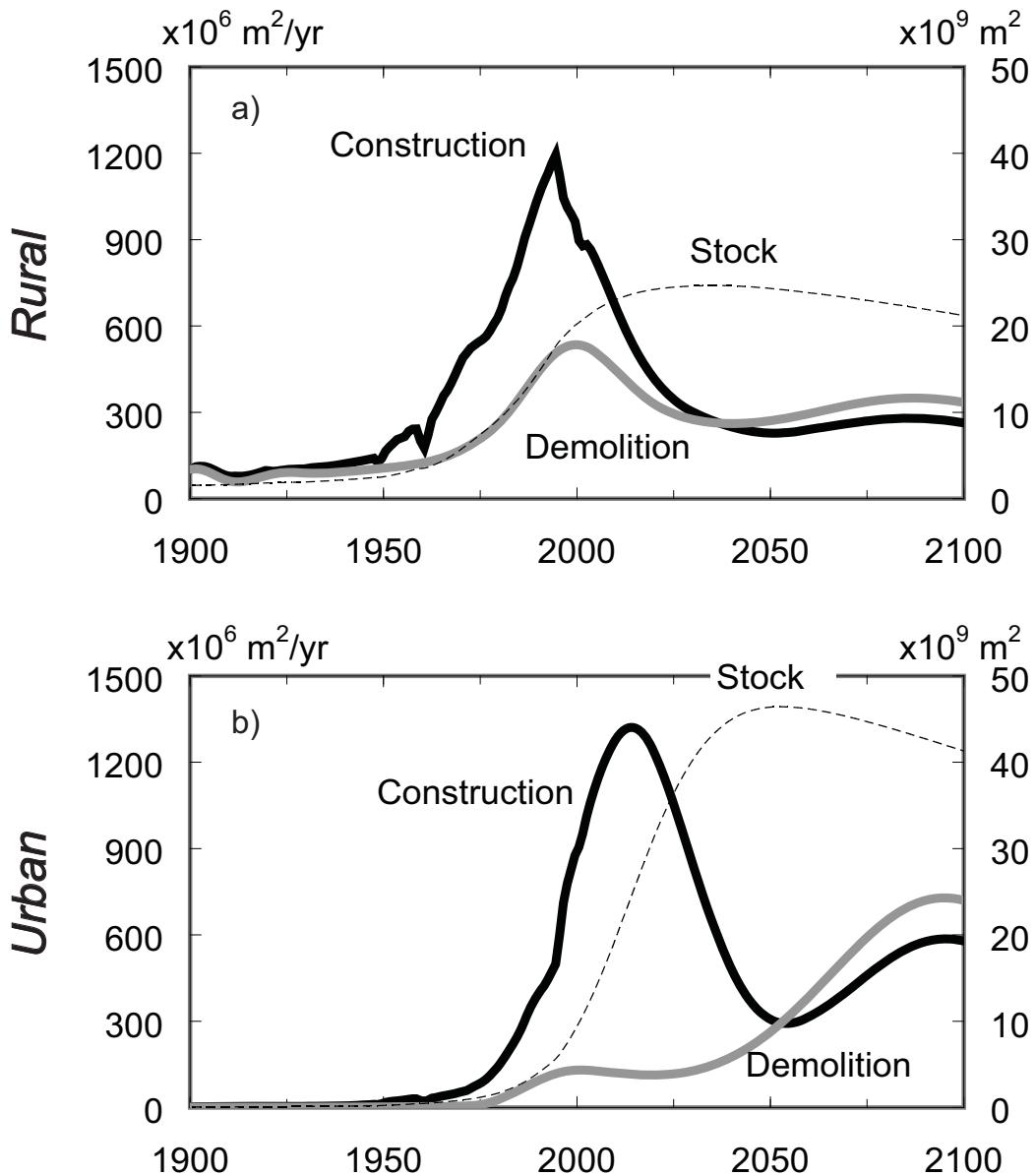


Figure 3.4 Simulation results for housing floor area stocks and flows in rural and urban China. Stocks are measured on the right axis and flows on the left. All input parameters are set at medium values given in Figure 3.2.

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

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

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

3.4.2 Sensitivity analysis

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

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

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

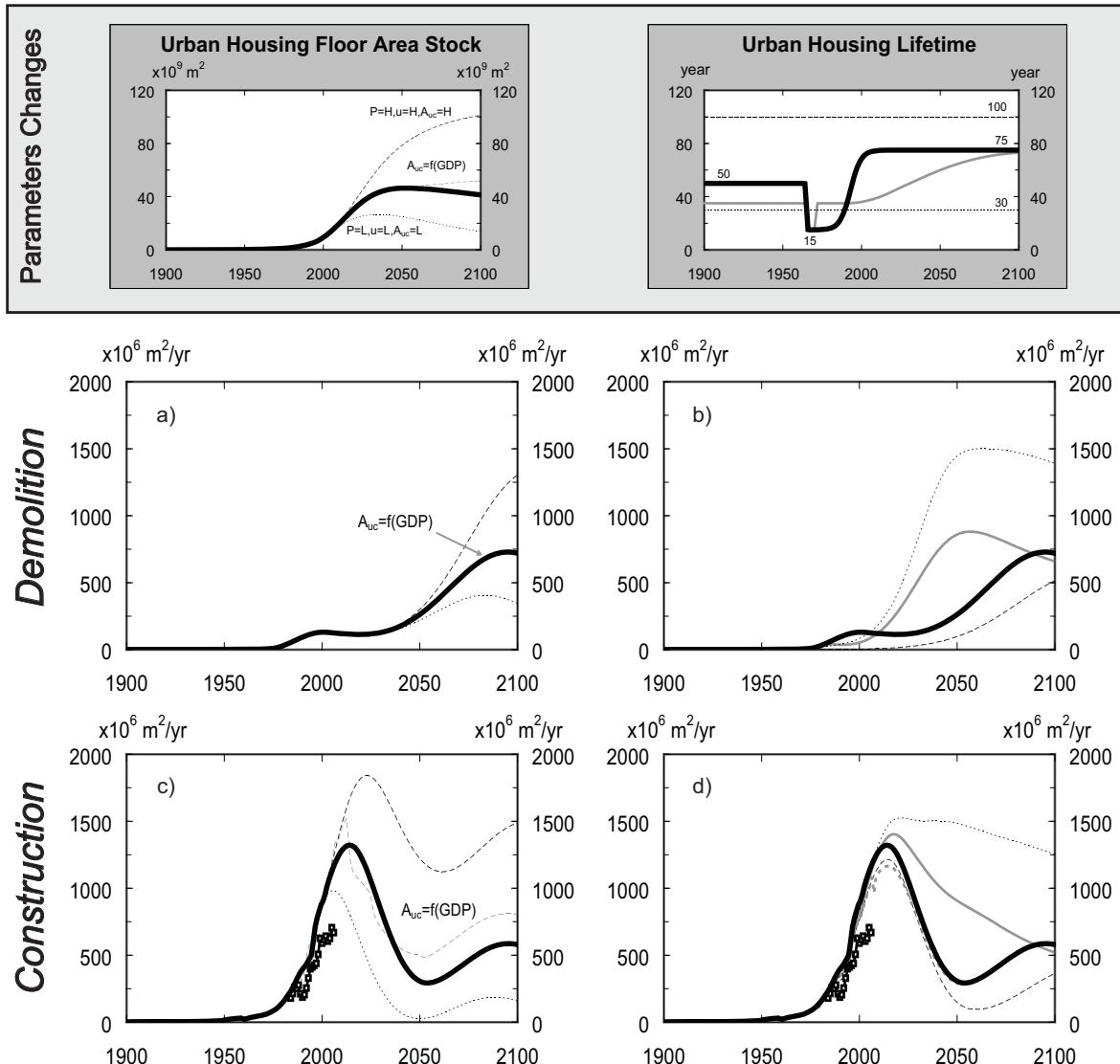


Figure 3.5 Sensitivity analysis for urban housing system. Outflow (Demolition) and inflow (Construction) in square meters per year, as influenced by floor area stock and lifetime variants low (dot line), medium (bold solid line), and high (dashed line). Dashed grey line represents GDP-driving- A_{uc}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

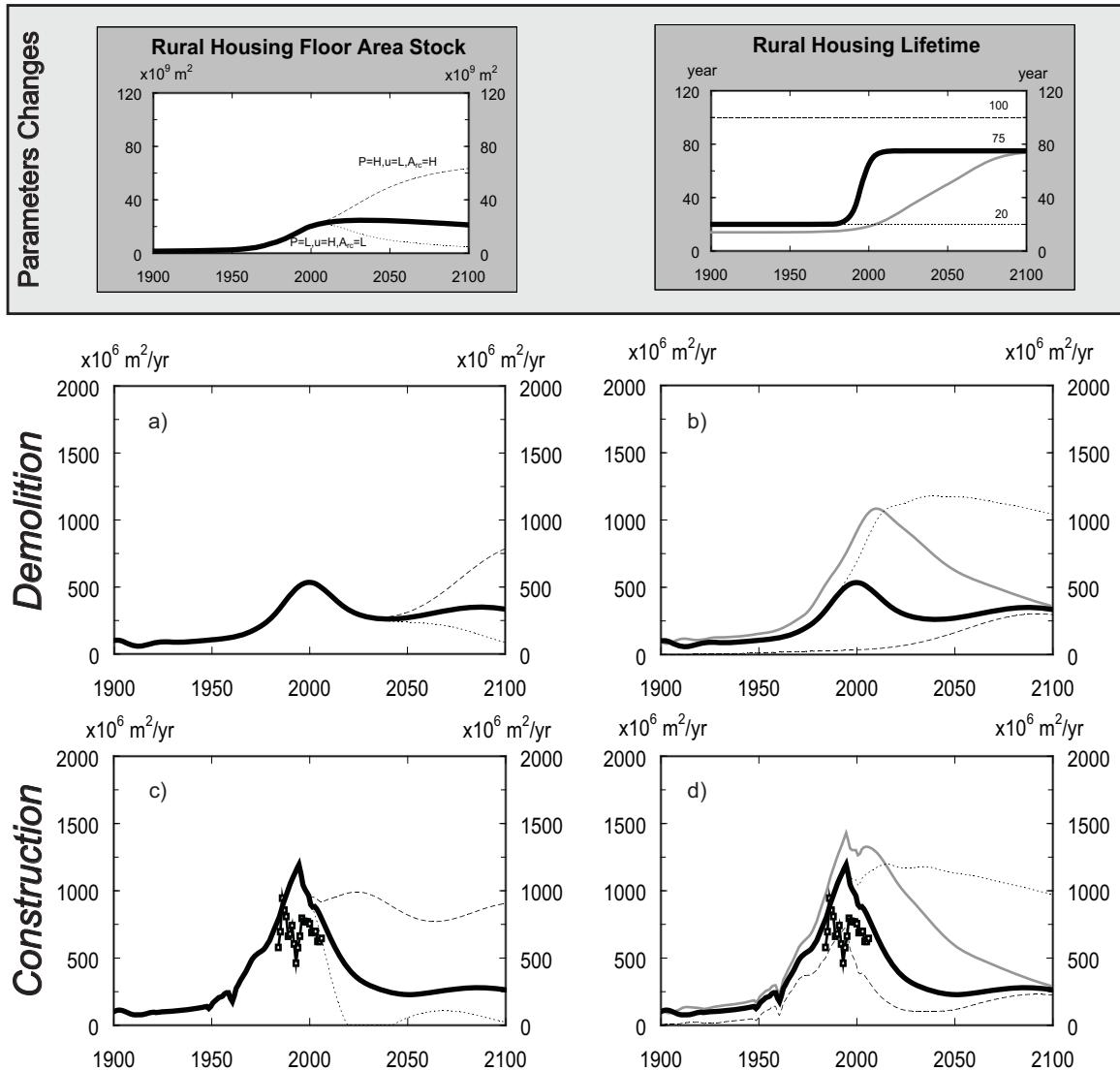


Figure 3.6 Sensitivity analysis for rural housing system. Outflow (Demolition) and inflow (Construction) in square meters per year, as influenced by floor area stock and lifetime variants low (dot line), medium (bold solid line), and high (dashed line). Solid grey line represents gradually-increasing-lifetime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

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

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

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

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

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

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

The sensitivity analysis for rural housing lifetime shows that:

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

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

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

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

3.5 Discussions

Limitations of the model

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

Implications of the oscillation

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

Options to dampen the oscillation

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

3.6 Conclusions

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

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

Reference to Chapter 3

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Appendices to Chapter 3

Appendix A: Calculation of internal migration flow

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

$$\frac{dP_r}{dt} = (i_r - e_r) + (b_r - d_r) - (m_u - m_r) \quad (\text{A } 1)$$

$$\frac{dP_u}{dt} = (i_u - e_u) + (b_u - d_u) + (m_u - m_r) \quad (\text{A } 2)$$

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

$$\frac{dP}{dt} = (i - e) + (b - d) \quad (\text{A } 3)$$

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

$$\frac{dP_r}{dt} \approx (b_r - d_r) - (M_u - M_r) \quad (\text{A } 1')$$

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

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

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

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

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

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

Fed with historical figures of b , d , u , P from NBSC for period between 1949 and 2007 and the forecasting data from UNPD's medium scenario, the results of $(m_u - m_r)$ calculated from (A4) and (A5) are slightly different (less than 1%). The net internal rural-urban migration in China is calculated as the average of the results from the two equations and is illustrated in Figure A.1.

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

growth and the urbanization trend foresee a steadily decrease till the end of 2050 and around 300 million people in China will shift their lifestyle from rural to urban by that time.

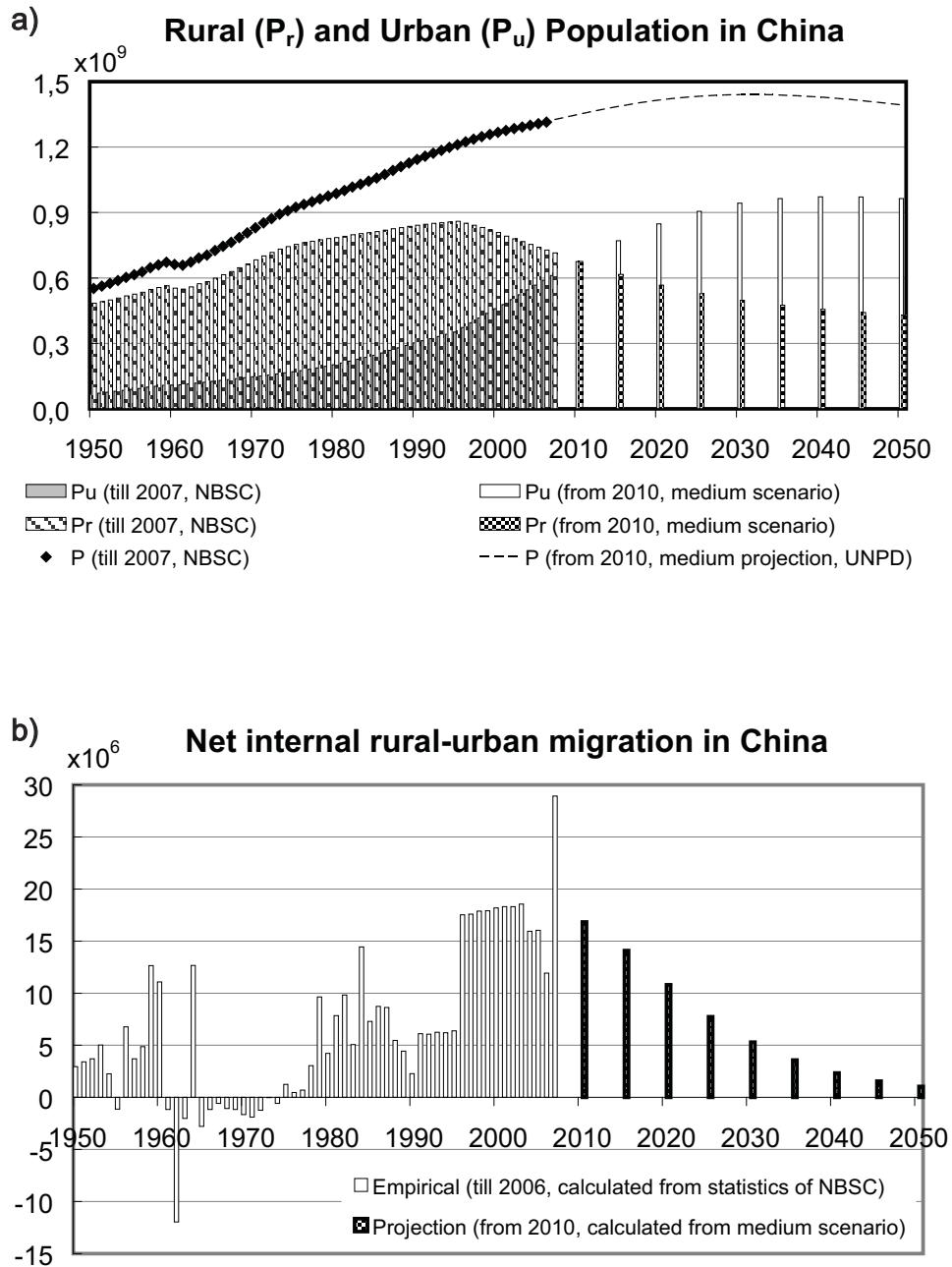


Figure A.1 Population components and net internal rural-urban migration in medium scenario. Data before 2006 are historical figures derived from National Bureau of Statistics of China (NBSC 1984-2007, 2005); forecasting data of China's national population is quoted from United Nations Population Division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

Appendix B: Stock dynamics model for housing floor area

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

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

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

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

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

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

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

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

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

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

Appendix C: Various forecasts for urbanization rate in China

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

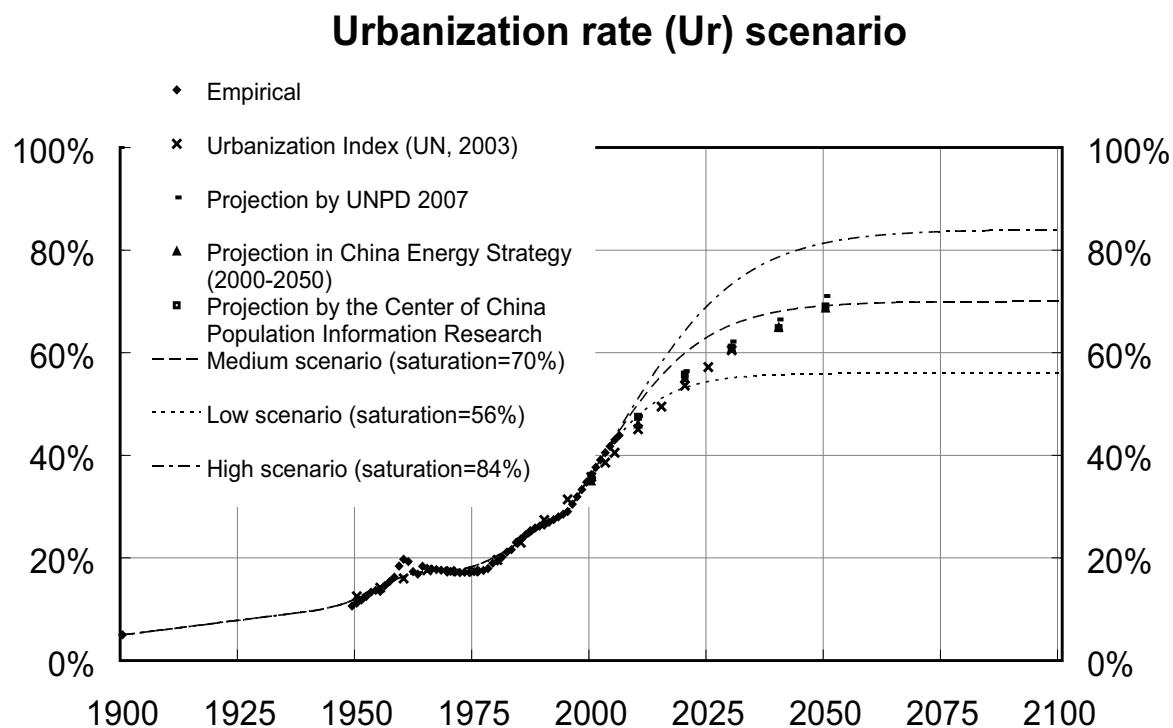


Figure C.1. Various forecasts for urbanization rate in China. Empirical data until 2006 are derived from National Bureau of Statistics of China (NBSC 1980-2007, 2005).

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

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

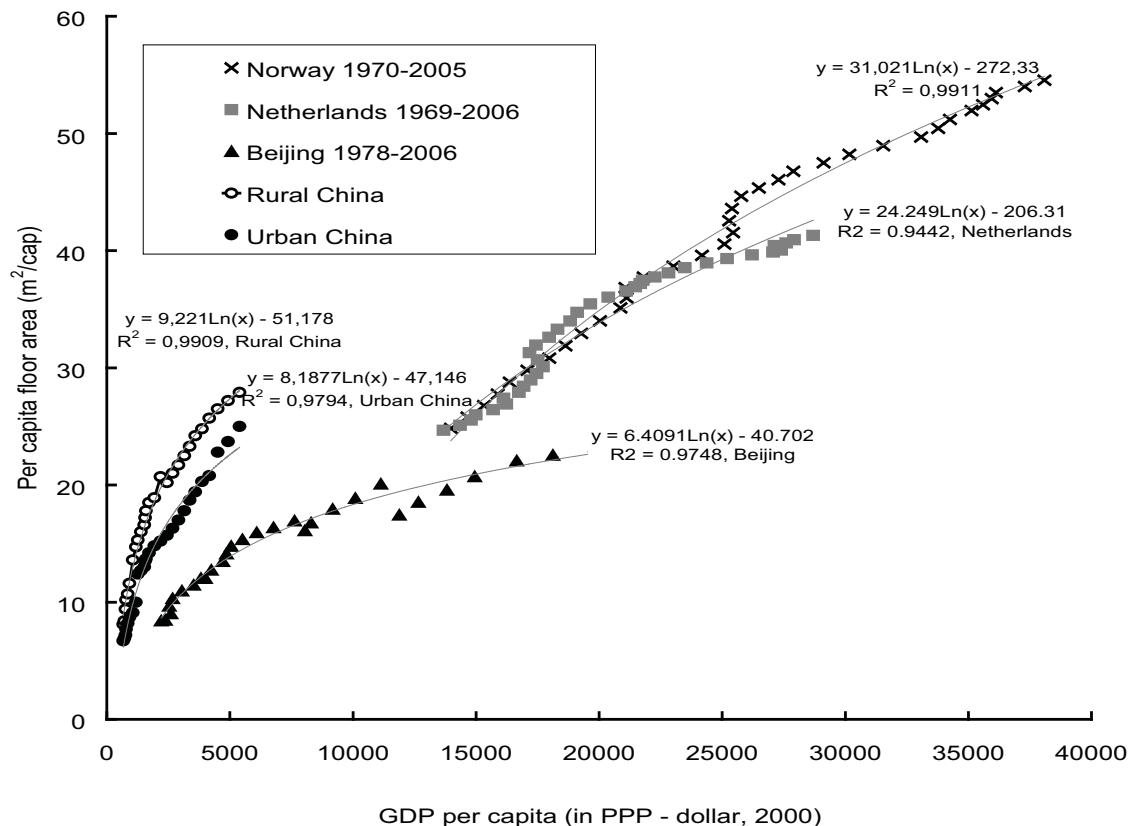


Figure D.1 Relation between floor area per capita and GDP per capita. Data sources: Bergsdal et al. (2007b), Müller (2006), NBSC (1984-2007, 2005), Eurostat (2009), World Bank (2008).

