From Urban Metabolism to Industrial Ecosystem Metabolism: A Study of Construction in Shanghai from 2004 to 2014

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Abstract

Amid the prolific studies on urban metabolism is the relatively sparse research focusing on a specific industrial ecosystem. A general urban metabolism framework disconnected from specific industrial background is at the risk to misunderstand the key drivers of metabolic process, thereby failing to propose applicable instructions for improving its sustainability. This paper aims to develop an industrial ecosystem level metabolism framework. This was conducted by following the major analytical tools such as material and energy flow analysis (MEFA) with a focus on the construction industry, which plays a pivotal role in materializing the urban meanwhile generating negative by-products such as greenhouse-gas (GHG), pollutants, and construction waste. The framework was further applied to the construction ecosystem in Shanghai for confirming the major components it includes. Using the data in Shanghai, it was also discovered that the construction industry is generally less efficient in terms of metabolic processes. It is indicated that population, urbanization rate, concrete input, real estate investment, and the housing demolished and newly built are the principal determinants explaining the huge construction waste generation in Shanghai. The framework can facilitate the understanding of the construction ecosystem metabolic process, investigation of construction and demolition (C&D) waste generation and its main drivers, and evaluation of urban sustainability at an industrial scale.

Keywords: Urban metabolism; Industrial Ecosystem Metabolism; Construction; C&D waste; Shanghai; China

1. Introduction

Urban metabolism provides a metaphorical framework for studying the link between natural and human systems (Pincetl et al., 2012). Wolman (1965) first introduced the term urban metabolism to treat city as an analogous ecosystem. Kennedy et al. (2007) defined urban metabolism as "*the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy and elimination of wastes*". Urban metabolism is generally applied to describe how material, food, water and energy flow into an urban ecosystem, and are consumed to support its metabolism, then grow and reproduce, consequently generating products and by-products (e.g. GHG, pollutants, and waste). Since early 1980s, particularly with the increasing concern of sustainable development (WCED, 1987), urban metabolism has become an important and leading perspective through which urban sustainability can be properly perceived (Fischer-Kowalski and Haberl, 1998; Gandy, 2004; Haberl, 2001a; Kibert et al., 2000; Newman, 1999).

However, existing studies on urban metabolism is mainly available on a city or regional scale. Little attention has been paid to particular industrial ecosystem of urban metabolism. There are multiple industrial ecosystems within a city or a region, which differ from one another in influencing the overall urban ecosystem. A general urban metabolism framework detached from industrial background is at the risk to miss the key drivers of metabolic process, thereby failing to propose applicable instruments for improving the sustainability of a city or region.

Construction is crucial for the overall urban ecosystem, as it is responsible for materializing the urban. However, construction has not been considered as environmentally friendly by its nature compared to other industrial sectors due to consuming massive natural resources and generating a vast quantity of greenhouse-gas (GHG), pollutants, and construction and demolition (C&D) wastes (Shen et al., 2004; Tam and Tam, 2008). In a case of China, it is estimated that about 1.13 billion tons of C&D waste were produced during 2014, taking up around 30-40% of total municipal solid waste generated annually (Lu et al., 2016).

Thus, issues on C&D waste have received widespread attention around the globe since last decades (Kofoworola and Gheewala, 2009); and the importance of sustainable construction sector for urban sustainability cannot be overemphasized. Construction metabolism provides a natural analogue for a sustainable built environment (Kibert et al., 2000). Therefore, understanding how construction ecosystem operates is especially beneficial to exploring urban metabolism and its drivers, thereby implementing effective policies for enhancing urban sustainability.

The study seeks to develop an industrial ecosystem level metabolism framework through three rigorous procedures: (1) reviewing research on urban metabolism, and identifying basic structure of a general urban metabolism framework; (2) qualifying specific features of industrial ecosystem level metabolism; and (3) building an industrial ecosystem level metabolism in specific industrial contexts (e.g. construction). Finally, an empirical study on the construction industry in Shanghai (China) is conducted to test the applicability of the industrial ecosystem level metabolism framework.

This research sheds light on sub-ecosystems of urban metabolism for better assessing urban sustainability in particular industrial ecosystem background. It provides a more comprehensive and powerful analytical tool for treating urban sustainability at an industrial scale than traditional urban level input-output analysis. More importantly, the integrated urban metabolism framework based on construction ecosystem may be transplanted to other industries and regions, or combinations thereof.

2. Literature review

2.1 Concept of urban metabolism

The concept of urban metabolism evolves constantly over time (Fischer-Kowalski, 1998, 1999; Kennedy et al., 2007; Wachsmuth, 2012). Essentially, metabolism is a biologic concept that refers to biochemical reactions carried in a cell or a living thing (Fischer-Kowalski and Haberl, 1998). Then, the concept of metabolism on the biological level expands from cell to ecosystem (Odum and Barrett, 2005). It is widely accepted that a city is an autotrophic and heterotrophic ecosystem, and a complex self-organization (Odum, 1988).

Urban metabolism research rose due to increasing environmental pollution and urban expansion worldwide in the 1960s. Wolman (1965) first introduced the concept of metabolism to probe the metabolic process of cities, and defined the metabolic needs of a city as "*all the materials and commodities needed to sustain the city's inhabitants at home, at work and at play*". Traditionally, urban metabolism research focuses on natural resources flow in an urban ecosystem, mainly examining natural and physical aspects of urban metabolism (Fischer-Kowalski, 1998; Kaika and Swyngedouw, 2000).

Recently, non-natural dimensions, namely social, cultural, political and institutional dimensions of urban metabolism have been heavily emphasized (Short, 1996). As an example, Newman (1999) developed an urban metabolism model integrated with socially livability indicators (e.g. health, education, employment), thereby expanding the scope of urban metabolism.

2.2 Urban metabolism analytical methods

Originally, material flow analysis (MFA) (Decker et al., 2000; Kennedy et al., 2015; Niza et al., 2009) and energy flow analysis (EFA) (Haberl, 2001a, b) are two fundamental analytical methods of urban metabolism. MFA focuses on the flows of material, water, food, and nutrient within an urban ecosystem, and may be used at different scales, such as global, national, regional, city and industrial level (Ayres, 1978; Fischer-Kowalski, 1999). Energy flow and material flow are two different but interwoven components of same urban metabolic process, and thus urban metabolism may be fully understood only if they are integrated in same urban metabolism framework (Kennedy et al., 2011).

Later, environmental accounting (EA) was merged into the MEFA framework (Odum, 1996), which concerns the generation, recycling, disposal and reuse of various wastes such as GHG, wastewater, and solid waste. Generally, MEFA mainly focuses on physical material and energy flows in urban ecosystem, while EA explains the hybrid material and energy flows in combined physical and monetary terms based on integrating socio-eco-environmental data (UN, 2003).

Recently, novel methods have emerged concerning the hybrid nature-socio-eco-politic metabolism mainly from the complex ecosystem viewpoint, including decision support analysis (DSA) (González et al., 2013), integrated urban metabolism tools (IUMTs) (Fung and Kennedy, 2005; Mostafavi et al., 2014), and life cycle analysis (LCA) (Goldstein et al., 2013; Mora, 2007).

2.3 Main components of urban metabolism analysis

Urban metabolism mainly involves quantification of the input, output and storage of water, material, energy, nutrients, and waste in a city (Kennedy et al., 2007). As an indispensable element of urban metabolism, numerous water metabolism studies have been conducted in the Greater Toronto (Sahely and Kennedy, 2007), the four largest Austria cities (Kenway et al., 2011), Athens (Rozos and Makropoulos, 2013), Oslo (Venkatesh et al., 2014), and Amsterdam (Hoek et al., 2017). Material is also critical for urban metabolism, and thus a great amount of MFA studies have been carried out (Decker et al., 2000; Fischer-Kowalski et al., 2011; Huang and Hsu, 2003; Krausmann et al., 2009; Moll, 1997).

Energy plays a crucial role in metabolism (Barles, 2010; Decker et al., 2000; Kennedy et al., 2015; Ngo and Pataki, 2008; Zhang et al., 2016). Additionally, food or nutrient metabolism is a key for a city (Barles, 2007; Forkes, 2007; Goldstein et al., 2017). In response to growing environmental crisis, waste metabolism has received widespread concern from multi-dimensions, involving waste flow (Lehmann, 2011; Rathi, 2006), ecological footprint (Luck, et al., 2001; Wackernagel et al., 2006), GHG emissions (Islam, 2017; Kennedy et al., 2009), and carbon metabolism (You et al., 2011; Zhang et al., 2014).

As for urban metabolism study on construction ecosystem, there are fewer studies on urban metabolism in construction industry context (Coelho, 2016; Huang and Hsu, 2003; Kibert et al., 2000; Wang et al., 2016). Additionally, several studies have considered the sustainability of Shanghai in China from the viewpoint of urban metabolism. A case study of Shanghai was undertaken to study the changes of human time and land use pattern by employing the socio-economic metabolism (Lu et al., 2016); six large Chinese cities, including Shanghai, were selected to examine the measurement and evaluation of the metabolic capacity of based on urban material metabolism (Zhang et al., 2009). The nexus between land us and social metabolism flow was explored in case of Shanghai (Cui and Wang, 2015). A multi-scale integrated analysis of socio-eco metabolism (MuSIASEM) was applied to compare the metabolic characteristics of four global megacities, including Shanghai, Tokyo, London and Paris (Han et al., 2018).

In summary, although urban metabolism provides a powerful tool for a holistic understanding of urban sustainability in a city or region scale, mainly via various natural resource flow analysis (e.g. MFA, EFA, and EA). Limited studies consider specific industry context of urban metabolism (Rosado et al., 2014). Particularly, there are rare studies on the integration of urban metabolism and construction ecosystem, despite the fact that construction might be the most relevant system in materializing the urban. Thus, in this paper it seeks to fill the research gap to build an integrated urban metabolism framework based on construction ecosystem. A closer understanding how construction ecosystem works can help examine the urban metabolism and its dynamics, in turn which can be beneficial to improve the overall sustainability of a city or region.

3. Methodology

3.1 Proposed urban metabolism framework

A general urban metabolism model consists of three interrelated core elements, namely, (1) inputs, (2) storage of natural resources and energy within an urban ecosystem, and (3) outputs of products and by-products (Fischer-Kowalski, 1998, 1999; Zhang, 2013). Essentially, urban ecosystem is composed of different sub-ecosystems such as agriculture, industry, construction, service and household ecosystems (see Fig.1). An ecosystem level urban metabolism framework focusing on particular context of construction ecosystem can be built through the following three steps:

Step 1: Identifying the fundamental components of a general urban metabolism framework;

Step 2: Quantifying the inputs, industrial activities and outputs of construction ecosystem; and

Step 3: Integrating construction ecosystem into the general urban metabolism framework.

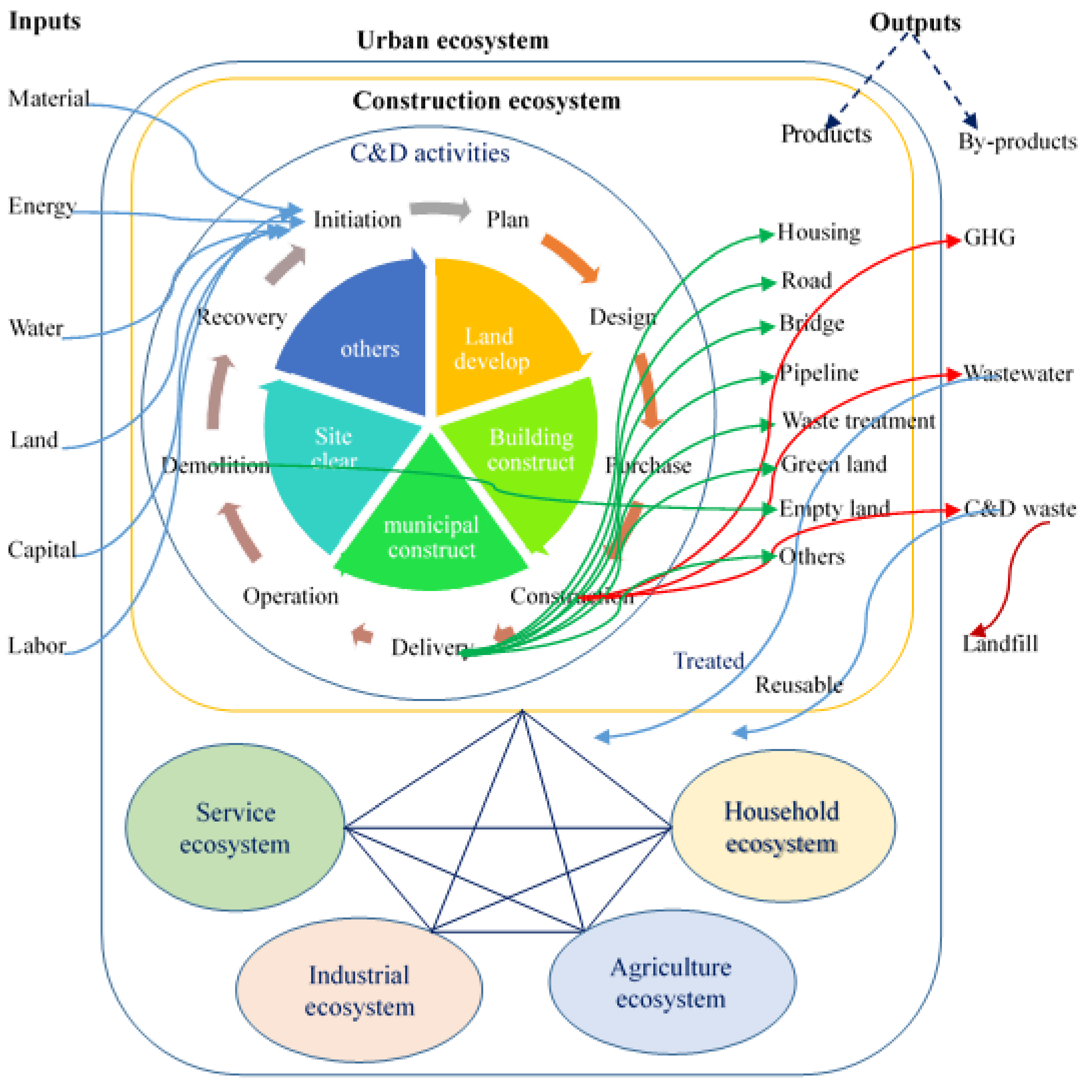


Fig. 1 An integrated urban metabolism framework based on construction ecosystem

Similar to the general urban metabolism framework, the architecture of construction metabolism consists of three principal components, including (a) inputs of natural resources, (b) construction ecosystem, and (c) outputs of various construction products and by-products (see Fig.1 and Table 1).

Table 1 Core components of construction ecosystem metabolism

Process	Component	Subcomponent
Inputs	Material	Steel, wood, concrete, stone, sand, glass, aluminum, plastic, textile, and others
	Energy	Coal, oil, electricity, gas, and others
	Water	Freshwater, rainwater, and others
	Labor	Employer, designer, consultant, contractor, supplier, worker, and others
	Land	Various land used in construction sector
	Capital	Investment in urban construction, public facility, real estate, and housing
Constructi	Construction	Land development, building construction, equipment installation,

on ecosystem	activities	municipal engineering, site clearance, demolition activity, and others
	Sustainable design and construction	Initiation, plan, design, purchase, construction, delivery, operation, demolition, and recovery
	Local & industrial economic support	GDP, population, urbanization, disposal income, value-added in construction sector, and others
Outputs	Products	Newly built or demolished buildings, road, bridge, pipeline, and others
	By-products: Waste	Soil, earth, silt, and others
	GHG	CO_2, CH_4, N_2O, and others
	Wastewater	C&D wastewater

However, the integrated framework is different from existing urban metabolism framework in that: (1) it introduces some non-natural elements to the framework (such as capital and labor), thereby describing the industrial ecosystem more accurately; (2) it examines the impacts of industrial activities on outputs, in particular the impacts of C&D activities on C&D waste; and (3) it considers the relationship between sub-ecosystems in an urban ecosystem, including agriculture, industrial, construction, household and service ecosystems.

3.2 Input of resources

Generally, the construction sector consumes massive construction materials compared with other sectors; hence, construction material accounts for a great proportion of total resource input. In line with different structures and features of planned construction projects, construction materials used within specific construction activities may include steel, wood, concrete, stone, sand, glass, aluminum, plastic, paper, textile and others. Among construction materials, some are reusable material; and others are disposable material. Usually the majority of materials can be transformed into various construction products, while a small portion consists of the source of C&D waste after use.

Effective energy supply is essential for a construction ecosystem. Generally, electricity and fuel are the most predominant energy consumed in production, such as lighting, powering vehicle and equipment. In addition, other energy forms (e.g. solar energy, coal) can be essential for construction. For instance, site-finished cement products can be cured in natural environment by absorbing solar energy. The majority of energy is degraded in the operation and unable to conduct further work (Kibert et al., 2002).

Construction is not a water-saving sector. Within the construction ecosystem, water can be used for different construction activities. Water may either be converted into an ingredient of construction material (e.g. water in the cement products), or possibly be consumed or evaporated during operation activities. Subsequently, wastewater may arise from construction activities. Usually, damaging components in water are not from water use itself, but from residuals of fuel and material consumption (Decker et al., 2000).

Construction activities are always attached to land. In the construction sector, a great amount of land may be occupied to build permanent buildings, infrastructure, or public spaces. However, some land, only temporarily utilized for construction activities, can be reused for other purposes.

Although labor and capital are crucial for sustainable construction, they are sparse in existing literature (Zhang, 2013). From a Marxism perspective, urban metabolism is firstly described as human transformation of nature through labor—a creative and social process that produces and reproduces both human life and the natural world (Wachsmuth, 2012). Within urban metabolism, natural resource flow is strongly interwoven with, or even driven by capital flow (Pincetl et al., 2012).

3.3 Construction ecosystem

The metabolism of construction ecosystem closely links with construction activities, and further with local and industrial economy. Construction activities refer to the process of constructing or demolishing a building or infrastructure, which generally begins with initiation, plan, design, biding, and finances and purchases, then constructs or demolishes until delivers a qualified construction project (see Fig.1). There is numerous construction activities, including land development, building construction, equipment installation, municipal engineering, site clearance and demolition (Shen et al., 2004).

Construction ecosystem and its metabolism are marked by long lifetime, with massive resources expended in it over its operational process. It also differs from other industrial sector in that buildings are not factory products, but are generally one-off products bespoke by the clients and delivered by widely varying teams of architects and engineers, and assembled at construction site using significant quantity of labor from a wide array of subcontractors and craftspeople (Kibert et al., 2002).

Construction activities involve various construction material flux. Different construction materials are purchased, then transported to construction site, stored in warehouse or operation site, and processed or pre-processed before installation. Buildings are assembled with construction material in five categories (Kibert et al., 2002): (1) manufactured, site-installed commodity products, systems, and components with limited site processing; (2) engineered, off-site fabricated, site-assembled components; (3) off-site processed, site-finished products; (4) manufactured, site-processed products; and (5) manufactured, site-installed, low mass products. Along with construction material flow, the metabolism of construction ecosystem is always mingled with the flow of energy, capital and labor in multi-facet of time, space, quantity and quality, accompanied by land use (see Fig.1).

3.4 Outputs of products and by-products

On the output-side, corresponding products and by-products of construction ecosystem can be produced through the metabolic process (see Fig.1). In particularly, the products of construction activities may mean a certain amount of building or infrastructure, such as open space, building, road, bridge, pipeline, and other facilities. Meanwhile, the metabolic process of construction ecosystem also produces numerous by-products, such as GHG, pollutants and C&D waste, which significantly offset the efficiency of material flow, water, energy, capital and labor input, and consequently threaten urban sustainability.

3.5 Application of the framework in Shanghai's construction industry

The application of the framework includes four interrelated procedures as follow (in Fig. 2): (1) research object selection; (2) data collection; (3) input-output analysis of construction ecosystem; and (4) statistical study on the nexus between C&D waste generation, input and C&D activities.

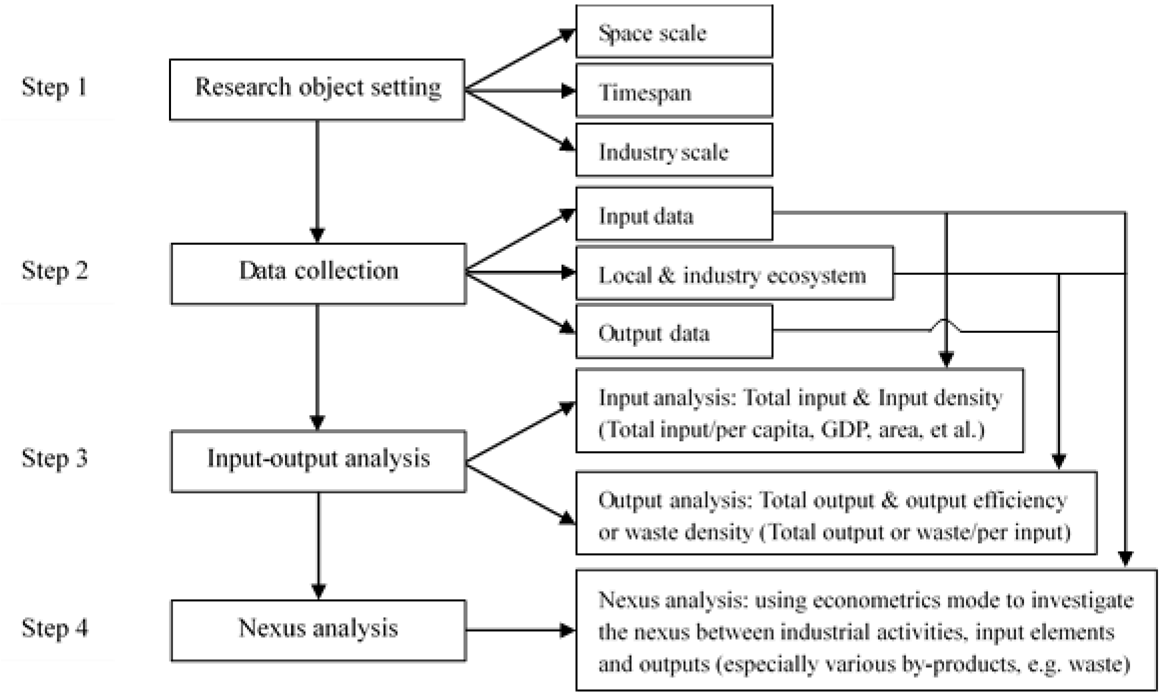


Fig. 2 Application of the integrated urban metabolism framework

First, it is necessary to select research object, and set the spatial, periodical and industrial dimensions. Construction industry in Shanghai is selected for the study sample to confirm the framework; and the study period is set between 2004 and 2014. Shanghai is the largest megacity and highly advanced economic center in China. It is also the leading city in the Yangtze River Delta Urban Agglomeration, which is located on the China eastern coast. The municipal boundary of Shanghai includes sixteen districts, and covers an area of about 6,340 km^2. Its population increased by 2.9% from 18.3 million in 2004 to 24.3 million in 2014. Correspondingly, the population density has grown from 2,894 per km^2 to 3,826 per km^2. The metabolic process of Shanghai's construction ecosystem is examined in order to investigate urban sustainability amid local socio-economic context of Shanghai.

An urban metabolism analysis requires complete input-output information about material, energy, water, waster, products and by-products of an urban region. The data can be classified into four main types: (1) the data on local economy (e.g. GDP and population); (2) the data on construction sector (e.g. materials, energy, water and labor); (3) the data on construction activity (e.g. land use, and construction investment); and (4) the data on environment (e.g.

waste, GHG and pollutants). The data can be separately obtained from Shanghai Statistical Yearbook (Bureau of Statistics of Shanghai [BSS], 2005-2015), China Statistical Yearbook on Construction Industry (National Bureau of Statistics of China [NBSC], 2005-2015), China Statistical Yearbook on Urban Construction (NBSC, 2005-2015), and China Statistical Yearbook on Land Resource (NBSC, 2005-2015).

Next, the input-output analysis of construction sector can be conducted by considering the indicators of (1) total input, examining various resource consumptions and its change trend over time; (2) per capita input, exploring resource input density and its change trend; and (3) total and per capita output, investigating construction productivity, and its change trend.

Finally, regression analysis is used to uncover the nexus among various inputs, construction activities and how the outputs of products and by-products are generated. This study repeatedly tried different regression functional forms using econometrics analyst Eviews 8.0. This study focuses on the C&D waste generation of Shanghai from 2004 to 2014, partially because: (1) the data were accessible; and (2) C&D waste is something tangible that can be easily measured and perceived. The indicators selected for the empirical study using the integrated framework are shown in Table 2.

Table 2 Indicators for the urban metabolism of Shanghai's construction ecosystem

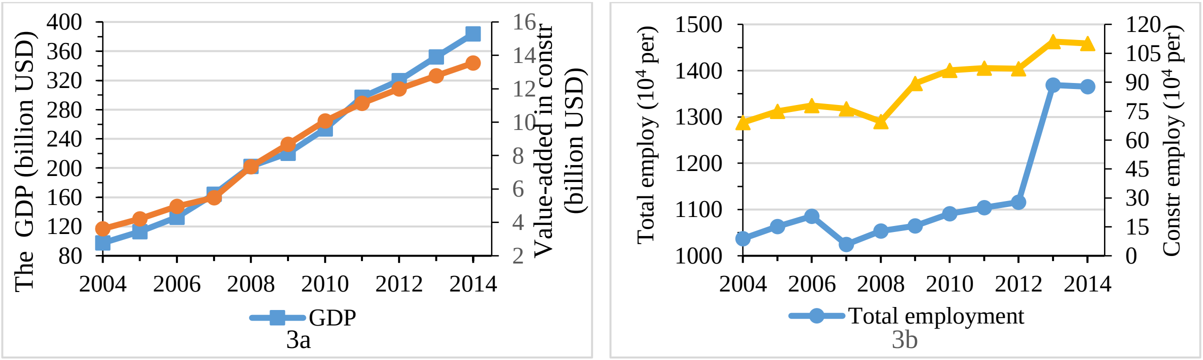
Process	Component	Indicator	Definition	Data resource
Inputs	Material	Total input of material	Annual use of steel, concrete and wood in construction	China Statistical Yearbook on Construction Industry
		The input density of material	Per capita annual use of steel, concrete and wood in construction	
	Energy	Total input of energy	Annual use of energy in construction	
		The energy input density	Per capita annual use of energy	
	Water	Total input of water	Annual use of freshwater in construction	
		The water input density	Per capita annual use of freshwater	
	Labor	Total input of labor	Annual use of labor in construction	
	Land	Total land use	Annual land use in construction	China Statistical Yearbook on Land Resource
		The land use density	Per capita land use in construction	
	Capital	Total input of capital	Annual investment in construction, municipal, real estate, and housing	China Statistical Yearbook on Urban Construction
		The capital input density	Per capita capital input in construction, municipal, real estate, and housing	
Local and industrial ecosyste	Local economy	GDP	Annual Gross Domestic Product	Shanghai Statistical Yearbook
		Per capital GDP	GDP per capita	
		Disposal income	Disposal income	

m			
	Population	Total population	Total urban and rural population
		Urbanization level	The ratio of urban to total population
		Total employment	Total employment
	Construction sector	Value-added	The Value-added in construction
		Value-added per capita	Per capita Value-added in construction
		Construction employment	The employment in construction sector
Outputs	Products	Total construction product	Annual generation of building, housing, residence, road and pipeline, and annual completion and demolition of housing
		Construction product per capita	Per capita generation of building, housing, residence, road and pipeline, and annual completion and demolition of housing
	By-products	Total C&D waste	Total C&D waste arising from C&D activity annually
		C&D waste per capita	Per capita C&D waste arising from C&D activity annually

4. Results

4.1 Overview of the construction sector in Shanghai

Shanghai has made remarkable economic increase in terms of GDP from USD 97.5 billion to USD 383.7 billion, with an annual growth rate of 11.3% between 2004 and 2014. As a pillar industry, the construction sector plays a crucial role in economic development (see Fig. 3).



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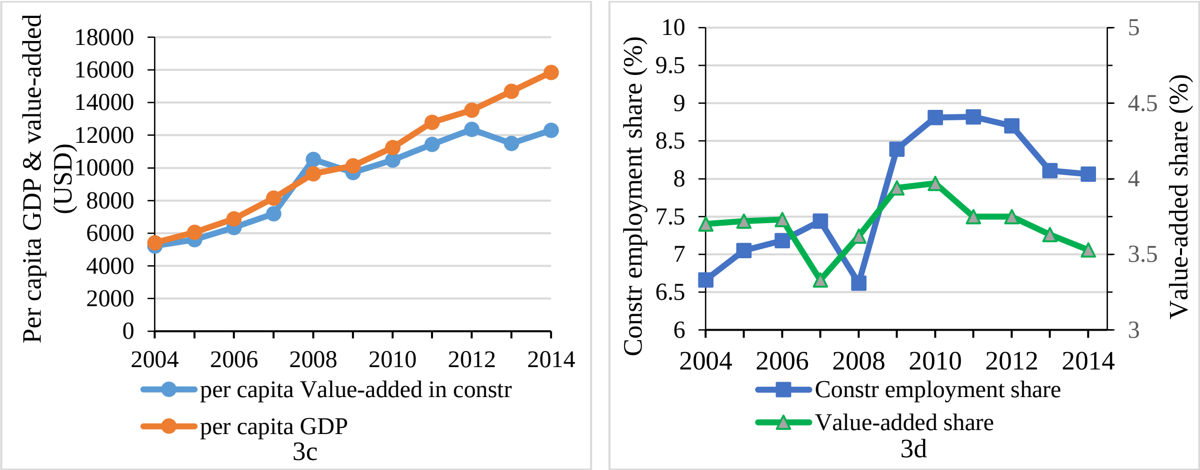

Fig. 3 Overview of construction ecosystem in Shanghai, China, 2004-2014

The construction sector materializes the built environment and creates added-value. Construction added-value experienced a rapid annual growth by 11.2% from USD 3.6 billon to USD 13.5 billion, with nearly three-time growth along the decade from 2004 to 2014 (see Fig. 3a). Construction is responsible for about 4.0% of the GDP. Meanwhile, construction substantially contributes to the employment of the city. Its employment has increased from 691 thousand to 1,001 thousand from 2004 to 2014, accounting for about 7-9% of total employment (see Fig. 3b). However, it is found that the growth rate of both total and added-value per capita in construction sector is slower than overall growth rates in the study period. This is in accordance with the patterns of GDP per capital growth in other economies (see Fig. 3c).

It implies that construction is not an efficient industry that needs significant improvement. With regard to industrial share, it is observed that its share in overall economy has significantly decreased in recent years. It has shown a decline trend in the proportion of construction sector, with a decrease from 3.7% to 3.5% from 2004 to 2014 (See Fig. 3d). The construction sector shows a significant upward trend in creating employment opportunities, and the number of employees absorbed by construction industry increased from 6.7% to 8.1% (See Fig. 3d). In summary, despite the construction sector produces a great amount of employment, its productivity is relatively low. In other words, the construction sector in Shanghai is still labor-intensive, but less productive.

4.2 Material, water, and energy input

Input analyses of construction materials, water and energy input analysis for Shanghai are shown in Fig.4. Total use of main construction materials, including steel, wood, and concrete, substantially increased over the past decade. Shanghai consumed 22.86 million tons of concrete in 2014.

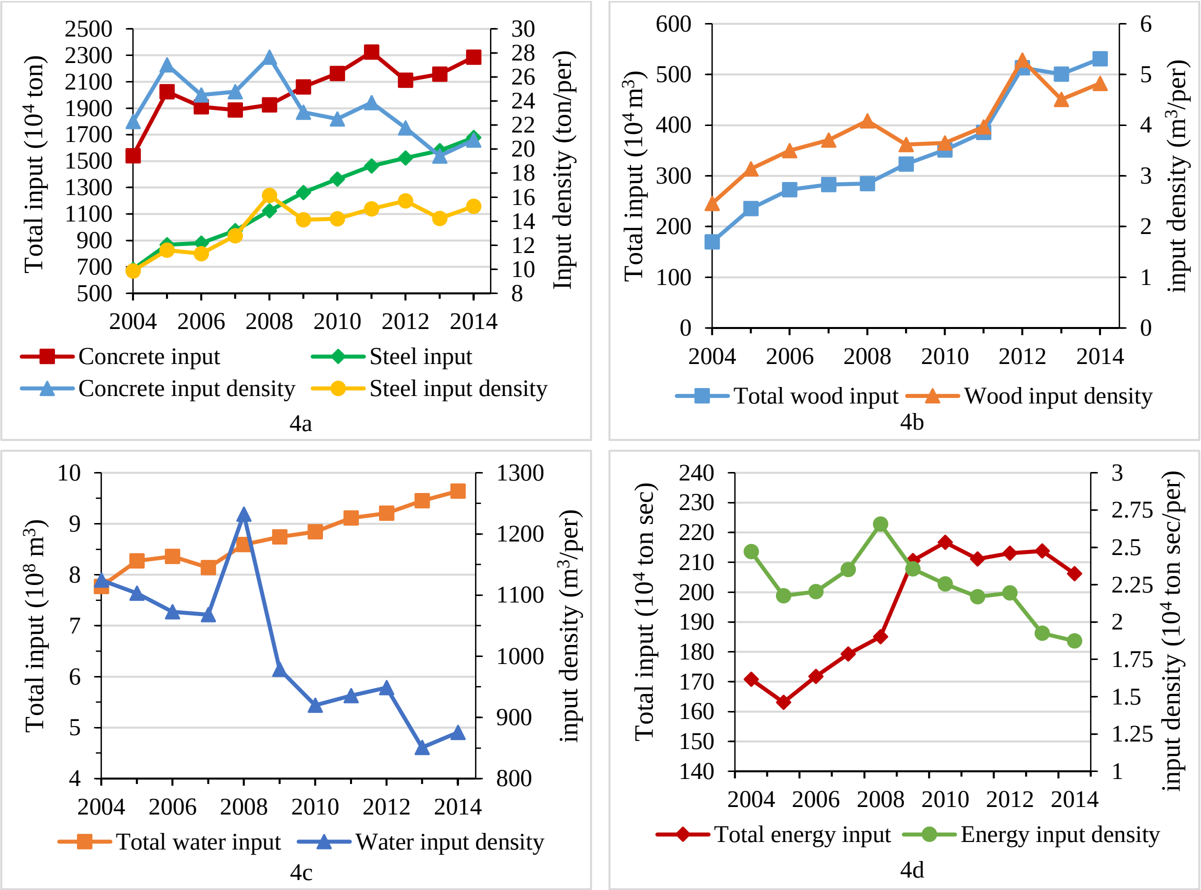

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Fig. 4 Material, water, and energy input of construction ecosystem in Shanghai, 2004-2014

Although the increase in total energy and water use is relatively slow by only 21% and 24% (see Fig. 4d), both water and energy utilized in construction sector in 2014 still amounted to 945 billion m^3 and 2.14 million ton, respectively. Material, water and energy input density, measured by the use of material, water and energy per capita, have declined significantly in 2004-2014 (see Fig.4). While among three main construction materials, except for a small decrease in input density of concrete per capita from 22.3 tons to 20.8 tons, input density of other materials experienced a remarkable growth over time. Particularly, the increase rate in input density of steel and wood reached between 54% and 96%.

4.3 Land, labor and capital input

Similar to material, water and energy, other factors such as land, labor and capital are indispensable for construction metabolism. Owing to strict land use policy at national and municipal levels recently, total and per capita land use considerably declined in 2004-2014 (see Fig.5). In contrast to continuous and significant decline trend in land use, total investments in construction, municipal, real estate and housing increased with the growth rate between 0.5 and 1.7. Especially, total investments in both housing and real estate have increased from USD 11.2 billion and 14.2 billion to USD 28.2 billion and 52.2 billion between 2004 and 2014, with a huge change rate of 0.9 and 1.7 separately.

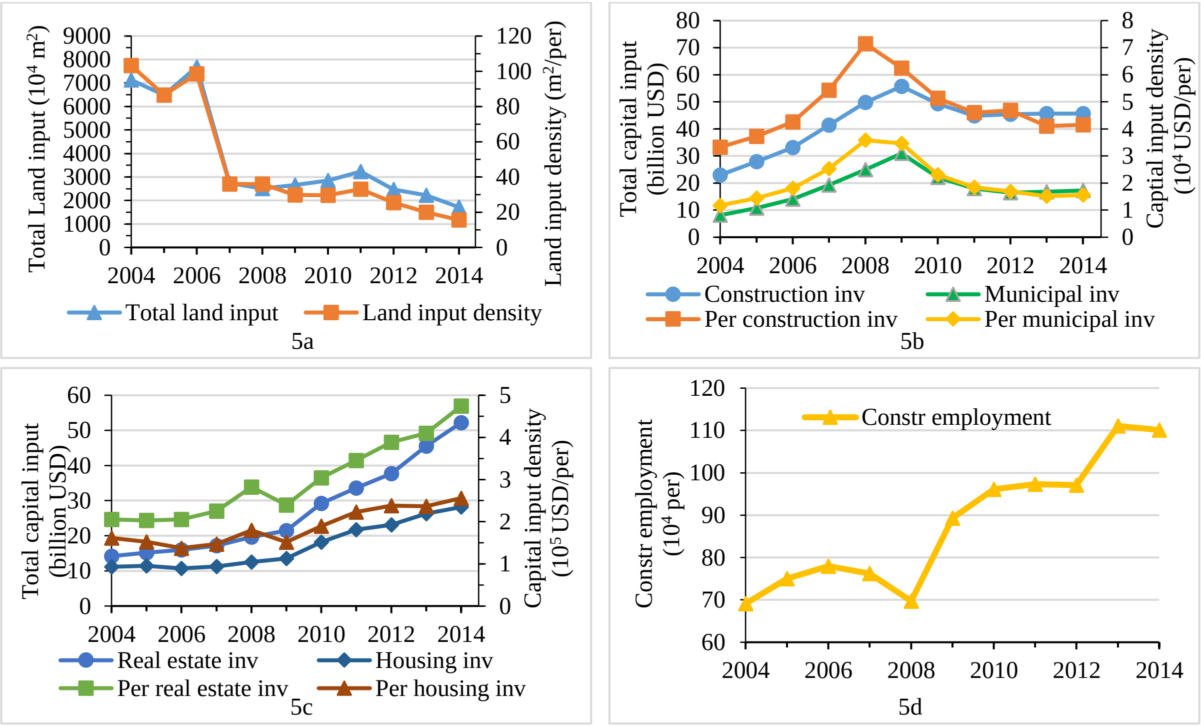
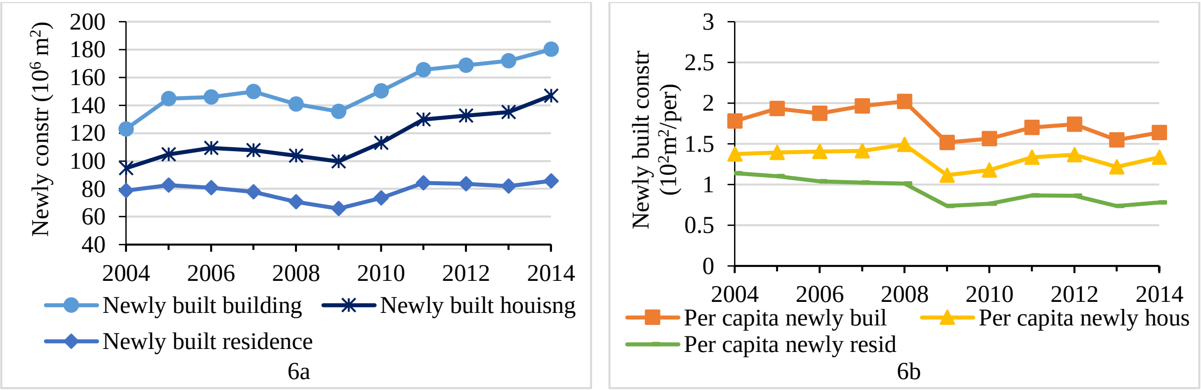


Fig.5 Land, labor and capital input of construction ecosystem in Shanghai, 2004-2014

The change trend in land use and capital input can be classified into three primary categories (see Fig. 5a, 5b, 5c). Total and per capita land use generally went downward straightly, whereas total and per capita investments in real estate and housing kept continuously upward. In contrast, both total input and input per capita in construction and municipal projects show an inverted U-shaped change trend, meeting the vertex in 2009 (see Fig. 5b).

4.4 C&D activities and products of construction ecosystem

Essentially, the metabolic process of construction ecosystem closely connects to various C&D activities, thus creating considerable products and by-products. Fig. 6 summarizes C&D activities and products of construction ecosystem in Shanghai during the period 2004 and 2014.



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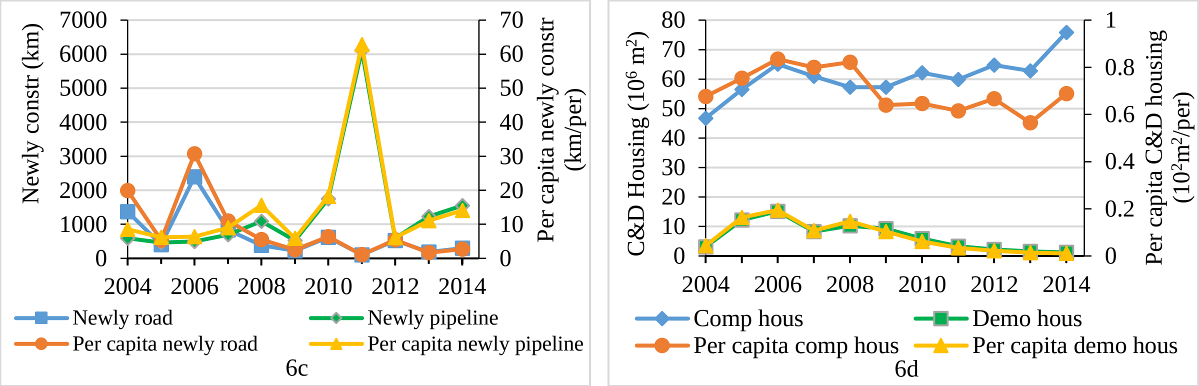

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Fig. 6 C&D activities and products of construction ecosystem in Shanghai, 2004-2014

It is inferred that new construction of building, housing, residence and pipeline is very energetic and constantly keeps on a high level (see Fig.6). For instance, newly built building increases from 122.9 billion m^2 to 180.1 billion m^2 from 2004 to 2014. The length of newly built pipelines expanded from 587 km in 2004 to 1,547 km in 2014. Although the length of newly built roads in 2014 is only 22% of the total length of roads in 2004, the annually average length of newly built roads still reaches 667.8 km.

Despite the quantity of demolished housing in 2014 is only 38% of the value in 2004, annual demolition areas arrive at 6.59 million m^2. There are two main change trends, namely smooth increase and inverted U-shaped growth (see Fig. 6d). Overall, the amount of building, housing and residence newly built, completed and demolished shows a mild growth trend. Although annual amount of road, pipeline and green land newly built indicates an obvious fluctuation, approximately reaching the summit in 2011.

4.5 C&D waste generation of construction ecosystem

C&D waste generation of construction ecosystem is summarized in Fig.7. It is observed that total waste generation increased by 34% from 8.0 million tons in 2004 to 10.7 million tons in 2014, with an annual average increase of 9.3 million tons. It is estimated that the share of C&D waste experienced a sharp growth by 70% from 1.9 million tons to 327 tons in the same period, with an annual growth rate of 5.47% and an annual value of 2.38 million tons.

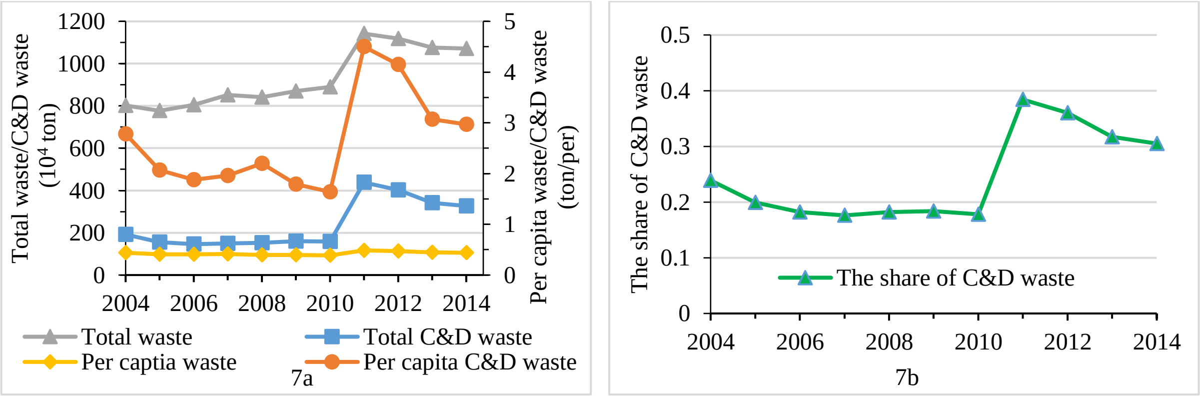

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Fig. 7 C&D waste generation of construction ecosystem in Shanghai, 2004-2014

On average, C&D waste generation contributes to about 26% of total waste generation, while the share of C&D waste rose from 24% in 2004 to 31% in 2014. Meanwhile, C&D waste generation per capital kept a slow growth rate of 7%. It shows a roughly same change trend in the generation of total waste, C&D waste, and C&D waste per capita, and the proportion of C&D waste after 2010, namely the inverted U-shaped structure, all of which generally arrived at the peak in 2011 (see Fig.7a, 7b). There was a dramatic growth in total waste, total and per capita C&D waste, and the share of C&D waste in 2011 because construction dregs began to be statistically regarded as C&D waste in Shanghai from 2011.

4.6 Main drivers of C&D waste generation

In order to uncover principal determinants of C&D generation from various components of urban metabolism, some equations of C&D waste generation with both relatively high goodness of fitting and better significance are reserved in Table 3.

Table 3 Equations of total C&D waste generation during 2004-2014

Component	Explanatory variable	Equation	$A.R^2$	Significance
a: Local and industrial economy	GDP	$y = 0.0001x^2 - 0.1632x + 213.7$	0.5049	equation
	Population	$y = 0.0016x^2 - 6.2747x + 6479.3$	0.6195	dual
	Population density	$y = 0.0006x^2 - 3.9694x + 6464.1$	0.6180*	dual
	Urbanization rate	$y = 7.9813x^2 - 1349.9x + 57191$	0.5486	dual
	Construction value-added	$y = 0.1432x^2 - 11.837x + 396.8$	0.5466	equation
b: Inputs	Steel	$y = 0.0004x^2 - 0.8033x + 516.96$	0.5442	equation
	Concrete	$y = 0.0009x^2 - 3.2677x + 3040.1$	0.5022*	dual
	Employee	$y = 33.36e^{0.0212x}$	0.5361	equation
	Housing investment	$y = -0.0345x^2 + 11.441x - 590.844$	0.6597	equation
	Real estate investment	$y = -0.0088x^2 + 4.9337x - 333.16$	0.5771*	dual
c: Construction activities and	Building newly built	$y = 0.1004x^2 - 25.618x + 1784.8$	0.5637	equation
	Housing demolished	$y = 1.9277x^2 - 47.222x + 426.31$	0.5711	dual
	Newly built housing	$y = 21.887e^{0.0201x}$	0.6037	dual

products	

Note: * means that the coefficient or equation is statistically significant at the confidence level of 10%; “dual” means that that both coefficient and equation are statistically significant at the confidence level of 5% or 10%; “equation” means that only estimated equation is statistically significant at the confidence level of 5% or 10%.

At local or industrial level, it is found that GDP, population, population density, urbanization, and value-added and employment in construction sector distinctly affect C&D waste generation (see Table 3a). With regard to function forms, the relationship between C&D waste generation and local or industrial indicators mainly shows U-shaped or monotonous descending. It is reasonable that the development of local economy and industrial sector, as an initial driver from the demand side, directly expands the needs for products of construction ecosystem, such as building, real estate, housing, and public infrastructure. In turn, additional construction material, water, energy, labor and capital are imported into metabolic process of construction ecosystem, which inevitably produces additional C&D wastes. Next, it shows that the consumption of construction material, water, and energy has a positive impact on C&D waste generation. It can be observed that estimated equations of main construction materials (i.e., steel and concrete) have relatively high goodness of fitting. However, the value of the goodness of fitting for energy and land is small and non-significant. Thus, there is a closer link between C&D waste generation and material flow comparative to land use and energy consumption.

Then, it comes to labor and capital input (see Table 3b). It is expected that growing use of labor means more construction activities, in turn producing additional C&D waste. It is interesting that there is differentiation among estimated equations of capital input. It is reasonable that housing investment have a positive impact on C&D waste, with a high goodness of fitting (0.6597) and monotonous rising trend. However, there is an inverted U-shaped tie between C&D waste generation and the investment in real estate and construction. Contrary to common sense, a monotonous descending connection is found between C&D waste generation and municipal investment. One possible explanation is that wastes arising from municipal construction are not included into C&D waste by current statistic policy.

In addition to demolition activities, new construction activities, such as newly built building, and housing have a positive impact on C&D waste generation (see Table 3). However, it is unexpected that completed housing and newly built pipeline may not be the accurate indicators reflecting C&D waste generation. It is partly due to current C&D waste statistic policy, which in practice does not cover the waste generated in the pipeline construction (belong to municipal construction).

In summary, it can be found that ‘*population*’, ‘*population density*’, ‘*urbanization rate*’, ‘*the consumption of concrete*’, ‘*real estate investment*’, and ‘*housing demolished and newly built*’ are main indicators driving the generation of C&D waste. It involves local economy, construction material flow, capital input and C&D activities, which coincides with the industrial level urban metabolism framework developed in this study.

5. Discussions

It can be inferred from the results of construction material use analysis for Shanghai that total and per capita input of main construction materials, such as steel, wood, and concrete, have been significantly increased between 2004 and 2014, except for a mild decline in the input of concrete. Consequently, there is no evidence of absolute dematerialization trend in construction ecosystem, which means it is still dominantly a material-consumed industry. In contrast to the huge increase in both total and per capita use of construction material, there is only a relatively low growth in the total use of water, energy and land. In particular, there exists a clear decline in the input density of water, energy and land. It may be owing to recent sustainable development policy applied in construction ecosystem in China, which leads to considerable increase in utilization efficiency of water, energy and land.

The results of capital flow analysis show that massive capital has been injected into construction ecosystem in Shanghai from 2004 to 2014. Total investments in construction and municipal engineering have increased by 47% and 57% respectively for the same period, particularly with an impressive growth rate of 173% and 88% in real estate and housing investment. Similarly, although a slight decrease in investment per capita in construction and municipal projects, investment in real estate and housing per capita experienced a significant growth. It can be concluded that construction sector in Shanghai is still a highly capital-intensive industry.

During the period between 2004 and 2014, new construction of building, housing, residence, and pipeline still kept a rapid growth trend, except for a fall in new road construction. Meanwhile, annual quantity of housing completed remarkably increased, whereas the number of housing demolished continuously declined in recent years. Despite of the considerable growth in total production of construction ecosystem, efficiency of construction sector measured by output per capita increased moderately. It can be inferred that construction ecosystem in Shanghai is still less productive compared with its considerable resources input and C&D activities.

In line with massive use of material, water, energy, land, labor and capital in construction ecosystem in Shanghai, a huge quantity of C&D waste also generated. From C&D waste perspective, it reflected the metabolic process of construction ecosystem. The ratio of C&D waste to total waste distinctly grew from 20% in 2004 to 30% in 2014. The link between input flows, C&D activities, and C&D waste generation reveals that *population*, *population density*, *urbanization rate*, *concrete consumption*, *real estate investment*, *demolished and newly built housing* are main drivers explaining C&D waste generation.

In summary, through a metabolism analysis, it is discovered that the construction sector in Shanghai is still material-consumed, labor-intensive, capital-intensive, waste-massive, and less productive. Although input density of water and energy has experienced a considerable decrease owing to sustainable development policy at local and national levels, total consumption of water and energy kept a speedy increase between 2004 and 2014. Thus, it is vital to continuously improve utilization efficiency of material, labor, capital, water, and energy, and strengthen C&D waste management, thus enhancing productivity and sustainability of construction ecosystem.

6. Conclusions

In this study, an industrial ecosystem level metabolism framework was developed by applying the major components (namely, input, output, and urban ecosystem) of a general urban metabolism in specific industrial contexts. The framework was built based on construction ecosystem and tested by an empirical study of the construction ecosystem in Shanghai. By adopting the industrial level metabolism framework, major inputs, outputs, and drivers of the construction ecosystem metabolism were identified. It was found that '*population*', '*population density*', '*urbanization rate*', '*the consumption of concrete and glass*', '*real estate investment*', and '*housing demolished and newly built*' are the main drivers leading to negative outputs, the generation of C&D waste in particular. Overall, construction is a less effective ecosystem in terms of metabolism.

The findings of this research are crucial for understanding urban metabolism of a city in the construction ecosystem context and developing effective policy for improving resource utilization efficiency and C&D waste management. The proposed framework may be used to assess environmental impacts under specific industrial ecosystem background, thereby improving overall urban sustainability. The method used in this study is novel in that: (1) it builds a combined framework of urban metabolism specific to construction ecosystem and its features; (2) it introduces some non-natural elements (e.g. land, labor and capital) to this framework; and (3) it considers the impacts of industrial activities (e.g. C&D activities) on outputs, besides the impacts of natural resource inputs. The proposed method can also be used to explore other negative environmental impact like carbon emission and its determinants.

In order to test the application of the framework, an empirical study on construction ecosystem in Shanghai (China) was conducted in the study. The empirical study shows that the proposed framework can be used to effectively estimate the generation of C&D waste. It is estimated that the generation of C&D waste is 369 billion tons according to the value of population density in 2015 in Shanghai.

In summary, the proposed framework and findings are important to develop effective policies and instruments for improving urban sustainability by exploring the nexus among inputs, outputs and industrial activities in the context of specific industrial ecosystem. It is essential to integrate descriptive urban metabolism analysis with comprehensive statistical methods to capture principal drivers of adverse environment impacts in specific industrial contexts. In a future study, it is necessary to investigate other environmental impacts (e.g. GHG, wastewater) caused by the industrial ecosystem metabolism.

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