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Methods of Estimating the Amount of Construction and Demolition Waste: Literature Review from 1993 to 2018

Metody szacowania ilości odpadów budowlanych - przegląd literatury od 1993 do 2018 roku

Over the past 25 years the management of construction and demolition (C&D) waste is becoming a popular research topic. This type of waste often contains valuable materials that can be recycled and utilized to produce new products but much of C&D waste is not managed well and this causes pollution problems. Researchers have established various methods for estimating and managing the amount of C&D waste generated during the life cycle of a project. This paper presents a literature review of C&D waste estimation methods and aims to find the most frequently used method in the past 25 years of literature. This literature review is based on 33 publications and presents estimation methods classified according to criteria developed by Y. Li (2013) and Z. Wu (2014). The methods used by Y. Li (2013) and Z. Wu et al. (2014) were studied and compared with the methods used in research papers either not included in the previous literature reviews or published after the last literature review that was conducted in 2014. The research conducted by Y. Li (2013) outlined three main types of models for quantifying C&D waste: the percentage model (MP), the estimation model based on general project parameters (MPP), and macroeconomic and microeconomic models (ME). In 2014 however, a group of Chinese scientists (Z. Wu, A.T.W. Yu, L. Shen, G. Liu) selected six methods for estimating the amount of C&D waste: site visit method (SV), generation rate calculation method (GRC), lifetime analysis method (LA), classification system accumulation method (CSA), variables modelling method (VM), and other methods (Pm). In contrast to the Li's classification, the classification applied by Wu uses detailed characteristics to differentiate the methods in detail. According to the literature review, the most popular method of estimating the amount of C&D waste is based on the general parameters of the project. This method can be named GRC as per the Wu (2014) classification or MPP and ME as per the Y. Li (2013) classification. The characteristics of the GRC method include those used in both MPP and ME methods. Furthermore, the GRC method was used on both the regional and project levels, while the MPP method was mainly used on the project level and the ME method only on the regional level. The advantage of the method based on the general parameters of a project is the ability to incorporate various project parameters, the one most frequently found in literature being the gross floor area. Estimations based on that parameter were considered the most precise and easiest to conduct. In practice this method was successfully implemented in Spain as the Alcores model and in the UK as the SMARTWaste system. Furthermore, a method based on a project's general parameters was developed by P.V. Saez in 2015 by adding the new parameter of the number of buildings. In conclusion, the literature review determined that the most frequently used method in research papers published during the last 25 years for estimating an amount of C&D waste is the method based on the general parameters of a project.

Keywords: **construction and demolition waste, methods of estimating amount of construction and demolition waste, models for quantifying C&D waste**

Introduction

The problem of waste generation, including construction and demolition waste, is a worldwide problem that has been addressed by many scientific studies. According to Eurostat statistics, 28 EU member states and Iceland, Liechtenstein, Norway, Montenegro, the former Yugoslav Republic of Macedonia, Kosovo, Serbia and Turkey produced 2.5 billion tonnes of waste in 2016, of which 13.4% was construction waste [1]. In Poland, according to a survey conducted by the Central Statistical Office (GUS), the fifth largest amount of waste in 2017 was construction and demolition waste [2]. The amount of construction waste can be minimised by, among other things, proper management of waste material on the construction site. A construction waste management plan can be adjusted better if the amount of waste is known. In order to determine the most effective methods of estimation of the amount of waste, the paper discusses 33 studies published in the last 25 years. The paper presents methods selected in the literature review by Wu et al. [3], Y. Li [4], and other scientific publications. Yashuai Li identified three main methods of estimating the amount of construction waste generated: (1) percentage method (MP), (2) estimation method (MPP), and (3) macroeconomic and microeconomic methods (ME) [4]. A group of Chinese scientists (Z. Wu, A.T.W. Yu, L. Shen, G. Liu), who analysed 57 scientific publications from 1993 to 2013, enumerated six methods for estimation of the amount of construction waste: (1) methods based on site visits (SV), (2) generation rate calculation (GRC), (3) lifetime analysis (LA), (4) classification system accumulation (CSA), (5) variables modelling method (VM), and (6) other methods (Pm). Each of the above mentioned methods can be applied in a construction project in combination with other methods [3]. Some of these methods, despite different names, share common characteristics, as shown in Table 1 that compares these methods.

1. Division of methods for estimating the amount of construction and demolition waste

The following division of the methods for estimating the amount of construction and demolition waste is based on two literature reviews conducted by Wu et al. (2014) and Li (2013). The literature references given for each method are publications from the last 25 years. Five scientific studies have been published in world literature on the methods of estimating the amount of construction and demolition waste after the last literature review conducted by Wu et al. (2014). The characterization of the selected methods was extended by the equations presented in the source texts.

1.1. Percentage method

Percentage method (MP) is a method that can be used to estimate the total amount of waste generated during construction works for a given construction project using a percentage of the total amount of materials used in this project.

By examining a selected group of building structures, it is possible to obtain a mean percentage of waste from the total amount of construction materials used during building these structures, which is used to estimate the total amount of waste generated during subsequent similar construction works [4]. The MP method was used by Bossink and Brouwers in the Netherlands, where from April 1993 to June 1994, the total amount of construction waste obtained from five new building construction projects was analysed [5]. The first construction project consisted of eight detached houses; the second - six detached houses; the third - 136 flats; the fourth - 16 detached houses; and the fifth - 18 detached houses. During the research, waste materials were selected and weighed, which allowed for creating a complete list of different types of construction waste. The study compared the amount of waste for each building material with the amount of material purchased, which showed that waste from the building structure accounted for 1 to 10% of the purchased materials [4, 5]. The advantage of the MP method is the accuracy of estimating the amount of waste, while the disadvantage is the need for using a large amount of time and labour intensity. The accuracy of MP makes it effective both in erecting and renovating buildings. No example was found in the literature to use the MP method for demolition works.

1.2. Estimation method

The estimation method (MPP), also termed the estimation model, is based on the general parameters of the building structure. Many examples of the use of this method have been presented in the literature. One of the popular parameters used in the estimation model is the total area of the building structure. Using this parameter, the amount of construction waste is equal to the product of the total area of the structure and the average amount of waste per unit of total area [4]. Studies using this parameter were conducted in Greece by Fatta and Kourmpanis [6, 7], in Thailand by Kofoworol and Gheewal [8], in Spain by Sáez [9], in China by Li [10], and in Shanghai by Xiao [4, 11]. At the time of the survey conducted by Fatta in Greece, statistics with a mean amount of construction waste generated were not available, and therefore these values were derived from the data related to construction activity and the number of demolition permits [6]. The average amount of waste taken from national statistics was used in a study conducted in Florida in 2007 [12] and in Shanghai [11]. The average amount of waste generated [13-15], the type of structure and function of the building [16] and the construction stage [4, 17] were also used as parameters for the MPP method. Below are selected formulae based on building parameters used to estimate the amount of construction waste.

In 2008, Kourmpanis et al. described the equations developed by the National Technical University of Athens (NTUA), where the total area is used to estimate the amount of waste material. The following two equations ((1), (2)) can be used at the project level. The first equation (1) can be used to calculate the amount of construction waste when erecting and/or refurbishment of a building [7]:

$$CW = (NC + OC) \cdot V \cdot D \tag{1}$$

Furthermore, the following equation (2) can be used to calculate the amount of demolition waste:

$$DW = ND \cdot ANF \cdot AS \cdot V \cdot D \tag{2}$$

The mean amount of waste generated during the demolition or construction of a new building was estimated by Fatta from the available statistics from 1991 to 2000, yielding the following assumptions:
- 1,000 m^2 of construction activity generates 50 m^3 of waste,
- 60 m^2 of each demolished building generates 114 m^3 of waste.

In order to convert quantitative data from cubic metre to tonne, mean density of construction waste was considered to be 1.5 tonne/m^3 [6].

The study by Jaime Solís-Guzmán et al. from 2009 described the operation of an estimation model based on general parameters of a construction project, called the Alcores model [14]. The Alcores model, which estimates generation of building waste was developed and successfully implemented in Los Alcores (Seville, Spain). The model has been used for the estimation of waste generated both in the construction and/or refurbishment of buildings and in the demolition works. Based on the above model, the National Decree 105/2008 regulating the production and management of construction waste [18] was drawn up in Spain. This detailed method makes it possible not only to determine the total volume of waste, but also to divide it into three categories: (1) construction waste generated during demolition, (2) waste of construction materials and components, including excess soil and (3) packaging waste. Obtaining these three values is related to the building volume (VAC_i). This value represents a combination of similar materials used in the building. These materials have similar specifications that ensure that the waste generated from them is relatively homogeneous. The volume is calculated using formula (3) [14]:

$$VAC_i = Q_i \cdot CC_i \tag{3}$$

The VAC_i value is used to estimate the quantity of the three above waste categories, both for new construction and demolition works. For new construction works, the volume of waste construction materials and components (VAR_i) is calculated using the equation (4):

$$VAR_i = VAC_i \cdot CR_i = Q_i \cdot CC_i \cdot CR_i \tag{4}$$

Furthermore, when erecting and/or refurbishing buildings, the volume of packaging waste is estimated from the equation (5):

$$VAE_i = VAC_i \cdot CE_i = Q_i \cdot CC_i \cdot CE_i \tag{5}$$

The last step to estimate the amount of waste in a new or refurbished building is to add the result of the multiplication of VAR_i (m^3/m^2) and VAE_i (m^3/m^2) by the building surface (m^2). In the case of demolitions, the volume of demolition waste is estimated using the equation (6):

$$VAD_i = VAC_i \cdot CT_i = Q_i \cdot CC_i \cdot CT_i \tag{6}$$

The last step in estimating volume of demolition waste is to calculate the product of the volume of demolition waste (m^3/m^2) and building surface area (m^2). All coefficients CC_i, CT_i, CR_i and CE_i were estimated based on the Andalusian construction cost database from 2008 and based on expert advice. After determination of the amount of waste, the Alcores model additionally computes the deposit to be paid by the developer to the City Hall for the duration of the new construction or demolition works [14].

Another example of MPP application is the SMARTWaste system, which was developed in the UK by Building Research Establishment (BRE). SMARTWaste is based on data from previous construction projects and calculates the amount of waste in 13 categories, for example ceramics, concrete, wood, etc. SMARTWaste is commonly used in the form of a program that helps monitor and create reports related to generation and management of waste or creation of a waste management plan. The use of SMARTWaste during the construction or renovation of a building allows for monitoring of any amount of waste, which results in the quantification of the total amount of waste after the completion of the construction works. This has been demonstrated in the studies carried out by Lawson (2001), who examined the process of construction of three buildings. The use of the SMARTWaste system allowed for cost reduction by reusing building materials, thereby reducing the purchase of new materials, and by transporting and disposal of waste [19]. An advantage of SMARTWaste is accuracy, which translates into individual projects and environmental and economic benefits to the country, such as minimization of the amount of waste sent to landfill or financial benefits in terms of lower landfill taxes [4, 20].

The estimation method was also selected as a separate method in the literature review by Wu, called the GRC method [3]. Similar to MPP, the GRC method can be based on the surface area of the building. In calculations by means of the GRC method, the product of the total building surface area and the waste generation factor must be obtained. In 2015, a group of researchers from Spain (P.V. Saez, C. Porras-Amores, M. del Río Merino) added an additional coefficient equal to the number of buildings to the GRC method using the building area [21]. The modified method was applied to new residential construction projects.

An advantage of the estimation method, called MMP or GRC, is the possibility of applying different parameters of the building structure. Using the total area of the building as a parameter offers the opportunities for minimization of the risk of errors in calculations. However, not all equations using the total building area as a parameter are equally accurate. Equations (1) and (2) are used to estimate the amount of non-separated construction waste, thus allowing a risk of error related to the density and dimensions of the material. With the Alcores model or the SMARTWaste system, the exact data are obtained, assigned to the respective waste material. This method has been widely used at both national and project levels. The method is also popular due to its ease of calculation and minimal risk of error because intermediate variable is not used. The literature review by Wu demonstrated that this was the most commonly used method of estimating the amount of construction waste by 2014.

1.3. Macroeconomic and microeconomic methods

Macroeconomic and microeconomic (ME) methods are based on macroeconomic variables needed to predict the total amount of construction waste generated from industry, a region, or a country [4]. Cochran and Townsend (2010) presented a method that analyses the flow of materials, from production to demolition. This method estimated demolition waste based on various historical data on the consumption of construction materials and mean lifetime of these materials. The Cochran's and Townsend's method was used to estimate the amount of construction waste in a large area in the United States [22]. James Y. Wang et al. (2004) compared the number of building permits with mean amount of waste generated during the construction of new buildings and during demolition, thus creating a method of estimation of the amount of waste in Massachusetts, USA [23]. In the research conducted in 2010, Martínez Lage developed a method for estimation of the amount of waste, comparing the population with statistics on new constructions, renovations and demolitions in the region of Galicia, Spain [24]. Furthermore, a macroeconomic method was used in two scientific studies from 1997 and 2003 [25, 26] taking into account the effects of technological changes, price inflation, interaction of various sectors, labour force use, energy consumption, production of materials and even political assumptions [4]. Due to the ME characteristics linked to national statistical data, these methods are not applied to individual construction projects. ME is applicable at a national level or at the level of a region in a country.

1.4. GRC method at a national level

In a literature review carried out by Wu et al. (2014), the GRC method had similar characteristics to those of MPP and ME. The method consists in using a coefficient in the calculations and can be applied to construction, refurbishment and demolition of buildings at regional and project levels. The principle in this method is to obtain a waste generation rate for a specific unit of activity (such as kg/m^2 and m^3/m^2) [3]. Using this method at a national level involves the use of population-based statistics, which provide basic information for a country or region of the country covered by the survey. This method can be used for new and refurbished buildings and for demolitions. Below are some methods of applying GRC at a national level using alternative parameters such as a multiplier per capita and extrapolation of financial value.

- Multiplier per capita

The multiplier per capita is a method based on the method of determination of the amount of municipal solid waste. This method was successfully used in 1993 in Waterloo, Canada, by McBean and Fortin, who used national data from seventeen years on the amount of construction waste divided by population [27]. Consequently, an annual amount of construction waste per capita was obtained, used to estimate the amount of construction waste in the country for the years to come. McBean and Fortin indicated in their study that this method would be more accurate if economic changes in the country are taken into account, which was confirmed in subsequent studies conducted in 1996 by Yost and Halstead [3, 28].

- Extrapolation of financial value

In 1996, Yost and Halstead developed a method reflecting the actual construction activity using the financial value of buildings based on building permits issued. A case study was described, with the amount of plasterboard waste estimated for the area of the United States. The estimation procedure was as follows:

1. Mean weight of plasterboard waste (kg/m^2) was determined based on observations from four building sites.
2. The cost of construction of 72 new buildings and the cost of refurbishment of 107 buildings were then compared to the total area of these buildings, resulting in a value of 1 square metre (\$/m^2).
3. Using national data from 1990, the total financial value of construction works (new and refurbishment) was estimated.
4. Comparison of the values obtained from the first and second points revealed that the relationship between the amount of gypsum waste per square metre (kg/m^2) and the value of a square metre (\$/m^2) could be established using the amount of plasterboard waste for each financial value (kg/\$).

Extrapolation of the financial value in this case uses the financial value of new and refurbished buildings. Consequently, the estimation is related to the structure and is more accurate than the multiplier per capita [3, 28]. However, the results of the estimation using this method shall include the risk of errors due to the use of an intermediate variable.

1.5. Methods based on site visits

With the site visit (SV) method, measurements must be conducted on the construction or demolition sites. Collection of the data on the amount of construction waste may be direct or indirect [3].

- Direct measurement

Direct measurement should be made at the construction site by weighing or measuring the volume of waste, and an appropriate method for calculating the amount of waste for the type of storage should be adopted. In a study carried out by Lau et al. [29], four types of waste storage were identified and appropriate formulae were developed to calculate the volume of waste, as shown below:

– formula (7) used to calculate the volume of waste stored in a prism with a rectangular base

$$V_s = 1/3 \cdot (L \cdot B \cdot H) \quad (7)$$

– formula (8) used to calculate the volume of waste stored in rectangular containers

$$V_g = L \cdot B \cdot H \quad (8)$$

After the calculation of V_s and V_g, the mass of construction waste was obtained by calculating the product of the volume multiplied by waste density. The third type of storage consists in irregular distribution of waste with similar dimensions (e.g. tiles). In order to compute the weight of waste stored in this way, the mean weight of three samples chosen randomly from the total waste should be weighed and estimated, and the mean weight obtained previously should be multiplied by the number of samples. Waste which varies considerably in size should be sorted into several groups of similar sizes so that the mass can be calculated using the method for irregularly arranged waste [3]. The advantage of direct measurement is the accuracy of calculation of the amount of waste, with material density, waste dimensions and the type of storage taken into account, while the disadvantage is time consumption and labour intensity.

- Indirect measurement

Indirect measurement can be made, for example, by recording the load of trucks, together with their capacity. Based on this information, scientists conducting an analysis in Hong Kong [13] obtained the total amount of waste. A similar method was used in Kuwait [30], where the number of trucks arriving at landfills was studied and compared with the records of construction waste processing in a given area [3]. The advantage of the indirect measurement is the short time needed to provide general information on the amount of waste generated, with the disadvantage being the quality of the data obtained, which are not accurate and only roughly reflect the real situation.

1.6. Lifetime analysis

The lifetime analysis (LA) is a method based on the principle of balance between the material used in the construction of a building and that obtained from the demolition of the building. There are two types of this method, linked to life of either buildings or materials [3].

- Lifetime analysis for a building

The analysis of life of a building assumes that the amount of demolition materials is proportional to the amount of materials used for construction of this building [31]. LA in this case is based only on an assumption, as no examples are present in the literature to support this theory in practice. It can be assumed that the accuracy of the estimation of the amount of construction waste obtained during demolition depends on the accuracy of the system that monitors the process of using materials needed for the construction of the building.

- Lifetime analysis for material

A study conducted in the USA [22] estimated the construction waste with the material flow analysed for the life cycle of the building. National data (United States) on the use of building materials and waste generation rate were evaluated based on the amount of building materials purchased in order to estimate the mass of construction waste generated during the construction of buildings. In contrast, historical national data on the use of construction materials and their average lifetime were used to estimate the construction waste generated during demolition. This allowed for calculation of construction waste using the following formula (9):

$$C_w = M \cdot w_c \tag{9}$$

For the calculation of demolition waste, the same assumption as in the lifetime analysis for buildings was employed i.e. the amount of demolition materials (D_w) is equal to the amount of material used for the construction of the building, less the amount rejected during the construction works, as shown in the equation (10):

$$D_w = M - C_w \tag{10}$$

For example, the amount of waste from materials that have a life of 50 years (produced in 1952 and obtained by demolition in 2002) can be calculated as follows (11) [3, 22]:

$$D_{w(2002)} = M_{(1952)} - C_{w(1952)} \tag{11}$$

1.7. CSA method

The CSA method uses existing classification systems [3]. It is based on the GRC method and has been used several times in recent years [14, 15, 32]. A characteristic feature of the CSA method is the development of a waste classification system that can be used in an existing system, such as the system for calculating the budget of construction projects or the European Waste List (EWL) [3]. In 2009, Solis-Guzman et al. used the CSA method, with the waste classification system based on the Spanish system for calculating the budget of the construction project. This means that the names of the chapters and subsections corresponded to the names and hierarchy of the Spanish system for calculating the budget of the construction projects. With this design of the system, the waste from individual materials was estimated and finally totalled up to obtain the total amount of waste. In the following years, other researchers used the waste classification system based on EWL [15, 32]. The system allowed them to obtain information about various waste materials which have different properties and require different handling. Consequently, the researchers obtained data which were used to develop the construction waste management plan. The benefit of the CSA method is the clear classification of waste, which allows for precise estimation of the amount of separated construction waste. If the CSA method is based on the existing and proven in practice classification system, it minimizes the risk of errors. The CSA method was chosen in the literature because of the method of waste classification based on existing classification systems. However, the evaluation of waste in the CSA method is based on an estimative method.

1.8. VM method

The VM method is emphasized in the literature due to taking into account factors affecting generation of construction waste. These factors may vary depending on e.g. construction budget, building characteristics, or building regulations. Predicting the amount of construction waste according to this method begins with determination of the factors that will be used in the calculations [3]. A study conducted in 2010 [33] assumed that the total amount of construction waste obtained at a given stage of construction is the sum of the amount of waste generated from each construction activity performed at the same stage of construction. This principle was called 'Waste generation based on activities'. The study identified five groups of factors affecting generation of construction waste:

(1) factors related to the type of activities performed during the construction and/or refurbishment of the building;
(2) factors related to workers and construction equipment;
(3) factors related to construction materials and their storage;
(4) factors related to the location of the plot and weather conditions;
(5) the company's policies.

The VM method may be more precise if detailed observations are applied during the construction works in order to collect as many factors as possible and establish relationships between each other [3, 33]. The VM method helps understand the relationship between individual factors and, consequently, to improve management of construction waste.

1.9. Other methods

In scientific research on the calculation of the amount of construction waste, other methods have also been used in addition to those described above. For example, in 2006, Shi and Xu [34] estimated concrete waste using data on annual cement production and total building area. Since cement is a component of concrete and its production is recorded, it was possible to estimate the amount of concrete waste by having data on the content of cement in concrete and concrete loss rates, and then by comparing these values to building surface area. Another example is the method used in 2008 by a group of scientists from Hong Kong (J.L. Hao, M.J. Hill, L.Y. Shen), which allows for easy estimation of waste and consists in using a fixed percentage (10%) of the purchased building materials [3, 35]. No other examples of the application of these methods were found in the literature. Therefore, they were grouped as 'Other methods' (Pm).

2. Comparison of methods for estimating the amount of construction waste

In a review of methods for estimation of the amount of construction waste, Li [4] and Wu et al. [3] mostly used the same scientific publications. It is obvious, therefore, that despite different names, the methods they analysed coincide. The classification used by Wu, in contrast to that presented by Li, differentiates between the methods in detail, providing their better characterization. Table 1 presents selected publications from the two above literature reviews [3, 4] and additional scientific studies published after the literature review presented by Wu et al., i.e. after 2014 [11, 21, 36-38]. The methods of estimation of the amount of generated construction waste described in these scientific studies [11, 21, 36-38] were compared to the methods selected by Wu and Li and, based on common characteristics, a type of method was proposed. In order to simplify the selection of the most commonly used method in publications over the last 25 years, the names used by Wu and Li were also used for the studies published after 2014. Furthermore, for publications not included by Wu and described in the literature review Li, and vice versa, the type of method was also assigned. With this comparison of the methods for estimation of the amount of construction waste, it was possible to choose the most frequently used method.

In a comparison of 31 selected literature items, it was shown that the most frequently used method according to the Wu classification [3] is the GRC method applied independently (9 publications) or with other methods (13 publications). Other scientific studies used the VM and SV methods (3 publications per method), VM and SV used in combination (1 publication), Pm (1 publication) and LA and Pm used in combination (1 publication). However, according to the classification presented by Y. Li [4], the most frequently used method among 31 selected literature items is MPP (16 publications), ME (7 publications), and MPP and ME used in combination (5 publications). In addition, the MP method (2 publications) was used, and the MPP and MP methods in combination (1 publication). In 5 scientific studies published after the last literature review by Wu (2014), the GRC method was used in all publications, including once with the SV method. Furthermore, the MPP method was used in 2 publications independently and in 2 in combination with the ME method. In total, the GRC method was used in 22 publications, whereas the MPP and ME methods in 29 publications.

Table 1 shows also the use of the methods from both classifications. According to Wu classification (2014), the most commonly used method that is GRC, used in scientific research independently or with other methods, was used at the project level in 7 publications, and at the level of a country or region in 15 publications. Furthermore, the MPP method, used in scientific studies independently or combined with other methods, was applied at the project level in 11 publications and at the level of a country or region in 11 publications. Furthermore, the ME method was used at the level of the selected country or region in a country in 7 publications.

Table 1. **A summary of the reviewed publications and methods for estimating the amount of construction and demolition waste [3, 4]**

No.	Scientific publication	Country	Construction activity that generates waste			Method		Classification by Wu et al. [3]	Classification by Y. Li [4]
			Construction and/or refurbishment of buildings	Demolition of buildings	Infrastructural initiatives	at the project level**	at the regional level***		
1	McBean, Fortin (1993) [27]	Canada	√	√			√	GRC	ME*
2	Bossink, Brouwers (1996) [5]	The Netherland	√			√		SV	MP
3	Yost, Halstead (1996) [28]	United States	√				√	SV + GRC	ME*
4	Poon (1997) [31]	Hong Kong		√			√	GRC + LA	MPP*
5	Bruvol, Ibenholt (1997) [25]	Norway	√				√	VM*	ME
6	Fatta et al. (2003) [6]	Greece	√	√		√		GRC	MPP
7	Ibenholt (2003) [26]	Norway	√	√			√	VM*	ME
8	Kartam et al. (2004) [30]	Kuwait	√	√			√	SV + GRC	MPP*
9	Poon et al. (2004) [13]	Hong Kong		√		√		SV	MPP
10	Wang et al. (2004) [23]	United States	√	√			√	GRC + CSA	ME
11	Shi, Xu (2006) [34]	China	√	√			√	GRC + LA	ME + MPP*
12	Cochran et al. (2007) [12]	United States	√	√			√	SV + GRC	MPP
13	Hao et al. (2008) [35]	Hong Kong	√			√		Pm	ME + MPP*
14	Kourmpanis et al. (2008) [7]	Greece	√	√		√		GRC	MPP
15	Lau et al. (2008) [29]	Malaysia	√			√		SV	MP*

16	Kofoworola and Gheewala (2009) [8]	Thailand	√				√	GRC	MPP
17	Solis-Guzman et al. (2009) [14]	Spain	√	√		√		SV + GRC + CSA	MPP
18	Cochran, Townsend (2010) [22]	United States	√	√	√		√	LA + Pm	ME
19	Lage et al. (2010) [24]	Spain	√	√	√		√	GRC	ME
20	Wimalasena et al. (2010) [33]	Canada	√			√		VM	MPP + ME*
21	Coelho, de Brito (2011) [32]	Portugal	√	√			√	SV + GRC + CSA	MP + MPP*
22	Katz, Baum (2011) [17]	Israel	√			√		SV + VM	MPP
23	Llatas (2011) [15]	Spain	√			√		SV + GRC + CSA	MPP
24	Huang et al. (2011) [16]	Taiwan		√			√	GRC + SV*	MPP
25	Saez et al. (2012) [9]	Spain	√			√		GRC + CSA	MPP
26	Li et al. (2013) [10]	China	√			√		SV + GRC	MPP*
27	Xiao, Ding (2014) [11]	Shanghai	√	√			√	GRC*	MPP*
28	Saez et al. (2015) [21]	Spain	√				√	GRC*	MPP + ME*
29	Lu et al. (2016) [36]	China	√	√	√		√	GRC*	MPP + ME*
30	Ram, Kalidindi (2017) [37]	India	√	√			√	GRC*	MPP*
31	Saez et al. (2018) [38]	Spain	√			√		GRC + SV*	MPP*

* assignment of the method suggested by the author
** for individual projects
*** for the selected country or region in the country

GRC, MPP and ME methods were chosen in two different literature reviews. Therefore, it is important to demonstrate their interrelations (Table 2). Due to the detailed classification presented by Wu, the GRC method was treated as a leading method to which the methods specified by Li were compared.

Table 2. **The relation of methods classified by Li (2013) to the most commonly used methods classified by Wu (2014) based on the summary of the reviewed publications in the Table 1**

The most commonly used methods according to the classification by Wu [3] compared to Table 1	Number of publications	Combination of methods classified by Li [4] compared to Table 1	Number of publications
GRC	9	MPP	5
		ME	2
		MPP + ME	2
GRC combined with other methods	13	MPP	9
		MPP + ME	1
		MPP + MP	1
		ME	2
Total	22		22

Table 2 shows that of 22 scientific studies based on the GRC method, there were 14 studies using the MPP method, 3 studies using both the MPP and ME methods, 1 study using both the MPP and MP methods and 4 studies using the ME method. In total, of 22 publications based on the GRC method according to the Wu classification (2014), 18 were based on the MPP method and 4 on the ME method according to the Y classification (Li (2013)). Furthermore, the characterization of the GRC method includes the characteristics of the two MPP and ME methods. This makes it possible to assume that the GRC method, which is an estimation method based on general parameters of a construction project, is the most frequently used method of estimation of the amount of construction and demolition waste in literature.

Conclusions

In the presented literature review, the most commonly used method of estimating the amount of construction waste used in publications from the last 25 years was chosen. According to the classification by Wu (2014), this is the GRC method, whereas according to the classification by Li (2013), two methods were the most popular: MPP and ME. Characterization of the GRC method includes the characteristics of the MPP and ME methods. The MPP method is an estimation method based on general parameters of buildings [4]. According to the literature review, the MPP is mainly used for individual construction projects, although in combination with other methods (ME and MP), it is applied at the level of a country or a region. The ME method is a macroeconomic and microeconomic method used to estimate the total amount of construction waste at the national level [4], as demonstrated in Table 1. However, the GRC method, which is also an estimation method based on general parameters of buildings [3], can be applied both at the level of a single project and at the level of a selected country or region in a given country. The advantage of the estimation method is the opportunity for using different parameters of the building. A popular parameter used in the estimation method is the total area of the building. The use of the total area of the building as a parameter helps minimize the risk of calculation errors. In a study conducted by P.V. Saez (2015), the estimation method was developed by adding another parameter of the number of buildings. In practice, the estimation method is termed in Spain the Alcores model and in the UK - the SMARTWaste system. The use of the estimation method in studies published after 2014 [11, 21, 36-38] confirms the need for this type of methods and shows that it is the most frequently used method of estimation of the amount of construction and demolition waste, used in scientific studies in the last 25 years.

The list of abbreviations and symbols

Abbreviation		Definition
ANF	-	mean number of storeys per demolished building
AS	-	mean area of the building to be demolished (m^2)
B	-	the width of the base of the prism
BRE		(*Building Research Establishment*)
CC_i	-	ratio of amount of "i" material in volume (VAC) in m^3/Q_i in the appropriate unit
CE_i	-	VAC to VAE conversion factor (dimensionless factor)
CR_i	-	VAC to VAR conversion factor (dimensionless factor)
CSA	-	a method based on the existing classification systems (*Classification System Accumulation*)
CT_i	-	VAC to VAD conversion factor (dimensionless factor)
CW	-	amount of construction waste (tonnes)
C_w	-	amount of construction waste generated during construction of the building
D	-	waste density (t/m^3)
DW	-	amount of demolition waste (tonnes)
D_w	-	the amount of waste generated during demolition
ELO	-	European Waste List (*European Waste List*)
GRC	-	an estimation method based on the calculation of the coefficient (*General Rate Calculation*)
H	-	height
L	-	the length of the base of the prism
LA	-	lifetime analysis (*Lifetime Analysis*)
M	-	all materials purchased in the country
ME	-	macroeconomic and microeconomic methods
MP	-	percentage method

MPP - estimation method
NC - area of new construction (m^2)
ND - number of buildings destroyed
NTUA - National Technical University of Athens
OC - area of additional structure or extension (m^2)
Q_i - amount of 'i' element per proper unit (m, m^2, m^3, kg or units/m^2)
Pm - other methods
SV - methods based on site visit
V - volume of construction waste per area of 100 m^2 (m^3 per 100 m^2)
VAC_i - the volume (m^3) of 'i' material per square metre (m^3/m^2)
VAD_i - volume of demolition waste for 'i' material (m^3/m^2)
VAE_i - volume of packaging waste for 'i' material (m^3/m^2)
VAR_i - volume of waste from materials and construction components, including excess spoils, for 'i' material (m^3/m^2)
V_g - the volume of construction waste stored in rectangular containers
VM - the method consisting in determination of factors affecting generation of waste (*Variables Modelling*)
V_s - the volume of construction waste stored in a prism with a rectangular base
w_c - the mean amount of construction waste and materials purchased but not consumed during construction, as derived from national statistics

References

[1] Eurostat, Generation of waste by waste category, hazardousness and NACE Rev. 2 activity, Environment and Energy, 18-12-2018.

[2] Główny Urząd Statystyczny (GUS), Analizy statystyczne, Ochrona Środowiska 2018, 143.

[3] Wu Z., Yu A.T.W., Shen L., Liu G., Quantifying construction and demolition waste: An analytical review, Waste Management 2014, 34, 1683-1692.

[4] Li Y., Developing a Sustainable Construction Waste Estimation and Management System, A Thesis Submitted to The Hong Kong University of Science and Technology in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Civil Engineering, Hong Kong, 2013, UMI Numer: 3613928.

[5] Bossink B.A.G., Brouwers H.J.H., Construction waste: quantification and source evaluation, J. of Con. Eng. and Management 1996, 122(1), 55-60.

[6] Fatta D., Papadopoulos A., Avramikos E., Sgourou E., Moustakas K., Kourmoussis F., Mentzis A., Loizidou M., Generation and management of construction and demolition waste in Greece - an existing challenge, Resources, Conservation and Recycling 2003, 40(1), 81-91.

[7] Kourmpanis B., Papadopoulos A., Moustakas K., Stylianou M., Haralambous K.J., Loizidou M., Preliminary study for the management of construction and demolition waste, Waste Management & Research 2008, 26, 267-275.

[8] Kofoworola O.F., Gheewala S.H., Estimation of construction waste generation and management in Thailand, Waste Management 2009, 29(2), 731-738.

[9] Saez P.V., Del Río Merino M., Porras-Amores C., Estimation of construction and demolition waste volume generation in new residential buildings in Spain, Waste Management and Research 2012, 30(2), 137-146.

[10] Li J., Ding Z., Mi X., Wang J., A model for estimating construction waste generation index for building project in China, Resources, Conservation and Recycling 2013, 74, 20-26.

[11] Xiao J., Ding T., Estimation of building-related construction and demolition waste in Shanghai, Waste Management 2014, 34, 2327-2334.

[12] Cochran K., Townsend T., Reinhart D., Heck H., Estimation of regional building-related C&D debris generation and compositions: Case study from Florida, Waste Management 2007, 27, 921-931.

[13] Poon C.S., Tit W.Y.A., Ching S.S., Cheung E., Minimizing demolition wastes in Hong Kong public housing projects, Construction Management and Economics 2004, 22, 799-805.

[14] Solís-Guzmán J., Marrero M., Montes-Delgado M.V., Ramírez-de-Arellano A., A Spanish model for quantification and management of construction waste, Waste Management 2009, 29, 2542-2548.

[15] Llatas C., A model for quantifying construction waste in projects according to the European waste list, Waste Management 2011, 31(6), 1261-1276.

[16] Huang R.-Y., Yeh L.-H., Chen H.-H., Lin J.-D., Chen P.-F., Sung P.-H., Yau J.-T., Estimation of construction waste generation and management in Taiwan, Advanced Materials Research 2011, 243-249, 6292-6295.

[17] Katz A., Baum H., A novel methodology to estimate the evolution of construction waste in construction sites, Waste Management 2011, 31(2), 353-358.

[18] Rząd Hiszpanii - Ministry of the Presidency, 2008, Madrid, Spain, National Decree 105/2008, February 1, which Regulates the Production and Management of Construction and Demolition Waste.

[19] Lawson N., Douglas I., Garvin S., McGrath C., Manning D., Vetterlein J., Recycling construction and demolition wastes - a UK perspective, Environmental Management and Health 2001, 12(2), 146-157.

[20] SMARTWaste, http://www.smartwaste.co.uk/home (04.07.2017).

[21] Saez P.V., Porras-Amores C., del Río Merino M., New quantification proposal for construction waste generation in new residential constructions, Journal of Cleaner Production 2015, 102, 58-65.

[22] Cochran K.M., Townsend T.G., Estimating construction and demolition debris generation using a materials flow analysis approach, Waste Management 2010, 30, 2247-2254.

[23] Wang J.Y., Touran A., Christoforou C., Fadlalla H., A systems analysis tool for construction and demolition wastes management, Waste Management 2004, 24, 989-997.

[24] Lage I.M., Abella F.M., Herrero C.V., Ordóñez J.L.P., Estimation of the annual production and composition of C&D Debris in Galicia (Spain), Waste Management 2010, 30, 636-645.

[25] Bruvol A., Ibenholt K., Future waste generation, Forecasts on the basis of a macroeconomic model, Resources, Conservation and Recycling 1997, 19, 137-149.

[26] Ibenholt K., Material accounting in a macroeconomic framework, Environmental and Resource Economics 2003, 26(2), 227.

[27] McBean E.A., Fortin M.H.P., A forecast model of refuse tonnage with recapture and uncertainty bounds, Waste Management Resources 1993, 11(5), 373-385.

[28] Yost P.A., Halstead J.M., A methodology for quantifying the volume of construction waste, Waste Management Resources 1996, 14(5), 453-461.

[29] Lau H.H., Whyte A., Law P.L., Composition and characteristics of construction waste generated by residential housing project, Int. J. Environ. 2008, 2(3), 261-268.

[30] Kartam N., Al-Mutairi N., Al-Ghusain I., Al-Humoud J., Environmental management of construction and demolition waste in Kuwait, Waste Management 2004, Dep. of C. Eng., Kuwait Un., 24, 1049-1059.

[31] Poon C.S., Management and recycling of demolition waste in Hong Kong, Waste Management Resources 1997, 15(6), 561-572.

[32] Coelho A., de Brito J., Distribution of materials in construction and demolition waste in Portugal, Waste Management Resources 2011, 29(8), 843-853.

[33] Wimalasena B.A.D.S., Ruwanpura J.Y., Hettiaratchi J.P.A., Modeling construction waste generation towards sustainability, Construction Research Congress 2010: Innovation for Reshaping Construction Practice, American Society of Civil Engineers, Banff, AB, Canada 2010, 1498-1507.

[34] Shi J., Xu Y., Estimation and forecasting of concrete debris amount in China, Resour. Conserv. Recycl. 2006, 49(2), 147-158.

[35] Hao J.L., Hill M.J., Shen L.Y., Managing construction waste on-site through system dynamics modelling: the case of Hong Kong, Eng. Constr. Architec. Manage. 2008, 15(2), 103-113.

[36] Lu W., Webster C., Peng Y., Chen X., Zhang X., Estimating and calibrating the amount of building-related construction and demolition waste in urban China, International Journal of Construction Management 2016, DOI:10.1080/15623599.2016.1166548.

[37] Ram V.G., Kalidindi S.N., Estimation of construction and demolition waste using waste generation rates in Chennai, India, Waste Management & Research 2017, 35, 6, 610-617.

[38] Saez P.V., Astorqui J.S.C., del Río Merino M., Moyano M. del P.M., Sanchez A.R., Estimation of construction and demolition waste in building energy efficiency retrofitting works of the vertical envelope, Journal of Cleaner Production 2018, 172, 2978-2985.

Streszczenie

W literaturze można odnaleźć wiele prac naukowych dotyczących metod szacowania ilości wytwarzanych odpadów budowlanych. W celu znalezienia najczęściej stosowanej metody szacowania ilości generowanych odpadów budowlanych w artykule zaprezentowano przegląd 33 badań naukowych opublikowanych od 1993 do 2018 r. Zaprezentowane metody pogrupowano według klasyfikacji Y. Li (2013) i Z. Wu (2014). Yashuai Li (2013) wyselekcjonował trzy główne metody szacowania ilości generowanych odpadów budowlanych: metodę procentową (MP), metodę szacunkową (MPP) oraz metodę makroekonomiczną i mikroekonomiczną (ME). Natomiast grupa naukowców z Chin (Z. Wu, A.T.W. Yu, L. Shen, G. Liu) w przeglądzie literatury opublikowanym w 2014 r. wyszczególniła sześć metod szacowania ilości odpadów budowlanych: metody oparte na wizytowaniu budowy (SV), metody obliczania współczynnika (GRC), metody analizy długości życia (LA), metody oparte na istniejących systemach klasyfikacji (CSA), metody wyznaczania czynników wpływających na wytwarzanie odpadów (VM) i pozostałe metody (Pm). Klasyfikacja zastosowana przez Wu, w przeciwieństwie do klasyfikacji użytej przez Li, szczegółowo różnicuje metody, dzięki czemu lepiej jest określona ich charakterystyka. Metody szacowania ilości wytwarzanych odpadów budowlanych w badaniach naukowych opublikowanych po 2014 r. zostały przyrównane do metod Wu i innych oraz Li. Dzięki tak zastosowanemu porównaniu została wyselekcjonowana najczęściej stosowana metoda w ciągu ostatnich 25 lat, którą jest metoda szacunkowa oparta na ogólnych parametrach projektu. Według klasyfikacji Wu i innych (2014), jest to metoda GRC, natomiast według klasyfikacji Li (2013) są to dwie metody - MPP i ME. Charakterystyka metody GRC zawiera cechy charakterystyczne metod MPP i ME. Walorem metody szacunkowej jest możliwość użycia różnych parametrów przedsięwzięcia budowlanego. Najczęściej stosowanym parametrem jest powierzchnia całkowita obiektu budowlanego. Jak wykazano w przeglądzie literatury, metoda GRC została użyta zarówno na poziomie pojedynczych przedsięwzięć budowlanych, jak i na poziomie krajowym. Natomiast metoda MPP została zastosowana głównie na poziomie pojedynczych przedsięwzięć budowlanych, a metoda ME tylko na poziomie krajowym. W przeprowadzonym przeglądzie literatury zostało potwierdzone, że metoda szacunkowa oparta na ogólnych parametrach obiektu budowlanego jest najczęściej stosowaną metodą szacowania ilości wytwarzanych odpadów budowlanych w pracach naukowych opublikowanych w ostatnich 25 latach.

Słowa kluczowe: **odpady budowlane, szacowanie ilości odpadów budowlanych, metody obliczania ilości odpadów budowlanych**