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Review

The State of the Art of Material Flow Analysis Research Based on Construction and Demolition Waste Recycling and Disposal

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Abstract: Construction and demolition waste (C&D waste) are widely recognized as the main form municipal solid waste, and its recycling and reuse are an important issue in sustainable city development. Material flow analysis (MFA) can quantify materials flows and stocks, and is a useful tool for the analysis of construction and demolition waste management. In recent years, material flow analysis has been continually researched in construction and demolition waste processing considering both single waste material and mixed wastes, and at regional, national, and global scales. Moreover, material flow analysis has had some new research extensions and new combined methods that provide dynamic, robust, and multifaceted assessments of construction and demolition waste. In this paper, we summarize and discuss the state of the art of material flow analysis research in the context of construction and demolition waste recycling and disposal. Furthermore, we also identify the current research gaps and future research directions that are expected to promote the development of MFA for construction and demolition waste processing in the field of sustainable city development.

Keywords: Material flow analysis (MFA); construction and demolition waste (C&D waste); recycling and reuse; environmental impact

1. Introduction

The construction and operation of buildings occupy almost 40% of the depletion of natural resources and 25% of global waste [1,2]. Construction and demolition waste has become a major source of urban waste and usually accounts for 10–30% of the total waste landfilled [3]. In the European Union (EU), construction waste occupies more than 30% of the total solid waste [4]. It has been widely noticed that construction and demolition waste (C&D waste) has been a vital issue in sustainable city development [5–8]. C&D waste recycling and disposal has received extensive attention from academia, the construction field, and government sectors. Some international and government departments have done extensive work and have set some goals to reduce and recycle C&D waste. For example, The United Nations SDG (Sustainable Development Goals) Goal 11 mentions waste management and Goal 12 points to substantially reducing waste generation through prevention, reduction, recycling, and reuse. Additionally, the EU Waste Framework Directive has set a target at recycling 70% of non-hazardous C&D waste by 2020.

However, the recycling and reuse of C&D waste still has some barriers. One of the barriers is that the C&D waste can include a broad range of materials and the quantitative primary data is not available in some cases [9]. Accurate estimation about quantities of various kinds of construction waste from a building projects is a prerequisite and a critical factor in successful construction waste management [10]. Material flow analysis (MFA) can quantify materials flows and stocks and is beneficial for the analysis of waste processing. Therefore, the MFA approach has been widely adopted in the quantitative evaluation of C&D waste recycling and disposal [11–13]. For example, material flow analysis has been used in the European waste management system, which includes construction and demolition waste processing [14]. The analysis of municipal solid waste recycling processes sometimes depends on the MFA method [15,16]. Moreover, a sound waste management and recycling system requires a good interpretation about the regulatory framework and the changing environmental implications, and MFA is a good tool to help implement this [17]. MFA also plays an important role in the development of planning and strategies in waste management [12]. In the new emerging economies, the new environmental policies and taxation could be proposed based on evidence from MFA [17]. In recent years, MFA has had some new developments and extensions to provide dynamic, robust, and multifaceted assessment results [18–20]. Material flow usually contains certain time and space scales. When faced with a dynamical and long-term period, dynamic material flow analysis (DMFA) is generally adopted to quantify materials stocks and flows [19,21,22], such as European copper flows [23], timber quantity from 2012 to 2100 [24], and strategic construction and demolition waste management [19]. Additionally, the integration between MFA and its spatial distribution can describe a broader scale of materials social usage and is beneficial for sustainable strategic planning [25] because this integration provides a basis for the formulation of a sustainable development strategy [26]. Furthermore, MFA has been deeply regarding the processing and management of C&D waste from a single waste material [27] and mixed wastes [28], and at regional [18,29], national [28,30], and global scales [31]. For a multifaceted assessment, MFA is combined with other analytical tools and optimal methods. The combination of MFA and Life Cycle Assessment (LCA) can accurately calculate embodied carbon or carbon emissions, and track material flows, which is helpful for estimating the potential impacts of the changes of urban metabolism [2,18,32,33]. An integration framework of MFA and LCA is presented to assess the potential impacts of concrete recycling and metabolism [18]. In some studies, the cost of recycling and reuse of building materials is also considered as an important factor [11,34]. Dahlbo et al. combined MFA, LCA, environmental life cycle costing (ELCC), and best available technology (BAT) approaches to assess the performance of the C&D waste management system [11]. Beyond all that, there are some other combinations for C&D waste processing, such as MFA combined with statistical analysis [35], MFA combined with eco-balancing methods [36], MFA combined with input–output analysis (IOA) [2,37], and so on. Although some C&D-waste-related review articles can be found, such as quantifying C&D waste [38,39], C&D waste management [40–43], and sustainable assessment of construction materials [44], a comprehensive analysis and summary about the state of the art of MFA based on C&D waste is required. In this paper, we will review the development of MFA based on C&D waste and comprehensively analyze and summarize research results.

Our contributions include: (1) analyzing the main academic research articles in academic databases and classifying them into three categories: traditional MFA, extension MFA, and combination MFA; (2) comparing and summarizing related articles about research methods, research objects, and application scopes to verify the research progress and results; and (3) identifying the current research gaps and potential future research directions. We also provide some summarized support to promote the development of MFA for C&D waste in the field of sustainable city development.

Following this introduction section, in Section 2, research methodology will be presented. Section 3 shows some analysis results and summarizes MFA development based on C&D waste in detail, while Section 4 provides some conclusions.

2. Research Methodology

For this systematic review of MFA research based on C&D waste, ("demolition waste" OR "building waste" OR "construction waste") AND ("material flow analysis" OR MFA) was chosen as the keywords for the topic and searches in Web of Science Core Collection, Scopus database, and Engineering Village database. The return results provided 36 articles in the Web of Science core databases, 40 in Scopus, and 31 in the Engineering Village database. After deleting some unfound full-text, non-English, duplicated, and unrelated articles, 28 articles were kept. These articles can be classified into three categories according to their employed methods, including traditional MFA, extension MFA, and combination MFA, as listed in Table 1. From Table 1, the combination MFA was most popular method for C&D waste recycling and disposal because it can provide multidimensional evaluation and analysis. An interesting finding was that all listed articles were from after the year 2000, although MFA was first proposed in 1970s. In 28 studies, there was one review paper about C&D waste quantification, in which Hassan et al. [39] reviewed the research on waste quantification in construction sites. In the next section, we will analyze and summarize the 27 articles in detail, but our discussion is not limited to these 27 papers.

Table 1. 28 An overview of 28 articles classified according to their models and methods.

References	Main Models and Methods	Number of References
[10,14,17,27,28,30,31,45–47]	Material flow analysis (MFA)	10
[19,22,24,25,48,49]	Extension MFA	6
[2,11,18,35–37,50–54]	Multi-Method Combination MFA	11
[39]	Review Literature	1

3. MFA Research Based on C&D Waste Recycling and Disposal

3.1. Traditional MFA Method

MFA can quantify material flows and stocks, so it is always used to analyze a specific waste material. For example, as for metal waste materials, Bertram et al. utilized MFA to quantify copper contents in different solid waste and identify the relevance of multiple waste streams within the copper life cycle [14]. The results showed that copper recycling had theoretically high recovery rates through appropriate technology and the right waste streams; however, because of uncertainties in waste generation and composition, more information about the waste's sources of copper is needed for building sensible strategies [14]. Chong et al. developed a comprehensive framework, using MFA, to assess and calculate the transportation energy used for steel recycling at the design stages of construction [27]. Their MFA framework ensured more accurate energy estimates by describing how materials flow during the extraction, manufacturing, transportation, and installation phases, and thus enabling construction stakeholders to better understand the sustainable material supply chain network [27]. As for non-metal waste materials, cement and concrete waste are the main research objects. Lockrey et al. pointed out that developing countries pay less attention to formal recycling systems and those similar systems replicated from developed nations [47]. Hence, they presented the practical challenges of recycling the C&D waste in Vietnam and adopted MFA to analyze material flows and recycling rates, and as a result, they identified existing recycling logistical bottlenecks [47]. Another similar study was conducted by Tangtinthai et al. [17], in which a comparative MFA between Great Britain and Thailand regarding cement/concrete materials had been proposed to analyze the different practices of the two countries. Also at the country level, Kapur et al. developed a cement stock and flow model based on MFA to construct the American contemporary cement cycle and pointed out that control of the rapid growth of C&D waste desperately required the joint efforts of all relevant stakeholders to minimize the amount of C&D waste disposed in landfills [30]. Cochran et al. utilized MFA to assess C&D cement debris generation and composition in the USA and found the MFA approach would benefit from the accurate estimation regarding the portion of raw material utilization and wastage during the product manufacturing stage [45]. We summarize some articles in Table 2 and list their research purposes, research objects, and research locations to better analyze and compare relevant articles.

Table 2. Summary and analysis of C&D waste processing based on traditional MFA.

Purpose and Description	Research Object	Location
Authors goals were to quantify waste generation rates and copper contents to appraise the correlation of waste streams in the copper life cycle [14].	Copper	Europe
Based on the framework of MFA, a national stock and flow model of cement was established to develop the contemporary cement cycle of the United States [30].	Cement	USA
This paper presents an evaluation of MFA to assess construction and demolition (C&D) debris generation and composition in the USA. The results showed that C&D debris generation would exceed the previous prediction estimated by other predictive methodologies and the more accurate the data sources, the better the results will be [45].	Construction/demolition debris	USA
Authors developed a comprehensive framework using MFA to assess and calculate the transportation energy used for recycling at the design stages of construction [27].	Steel	Global and regional
A quantitative estimation model was developed to increase the accuracy of construction waste estimation, which was based on the mass balance principle, work breakdown structure, and the consideration of four construction waste origins [10].	Quantitative construction waste model	Tangshan
Lockrey et al. presented the practical challenges of recycling C&D waste in Vietnam and adopted MFA to analyze material flows and recycling rates [47].	Concrete	Vietnam
A method for the estimation of dense and heterogeneous building stock was proposed, which considers the material intensity and land occupation. Moreover, this study also analyzes waste flows and predictions for its waste generation in Rio de Janeiro using the MFA approach [46].	Residential building stock	Rio de Janeiro
To improve the estimation accuracy of nonmetallic minerals, a feasible method was proposed, which combined the consumptions of bitumen, bricks, cement, and railways and infers the actual yearly consumption of nonmetallic minerals at national and global levels [31].	Non-metallic minerals	global scale
Through an enhanced MFA at the Italian national level, a functional-cognitive framework was proposed to evaluate the current status of raw materials and waste production, and to improve sustainable waste management within the entire supply chain [28].	Raw materials and waste production	Italy
A comparative MFA between Great Britain and Thailand for cement/concrete materials was proposed to analyze the different practices of the two countries [17].	Cement/concrete	Britain, Thailand

From Table 2, except for some specific materials waste, it is recognized that researchers have achieved some effective assessment methods for mixed wastes, such as construction and demolition debris [45], non-metallic minerals [31], and raw materials and waste production [28]. Moreover, from Table 2, the location of the research is not limited to a small district, but ranging from a city, a country, many different countries, to a global scale. Through MFA, researchers can analyze the wide range of waste types within a wide geographical range, which also proves the flexibility and practicability of MFA regarding waste treatment.

3.2. Extension MFA

MFA has had some new research developments in recent years and has provided some new features to the traditional MFA, such as dynamic material flow analysis, spatial material flow analysis, and continuous MFA.

3.2.1. Dynamic Material Flow Analysis

Dynamic material flow analysis has an obvious characteristic, different with MFA, which is that it considers a time span of years, or even decades. In dynamic material flow analysis, some historic data or historic development models of materials stocks and flows are utilized to evaluate the materials flow and stock in robust scenarios. For example, based on consumption data during 1900–2016, Wang et al. analyzed the current in-use copper stocks and predicted the amount of copper scrap generation until 2031 through dynamic material flow analysis [55]. Serrenho et al. used dynamic material flow analysis to design a stock dynamic flow model for England buildings to assess the embodied and operational emissions between new building constructions and existing building refurbishments [56]. Also using dynamic material flow analysis, Hu et al. analyzed the subsequent effects on the concrete consumption and concrete waste generation during house construction and demolition in Beijing's urban housing system from 1949 to 2050 [19]. They proposed that extending the lifetime of a house can delay the arrival of the C&D waste peak, and C&D waste recycling is strongly recommended for long-term, sustainable C&D waste management [19]. A brief summary of some articles related C&D waste is listed in Table 3, including the research description, time span, research object, and background research location.

Table 3. Summary and analysis of C&D waste processing based on DMFA.

Purpose and Description	Time Span (Years)	Research Object	Location
An analysis about the dynamics dwelling floor area and material use was presented for Norway's residential stock through dynamic material flow analysis (DMFA) [22].	1900–2100	Dwelling stock	Norway
Based on the requirement of the stock of housing floor area, Hu et al. utilized DMFA to analyze Beijing's urban residential system and to investigate the subsequent effects of C&D waste and consumption of concrete in three different scenarios [19].	1949–2050	Concrete	Beijing
DMFA was employed to explore the current and future timber quantity in the residential buildings stock and building demolition waste [24].	2012–2100	Timber	Austria
Some construction materials containing engineered nanomaterials (ENMs) were analyzed using DMFA to evaluate the fate and end-of-life phase of ENM, including the ENM use phase, waste collection, waste pretreatment, treatment of residues, and recycling or disposal in Japan's construction sector [48].	1981–2016	ENM	Japan

3.2.2. Spatial Material Flow Analysis

Spatial material flow analysis models have been developed using the spatial allocation of material flows [26]. The relevant challenges regarding spatial material flow analysis have been studied from economic and environmental perspectives [25,26]. There is only one study about C&D waste using spatial material flow analysis, in which two construction indicators and a network-based spatial material flow analysis are presented [25]. Vivanco et al. aimed to accurately describe waste flows, both in terms of mass and spatial attributes, and to allow for the verification of municipal solid waste management's sustainability performance according to the efficiency in converting waste into products and the required transport intensity [25].

3.2.3. Continuous Material Flow Analysis

Schiller et al. [49] presented a continuous MFA concept and a conceptual framework of continuous material flow analysis, which included traditional MFA and a reverse flow. This reverse flow includes the capturing of high-quality waste in deconstruction processing, the processing captured waste into recycling aggregates, and the mixing of these aggregates to new products. Schiller et al. aimed to assess and quantify the entire building material cycle by considering the conversion of bulk nonmetallic mineral into recycled aggregates [49].

3.3. Combination Methods Based on MFA

Through the material flow analysis of building materials, information can be acquired about the current/future reuse, stock, and waste disposal of C&D waste. However, it is difficult to accurately analyze and quantify the exact impact of building materials on the environment and the economy. Therefore, many scholars combine MFA and other methods to achieve an accurate economic and environmental assessment, which further extends the MFA applications. One of typical combination applications is the integration of MFA and LCA methods [2,11,18,53]. Zhang et al. illustrated through the integration between MFA and LCA that the recycling of C&D waste can generate the co-benefits of land use reduction and greenhouse gases mitigation [18]. Teh et al. developed a mixed-unit hybrid LCA to analyze recycled construction materials and used the merging of physical and monetary units of building materials industrial systems to provide a more accurate calculation of embodied carbon and to increase the accuracy of tracking material flows [2]. Heeren et al. proposed a new bottom-up building stock model to evaluate materials impacts at the building level by utilizing GIS data sets, along with MFA and LCA approaches, which provided more accurate data and a higher flexibility in the space and time scales than previous bottom-up building models [53]. Additionally, GIS was also integrated with MFA to demonstrate the spatiotemporal patterns of the material stocks and flows with the development of infrastructure. The high spatial resolution maps included the quantity and composition of waste flow, which could provide a decision-making basis for a municipal government and relevant enterprises in terms of site selection, capacity, cost allocation, and technology selection for demolition and construction waste collection and disposal [50]. There are some different combination approaches for C&D waste recycling and disposal, such as MFA combined with input–output analysis (IOA) [37], MFA combined with environmental life cycle costing (ELCC) [11], MFA combined with statistical entropy analysis [57], etc. A summary of related articles is listed in Table 4, including their research purposes and descriptions, research methods, objects, and research location scale.

We also found some of the same waste materials as research objects, but the processed methods were different, as shown in Table 5. Although some articles focused on the same waste material processing, authors had different purposes and application backgrounds.

Table 4. Summary and analysis of C&D waste processing based on combination MFA.

Research Purpose and Description	Methods	Objects	Location
This paper adopted material flow and ecological energetic analyses to investigate Taipei's urban construction sustainability. It focused on the analysis of materials flows and the evaluation of indicators [54].	MFA + ecological energetic analysis	Urban construction	Taipei
MFA and ecobalancing methods were employed to assess the pros and cons of the usage of recycled aggregates in structural engineering in Germany [36].	MFA + ecobalancing methods	Recycled aggregates	Germany
Authors investigated the occurrence and distribution of heavy metals in municipal solid waste (MSW) and their implications for the integrated MSW management system through MFA and statistical analysis. They also provided a good statistical basis regarding the mass and metals composition of the waste from three MSW treatment facilities in Shanghai [35].	MFA + statistical analysis	Heavy metals	Shanghai
A new framework for policy formulation and analysis is proposed by the integration MFA and system dynamics. This framework includes the supply and demand model and the recycle and filled soil site capacity model to evaluate the future use of construction aggregates [52].	MFA + system dynamics	Construction aggregates	Taiwan
Using a cradle-to-product life cycle method, a thermodynamic framework was proposed to demonstrate the resource consumption of the construction sector in 2001 in Catalonia using material flow analysis (MFA) for the evaluation of material inputs/waste and exergy accounting methodologies for the quantification the total energy inputs/recycled in the sector [51].	MFA + exergy accounting methodologies	Material and energy inputs recycling	Catalonia
Using the complementation of four different methodologies, the holistic environment performance of a common C&D waste management system is evaluated in Finland [11].	MFA + LCA + ELCC + BAT	C&D waste	Finland
MFA was adopted to assess the urban residential buildings material stock and future demolition waste, and then employ IOA to analyze the embodied energy and CO_2 emissions of building materials [37].	MFA + IOA	Material stock and C&D waste	Jakarta and Bandung
An integration of MFA and GIS was proposed to demonstrate the spatiotemporal patterns of the material stocks and flows with the development of infrastructure [50].	MFA + GIS	Material stocks and waste	Shanghai
A bottom-up building stock model was presented to assess volumetric information of material stocks, to evaluate future material flows of individual buildings, and to analyze six scenarios with different assumptions [53].	MFA + GIS + LCA	Building material	Swiss
An integration framework of MFA and LCA was presented to assess the potential impacts of concrete recycling and metabolism under the changes of the Chongqing urban development, where four various concrete recycling routes were analyzed and compared [18].	MFC + LCA	Concrete	Chongqing, China

Note: LCA: Life Cycle Assessment; ELCC: environmental life cycle costing; BAT: best available technology; IOA: input–output analysis.

Table 5. Statistics regarding special materials and research methods.

Materials	Number of Articles	Methods and References
Metal	3	MFA [14,27] MFA + statistical analysis [35]
Aggregates	3	MFA + ecobalancing methods [36] MFA + system dynamics [52] Continuous MFA [49]
Cement/Concrete	7	MFA [17,30,45,47] DMFA [19] MFC + LCA [18] MFA + IOA + LCA [2]
Building Material Stocks and Waste	4	MFA + GIS [50] MFA + IOA [37] MFA + GIS + LCA [53] MFA [46]

4. Conclusions

Based on the above analysis, a few consensuses can be drawn from the some analyzed articles One of them is that the MFA validity can be improved by using comprehensive data sources and data accuracy [14,45]. However, some waste generation is sometimes ignored or indistinct, such as the wastage in the product manufacturing [45], transportation, storage, and installation stages [27]. Bertram et al. suggested the establishment of a public, open, central data bank to collect all available information about the generation and composition of wastes [14]. The second consensus is that some research recommended effective waste classification should be processed at the construction site, which can achieve emission reduction and effective waste recycling [18,36,58]. However, classification at the construction site could be an expensive and complicated process, which is limited by the classification technology's level, equipment level, workers' skill, waste type purity, processing time, site space, cost, etc. Additionally, it is clear that the potential of the recycling and reuse of C&D wastes is not adequately exploited, and further efforts are urgent [6,12,28], which include national policies and strategies [17,28,42,44], effective analysis methods [12,39], waste processing technologies and management [3,9,11], and so on.

This study analyzes the current MFA application research and developments based on C&D waste processing, and summarizes the research methods, research objects, and application scale. We classify MFA research into three categories: traditional MFA, extension MFA, and combination MFA, and then, discuss their own specialties. From Table 5, it is noticed that the combination methods have received more attention. This is because C&D waste management is a complex project, in which material flow analysis, energy evaluation, green gas emission evaluation, and cost are important analysis elements [18,53,54]. Moreover, in sustainable urban development, single element analysis may not provide an effective basis for existing policy improvement about C&D waste recycling and disposal. Therefore, the combination methods still constitute the mainstream research approach in C&D waste processing and management.

However, the integration of multiple methods, multi-source data acquisition, and multi-source data processing may bring some new challenges. These may help to explain why current research articles and adopted combination methods tend to research a single specific material, and why research location is limited to within a city or a country. Therefore, extending research objects and research position scales in combination methods based on MFA can be a future research direction to provide broad wastes analysis and large-scale policy support.

Urban development is a dynamic process that encourages the exploration of urban C&D waste management from a long-term and dynamic perspective. According to these analyzed articles, it can be found that current dynamic MFA research based on C&D waste still focuses on just one waste material. Although considering some materials' life spans, such as 40 years for infrastructures, 38 years for wooden buildings, 39 years for non-wooden buildings, etc., Suzuki et al. [48] still concentrated on ENM flows, stocks, and waste processing. A research gap is found regarding utilizing dynamic MFA for mixed wastes processing and analysis. Mixed wastes consist of multiple components with different life spans and probability distributions, which will increase the difficulties of data collection and analysis. The difficulties of dynamic MFA for mixed waste is not ignored; nevertheless, its demand is also not ignored.

The next future research direction may be the integration other methods with dynamic MFA for C&D waste recycling and disposal. Dynamic MFA can quantify materials stocks and flows in a dynamical and long-term manner, but the economic and environmental impacts of these materials stocks and flows over certain time spans are ambiguous, which makes them worthy of further research.

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