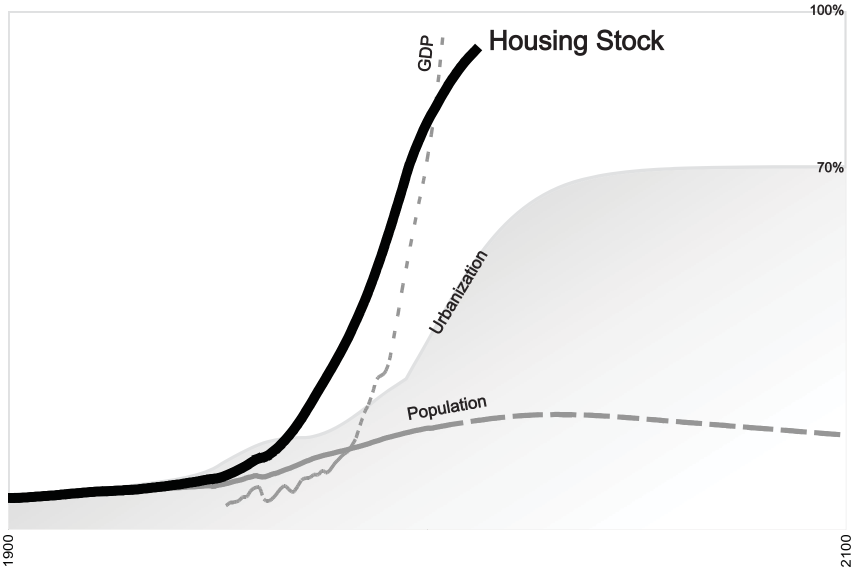
Dynamic material flow analysis to support sustainable built environment development

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

Chapter 1 Introduction



1.1 Sustainability challenges in built environment development

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

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

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

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

---

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

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

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

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

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

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

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

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

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

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

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

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

---

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

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

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

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

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

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

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

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

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

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

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

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

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

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

---

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

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

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

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

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

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

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

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

1.6 Research questions

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

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

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

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

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

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

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

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

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

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

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

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

1.7 Thesis outline

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

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

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

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

Reference to Chapter 1

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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