Dynamic material flow analysis to support sustainable built environment development

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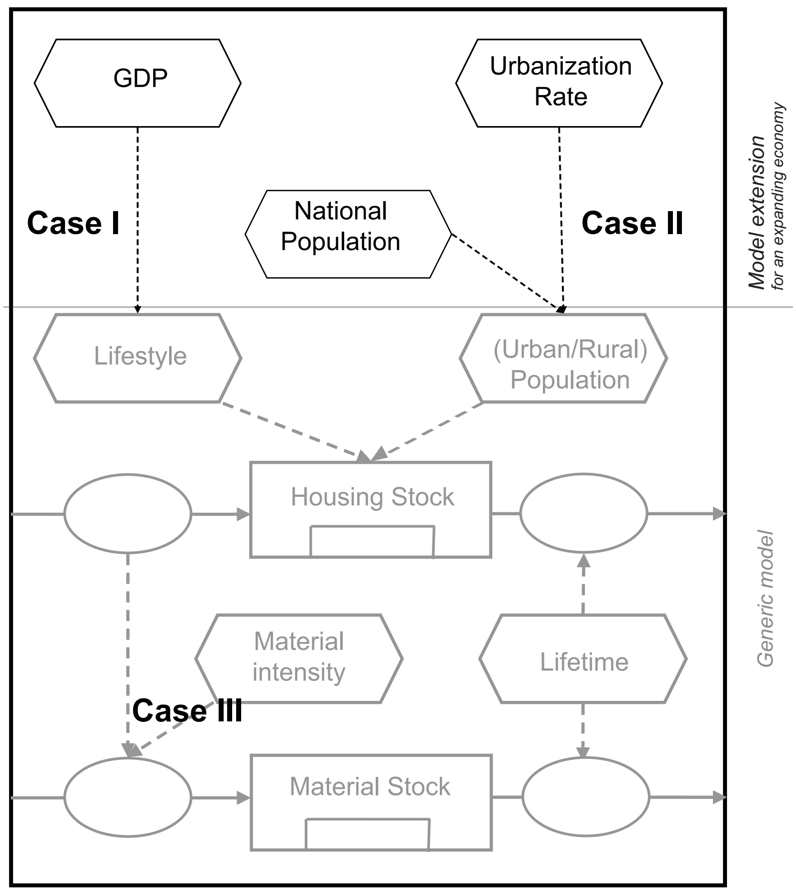
Chapter 5 Discussion, Conclusions and Recommendations



5.1 Introduction

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

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

5.2 Discussion and evaluation of the case studies

5.2.1 Hypotheses

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

(1) 'metabolism metaphor' is useful;

(2) dynamic material flow analysis is essential;

(3) stock dynamics driving dynamic MFA is suitable.

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

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

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

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

5.2.2 Limitations of stock dynamics model and its uncertainties

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

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

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

5.2.3 Evaluation of the case studies

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

Q1. Trends for inflows (in construction)

Q2. Trends for outflows (in demolition)

Q3. Environmental impacts

Q4. Implications for industries

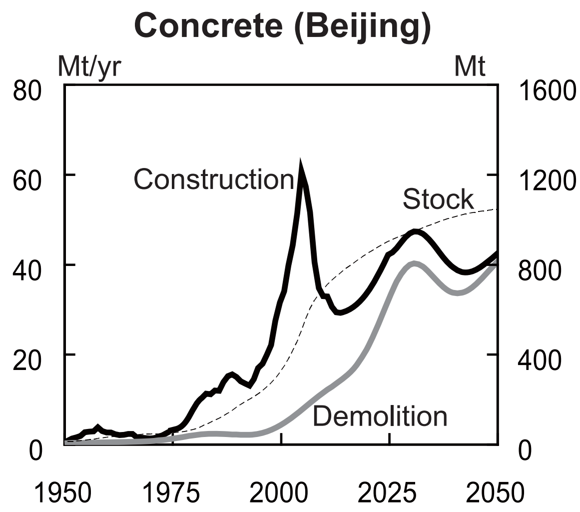
With the support of the developed stock dynamics dynamic MFA models, these questions have been investigated through three case studies that are presented from Chapter 2 to 4, as indicated in Table 1.1.

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

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

* Reproduction of Table 1.1, Chapter 1.

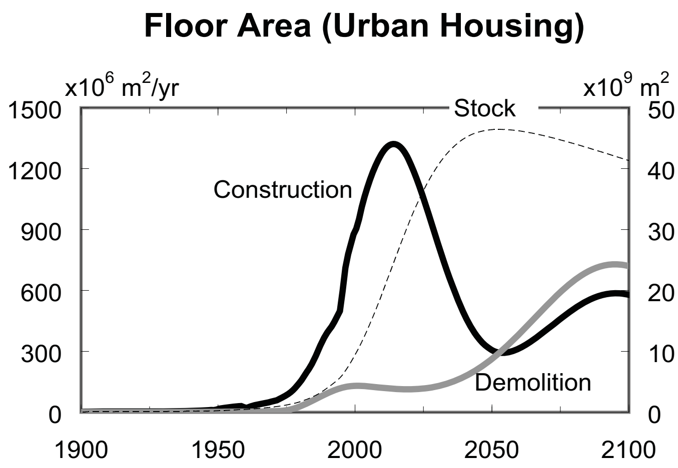
Case I (Chapter 2) develops a GDP driving dynamic MFA model for examining the concrete diffusion in Beijing's urban housing system. It answers the questions *Q1* and *Q2*. Regarding '*Trends for inflows*', it states that the concrete demand for new residential construction in Beijing is probably to drop over the next decade, even with an extremely high GDP growth. With regard to '*Trends for outflows*', it states that, in the coming decades, the demolition activities and related concrete debris in Beijing will rise,



(from Figure 2.10, Chapter 2)

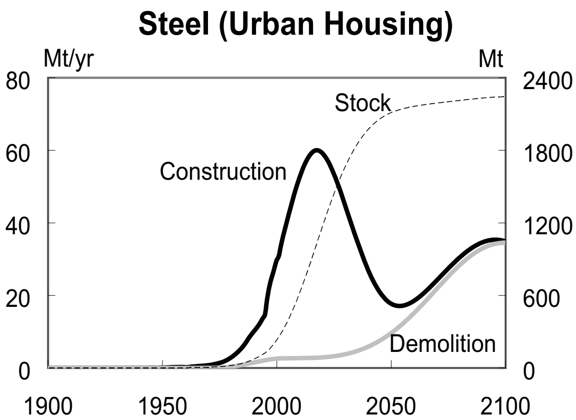
unavoidably. If the current short lifespan of buildings (ca. 25 years) continues, Beijing will face a dramatic rise of demolition concrete through 2050. Doubling the lifespan can push the significant rise to a more distant future but cannot avoid it. The amount of concrete released from demolition will almost catch the level of construction demand by 2050. Hence developing concrete recycling techniques have an increasing potential to close this material loop in Beijing's residential construction.

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



(from Figure 3.4, Chapter 3)

upstream suppliers.



(from Figure 4.4, Chapter 4)

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

5.3 Conclusions

5.3.1 Methodology

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

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

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

5.3.2 Housing service units

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

5.3.3 Construction materials

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

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

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

5.4 Recommendations

5.4.1 Technical and policy recommendations

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

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

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

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

Reference to Chapter 5

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

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

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