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Waste Reduction Methods Used in Construction Companies with Regards to Selected Building Products

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Abstract: This article presents research that aims to identify waste reduction methods used in the construction industry in relation to the following materials: steel, concrete, masonry products, finishing products (i.e., ceramic, and stone tiles), and wood and the dependence between the use of these methods and the size of the construction company. The research is based on surveys conducted amongst construction site managers in Sharjah, United Arab Emirates. In the research, 13 methods of reducing construction waste were analyzed using Pearson's independence test and the SPSS-26 software. Methods of reducing construction waste were identified. The study determined the frequency with which waste reduction methods in each material group were used, depending on the size of the company. Amongst the 13 methods analyzed, the ones which demonstrate a relationship between frequency of methods and size of the company were identified (for all groups of materials): the use of monitoring systems, reuse of materials within the construction, use of prefabricated elements, adequate storage, and engagement of subcontractors. In the case of the other tested methods, no such relationship was found.

Keywords: construction waste; construction products; construction companies; methods of reducing construction waste; survey research; chi-square test

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Citation: Białko, M.; Hoła, B.; Topolski, M.; Woźniak, Z. Waste Reduction Methods Used in Construction Companies with Regards to Selected Building Products. *Appl. Sci.* **2022**, *12*, 5387. https://doi.org/10.3390/app12115387

Academic Editor: Srinath Perera

Received: 25 April 2022
Accepted: 23 May 2022
Published: 26 May 2022

1. Introduction

Technological progress, which is an inherent element of the development of society, has both positive and negative effects on the environment. One of the areas of the economy that has a huge impact on environmental changes is the construction industry [1], which is a source of a significant amount of waste. According to Eurostat, in 2018, 27 EU member states generated 2.3 billion tonnes of waste, 35.9% of which was construction waste [2]. In the United Arab Emirates, the latest (2021) government statistics show that in 2016 the amount of collected waste amounted to approx. 35 million tonnes. It has also been noted that since 2015 the amount of collected waste has increased by around 19% due to a significant increase in the amount of construction waste. The construction waste collected in Dubai accounted for about 56% of all waste, in Abu Dhabi for about 28%, in Sharjah for about 8%, and in the remaining Emirates for about 8% of all waste. In 2016, only as a result of construction and demolition works, the share of construction waste in the total amount of waste was about 66%, i.e., about 22 million tonnes [3]. The amount of construction waste can be minimized through its proper management. The effectiveness of construction waste management depends on many things, including the correct identification of the sources and factors that influence the production of waste and the use of waste reduction methods. The most desirable method of reducing construction waste is to minimize its amount by reducing the consumption of construction products that generate waste.

The aim of the research and analyses presented in the article is to learn about:

1. which waste reduction methods are most often used in the construction industry in relation to: steel, concrete, masonry products, finishing products, and wood;
2. whether the application of individual waste reduction methods depends on the size of the construction company.

The research and analyses were based on surveys conducted among construction site managers. The research was carried out in companies which, in terms of the number of employees, were classified into five groups: from 1 to 9 employees (1), from 10 to 49 employees (2), from 50 to 99 employees (3), from 100 to 249 employees (4), and 250 employees or more (5). The studies were conducted in the Emirate of Sharjah in the United Arab Emirates (UAE). The analyses were performed with the use of the SPSS 26 statistical software.

2. Literature Review

2.1. Definition of Construction Waste

There are several definitions of construction waste in the subject literature. One says that construction waste is the primary waste stream generated by modern society, the amount of which is increasing with worldwide urbanization [4]. Generally, construction waste can be defined as materials produced "by the production, construction, renovation, or demolition of structures" [5], as well as during excavation work [6]. According to Building Research Establishment (BRE) (1978), construction waste is defined as "the difference between materials ordered and those used to build a building". A more precise definition was given by A. Dania [7], and it reads: "construction and demolition waste is a complex waste stream, which consists of a wide range of materials, such as rubble, earth (author's note—cut and fill), concrete, steel, wood, and a mixture of materials resulting from a variety of construction activities including ground removal, demolition, road works, and building refurbishment created during the construction, renovation, and demolition of buildings, roads, and bridges." [8]. According to studies by W. Biały and A. Kuboszek, construction waste generated throughout the life cycle of a building "is waste generated during the construction, renovation, reconstruction, superstructure, and demolition phases of a building object". [9]. In Polish legislation, in the Regulation of the Minister of the Environment from 9 December 2014 regarding the cataloguing of waste, waste was classified into 20 groups—depending on the source of its origin. Construction waste is defined as "waste from the construction, renovation, and dismantling of buildings and road infrastructure (including ground and soil from contaminated areas)" [10].

The federal law of the United Arab Emirates defines waste as all toxic and non-toxic waste, including nuclear waste, that must be disposed of and utilized in accordance with the law. It includes solid waste, such as municipal, industrial, agricultural, medical, and construction waste [11]. In Abu Dhabi, construction waste is defined in a very detailed way as a non-segregated product (other than an asbestos-containing product) that comes from: (1) the demolition, assembly, construction, renovation, or reconstruction of buildings other than: chemical plants, waste disposal facilities, mines, container renovation plants; (2) the construction, replacement, repair, or modification of infrastructure, including products such as: bricks, concrete, paper, plastic, glass, metal, and wood (including unsorted wood but excluding wood chemically treated with such agents as: chromium copper arsenate, creosote, organic solvents, and impregnating agents). Construction waste does not include soil obtained during the removal of land for construction [12]. According to local Dubai law, construction waste is construction and demolition waste that contains materials such as wood, steel, concrete, dust, sand, etc. [13].

A report prepared by the Symonds group on behalf of the European Union Commission in 1999 defines construction waste as a wide range of products that result from the complete or partial demolition of buildings/roads, the construction of buildings/roads, land removal, construction works, and restoration works on buildings/roads [14]. The definitions cited above show that construction waste is an unnecessary material generated during all construction activities [15].

2.2. Construction Waste Classification

Many factors can be used to classify construction waste. One of them is legislation applicable in a country or a group of countries. The European Union has developed the European Waste Catalog for its Member States. This catalog lists construction waste, which includes the following products: (1) concrete, bricks, ceramic tiles, ceramics, and gypsum-based products; (2) wood; (3) glass; (4) plastics; (5) asphalt, tar, and tarred products; (6) metals (including metal alloys); (7) cut and fill soil; (8) insulation products; (9) mixed construction waste; and (10) hazardous construction waste [14,16].

In Poland, in the National Waste Management Plan for 2022, which is in line with the guidelines of Directives 2018/851 and 2008/98/WE, waste was also divided. The fourth category is "other" waste, which includes "waste from the construction, renovation, and disassembly of buildings and road infrastructure".

In the UAE, categories of construction waste vary in each individual emirate. There are three types of construction waste in Sharjah: mineral construction, mixed construction, and asphalt [17]. Abu Dhabi also lists three categories of construction waste: (1) non-toxic solid waste (biodegradable solid waste, non-recyclable and non-biodegradable solid waste, recyclable and biodegradable solid waste); (2) non-toxic liquid waste; and (3) toxic waste (liquid and solid). In contrast, construction waste in Dubai is classified into four main categories: municipal, green, construction, and hazardous [13].

Research carried out by the Deloitte group at the request of the European Union Commission in 2015 which aimed to examine the current situation in the field of construction and demolition waste management in EU Member States showed that in most Member States the main types of waste are concrete, bricks, tiles, and ceramics [18]. According to studies carried out in Canada, the most common construction waste includes: concrete, steel, brick, insulation products, glass, ceramics, aluminum, plastic, paints, wood, gypsum board, cardboard, and asbestos-containing products [5].

Construction waste can be also classified as per the mass of generated waste [3], composition [5], properties of the products [19], or the size of a company that generates it [20].

2.3. Construction Waste Reduction Methods

Based on the literature review, it can be assumed that the following methods of reducing construction waste are used in construction companies: (1) adequate storage to protect products against mechanical damage and weather conditions; (2) ordering products as per size and in the right quantity, thus reducing the need to trim them; (3) training employees in waste management; (4) the use of monitoring systems; (5) proper transportation and unloading to prevent damage to products; (6) appropriate involvement of subcontractors; (7) site security to protect a construction site against theft or vandalism; (8) the use of prefabricated elements, which minimizes the amount of waste that is generated when producing elements on a construction site; (9) the waste segregation on site; (10) the designation of a waste segregation place for its preparation for recycling or reuse; (11) reuse of products within the construction, e.g., wood used several times in formwork, waste concrete used as rubble for temporary roads and sidewalks, or waste steel bars used as markers for landmarks on the construction site; (12) timely delivery of products that reduces the storage time and the risk of damaging them; and (13) a waste management plan that includes the processes and actions needed to manage construction waste [21–24].

Considering the conducted literature review and the local construction solutions for residential and mixed-used buildings, five types of the most common construction waste, for which the research was carried out, were specified. These include: steel, concrete, masonry products, finishing products: ceramic and stone tiles, and wood. The research examines frequency of use of the above-mentioned waste reduction methods in relation to these products and the dependence of their use on five groups of construction companies.

3. Materials and Methods

The research was carried out in construction companies that erect residential and mixed-used buildings, with the number of storeys from one to eight (Figure 1).

(a) (b)

Figure 1. (a) A multi-family residential building in Sharjah with commercial premises on the ground floor and a two-level internal car park [own materials]. (b) A detached single-family house in Sharjah [own materials].

The assessed buildings had the following construction elements:

- cast-in-situ or prefabricated reinforced concrete foundations;
- steel, reinforced concrete, prefabricated or cast-in-situ columns;
- internal walls made of solid concrete blocks, autoclaved aerated concrete blocks, or bricks;
- external walls made of insulated concrete blocks;
- cast-in-situ or prefabricated reinforced concrete floors and roofs;
- steel or cast-in-situ roof structures.

In buildings with over eight storeys (Figure 2), no prefabricated elements are used. The structure of such buildings is as follows:

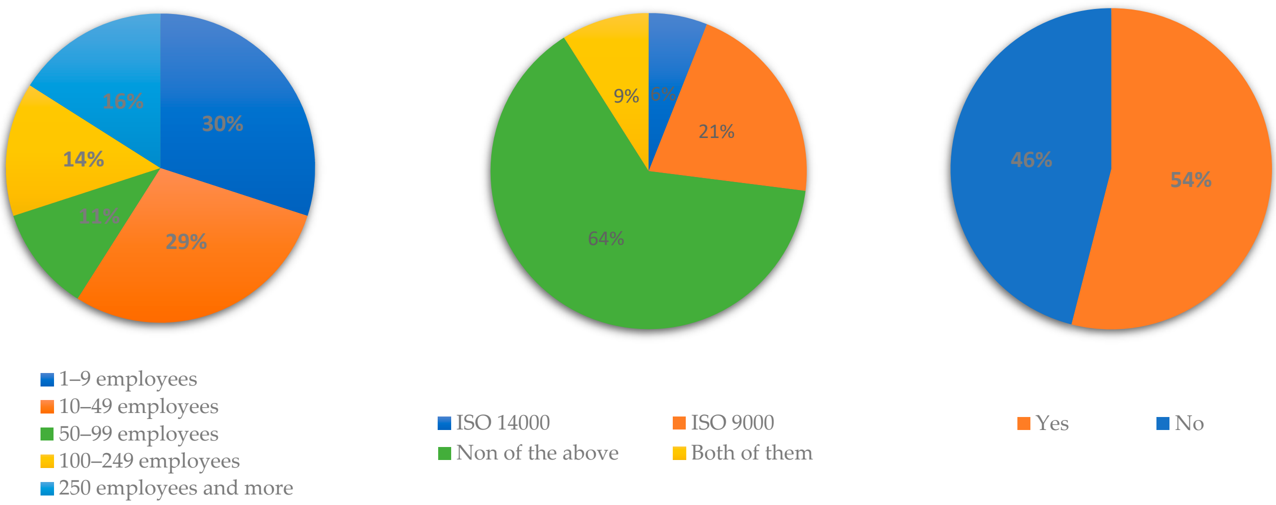
- cast-in-situ foundations;
- cast-in-situ columns;
- internal walls made of solid concrete blocks, autoclaved aerated concrete blocks, or bricks;
- external walls made of insulated concrete blocks;
- cast-in-situ floors and flat roofs;
- cast-in-situ roofs.

3.1. The Size and Structure of the Studied Population

The analyses were based on the results of a survey conducted among engineers employed in 140 construction companies of various sizes. The companies were chosen randomly in one administration area (the Emirate of Sharjah). The research was carried out using the technique of personal interviews and telephone interviews. Figure 3 shows the structure of the surveyed population with regards to the number of employees, ISO certificates, and internal regulations related to waste reduction.

(**a**) (**b**)

Figure 2. (**a**) High-rise buildings under construction in Sharjah [own materials]. (**b**) High-rise buildings under construction in Sharjah [own materials].



(**a**) (**b**) (**c**)

Figure 3. The structure of the surveyed population: (**a**) the number of employees; (**b**) held ISO certificates; (**c**) the internal regulations related to waste reduction.

Figure 3a shows the percentage share of construction companies in the surveyed population with regards to the number of employed people. In the surveyed representative group, 30% of companies employed from 1 to 9 employees; 29% of companies employed from 10 to 49 employees; 11% of companies employed from 50 to 99 employees; 14% of companies employed from 100 to 249 employees; and 16% of companies employed 250 employees or more.

Due to the lack of a consistent construction law in the Emirate of Sharjah [25], a representative sample was also tested in terms of ISO 14000 and ISO 9000 certificates, as well as internal waste management regulations. Figure 3b shows the percentage of companies included in the surveyed population with regards to the number and type of held certificates. In the surveyed representative group, only 6% of companies had ISO 14000 certification; 21% of companies had ISO 9000 certification; 64% of companies did not have any certification; and 9% of companies had both certificates.

Companies were also surveyed in terms of their own procedures for reducing construction waste. Figure 3c shows the percentage share of companies in the studied population with regards to the existence of internal regulations concerning the reduction of construction waste. In the examined representative sample, 54% of companies had internal regulations concerning the reduction of construction waste, and 46% of companies did not have any such regulations. The difference between the companies with and without internal regulations is not significant and equals 8%.

3.2. Methodology of the Identification of Methods for Reducing Construction Waste

Based on the respondents' answers to the survey questions, five subsets of data were created. Each of them included data concerning 13 waste reduction methods that are used in relation to a specific building product, namely, steel, concrete, masonry products, finishing products, and wood (Figure 4).

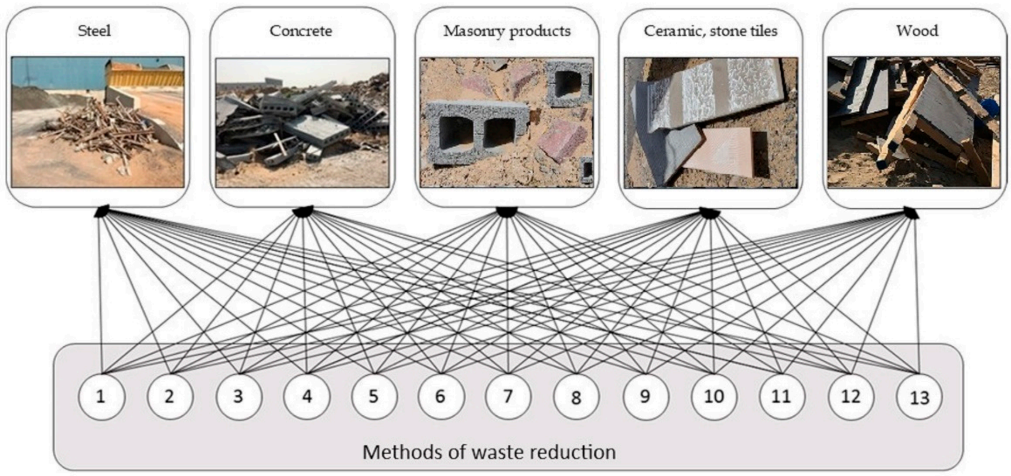


Figure 4. Schematic diagram of linking construction waste reduction methods with the studied groups of building products [graphic and photos are own materials].

- In each group of products, for each waste reduction method, the number of positive answers (YES), which confirm the use of the method, and the number of negative answers (NO), which do not confirm the use of the method, were determined;
- The frequency of using particular methods in the analyzed groups of products was determined. The following basis for the classification of individual methods was adopted:
  a. very often used—when the number of YES answers is ≥100 (71% of companies);
  b. often used—when the number of YES answers is between 60 and 99, (42–71% of companies);
  c. rarely used—when the number of YES answers is within the range of 0–59 (less than 42% of companies).
- It was examined whether, in a given group of products m; m = 1, ... ,5, there is a dependence between the use of individual methods of waste reduction n, {n = 1, ... 13} and the size of the company p; {p = 1, ... 5}.
- For this purpose, Pearson's χ^2 (chi-square) test of independence [26] was used for nominal variables. This test is used to test a relationship between the two nominal variables X and Y. In the conducted research, the nominal variable Y is the size of a company, while the nominal variable X is the number of YES/NO answers.
- The statistic of the χ^2 test has the form of Formula (1):

$$\chi^2 = \sum_{i=1}^{r} \sum_{j=1}^{c} \frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}}, \quad (1)$$

where:
χ^2—chi-square statistic,
O_{ij}—observed population size—obtained from surveys—for individual sizes of companies;
E_{ij}—theoretical population size that corresponds to the individual sizes of companies;
R—number of levels of variable X (X = 5) (number of companies groups);

C—number of levels of variable *Y* (*Y* = 2) (number of possible answers).

- The null hypothesis H_0 and the alternative hypothesis H_1 were formulated:

H_0: the variables *X* and *Y* are independent if $p > \alpha$
H_1: the variables *X* and *Y* are not independent if $p \leq \alpha$
p—denotes the probability that is determined on the basis of the tables of the χ^2 test (the *p* value is compared to the theoretical value of α).
α —significance level. It was assumed at a level of $\alpha = 0.05$.

The *p* value, which is determined for the calculated χ^2 statistic test, is compared with the critical significance level α; $\alpha = 0.05$.

If $p > \alpha \Rightarrow$ then it is assumed that there are no reasons to reject the H_0 hypothesis. This means that there is no significant relationship between the size of the company and the use of the analyzed method of reducing waste for the tested building product. The result is statistically insignificant.

If $p \leq \alpha \Rightarrow$ then it is assumed that there are reasons for rejecting the H_0 hypothesis. On the basis of the tested sample, it is possible to assume the H_1 hypothesis, which states that there is a relationship between the size of a company and the use of the analyzed method of waste reduction *n*, {*n* = 1, ... 13}, for the tested building product *m*; {*m* = 1, ... ,5}. The result is statistically significant.

The calculations of the χ^2 statistics and the *p* probability were performed using the SPSS–26 statistical software commonly used to solve research problems.

4. Results

Table 1 presents the results of the questionnaire studies concerning the use of the above-mentioned methods of reducing construction waste in relation to the five tested building products.

Table 1. The application of construction waste reduction methods for the five tested building products.

No	Methods of Reducing the Amount of Construction Waste	Respondent's Answer	Steel	Concrete *	Masonry Products	Ceramic and Stone Tiles	Wood
1	Adequate storage.	Yes	120	89	86	92	100
		No	20	51	54	48	40
2	Ordering products as per size and in the right quantity.	Yes	123	73	77	93	95
		No	17	67	63	47	45
3	Training of employees in waste management.	Yes	111	103	91	89	101
		No	29	37	49	51	39
4	Use of monitoring systems.	Yes	89	91	78	79	81
		No	51	49	62	61	59
5	Proper transport and unloading of products.	Yes	124	117	114	111	110
		No	16	23	26	29	30
6	Appropriate involvement of subcontractors.	Yes	83	81	67	73	73
		No	57	59	73	67	67
7	Site security.	Yes	127	124	121	122	123
		No	13	16	19	18	17
8	Use of prefabricated elements.	Yes	54	51	22	25	25
		No	86	89	118	115	115
9	Waste segregation on site.	Yes	82	68	57	48	64
		No	58	72	83	92	76

Table 1. *Cont.*

No	Methods of Reducing the Amount of Construction Waste	Respondent's Answer	Steel	Concrete *	Masonry Products	Ceramic and Stone Tiles	Wood
10	Designation of a place for waste segregation.	Yes	82	68	57	48	64
		No	58	72	83	92	76
11	Reuse of products within the construction.	Yes	80	41	26	22	100
		No	60	99	114	118	40
12	Timely delivery of products.	Yes	111	99	97	88	95
		No	29	41	43	52	45
13	Use of a waste management plan.	Yes	54	37	33	31	81
		No	86	103	107	109	59

* including a concrete mix and precast concrete elements.

The analysis of the results contained in Table 1 shows a significant diversification of the YES/NO answers, which proves that the specified methods are used with varying degrees of intensity in construction companies. Figure 5 presents charts that illustrate—in each group of products—the frequency of using individual waste reduction methods, which are ranked from the maximum to the minimum. The most frequently used methods are marked in green, frequently used—in blue, and rarely used—in red.

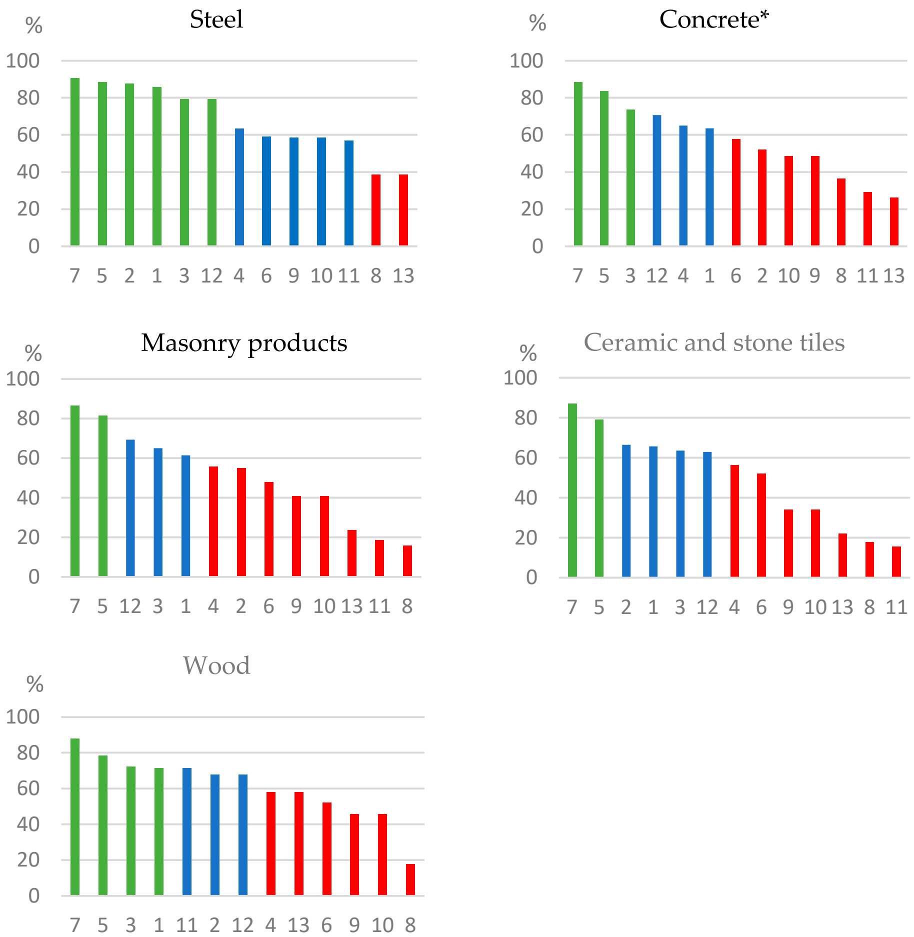


Figure 5. The distribution of the frequency of application of individual methods of waste reduction in relation to the studied groups of products (* including a concrete mix and prefabricated concrete elements).

As shown in Figure 5 and Table 2, surveyed companies use waste reduction methods most often on steel and wood products; that is probably related to the purchase costs of materials.

Table 2. Classification of waste reduction methods in terms of their frequency of use in construction companies.

Building Product	Affirmative Responses from the Respondents (YES) Regarding the Use of Waste Reduction Methods		
	Very Often (≥100 Enterprises)	Often (60–99 Enterprises)	Rarely (0–59 Enterprises)
Steel	(1) Adequate storage (2) Ordering products as per size and in the right quantity (3) Training of employees in waste management (5) Proper transportation and unloading (7) Site security (12) Timely delivery	(4) Use of monitoring systems (6) Appropriate involvement of subcontractors (9) Waste segregation on site (10) Designation of a place for waste segregation (11) Reuse of products within the construction	(13) Having a waste management plan (8) Use of prefabricated elements
Concrete	(3) Training of employees in waste management (5) Proper transportation and unloading of products (7) Site security	(1) Adequate storage (2) Ordering products as per size and in the right quantity (4) Use of monitoring systems (6) Appropriate involvement of subcontractors (9) Waste segregation on site (10) Designation of a place for segregation (12) Timely delivery of products	(8) Use of prefabricated elements (11) Reuse of products within the construction (13) Having a waste management plan
Masonry products	(7) Site security (5) Proper transportation and unloading of products	(1) Adequate storage (2) Ordering products as per size and in the right quantity (3) Training of employees in waste management (4) Use of monitoring systems (6) Appropriate involvement of subcontractors (12) Timely delivery of products	(8) Use of prefabricated elements (9) Waste segregation on site (10) Designation of a place for waste segregation (11) Reuse of products within the construction (13) Having a waste management plan
Ceramic and stone tiles	(5) Proper transportation and unloading of products (7) Site security	(1) Adequate storage (2) Ordering products as per size and in the right quantity (3) Training of employees in waste management (4) Use of monitoring systems (6) Appropriate involvement of subcontractors (12) Timely delivery of products	(8) Use of prefabricated elements (9) Waste segregation on site (10) Designation of a place for waste segregation (11) Reuse of products within the construction (13) Having a waste management plan
Wood	(1) Adequate storage (3) Training of employees (5) Proper transportation and unloading of products (7) Site security (11) Reuse of products within the construction	(2) Ordering products as per size and in the right quantity (4) Use of monitoring systems (6) Appropriate involvement of subcontractors (9) Waste segregation on site (10) Designation of a place for waste segregation (12) Timely delivery of products (13) Having a waste management plan	(8) Use of prefabricated elements

The chi-square test was performed for five groups of products and 13 methods of reducing construction waste. The calculated values of the χ^2 statistics (4) and the probability p are presented in Table 3. The results of the research allowed, with a high degree of probability, for the determination of whether the application of a given method of waste reduction in relation to particular building products depends on the size of the company.

Table 3. Chi-square test statistics.

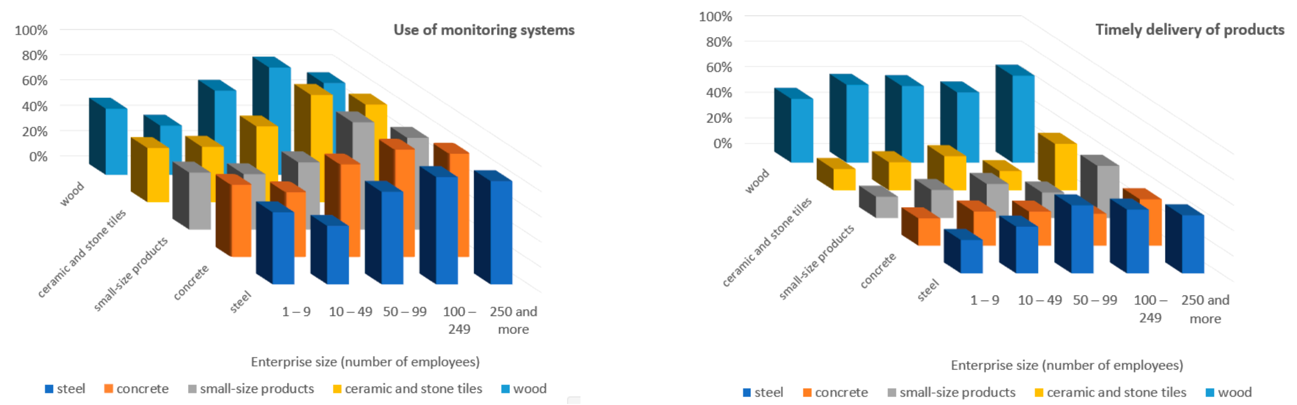
No.	Methods of Reducing the Amount of Construction Waste	Building Material				
		Steel	Concrete	Masonry Products	Ceramic and Stone Tiles	Wood
1	Adequate storage	χ^2 = 5.26; p = 0.261	χ^2 = 5.81; p = 0.213	χ^2 = 10.71; p = 0.03	χ^2 = 11.43; p = 0.022	χ^2 = 11.17; p = 0.025
2	Ordering products as per size and in the right quantity	χ^2 = 3.057; p = 0.548	χ^2 = 8.186; p = 0.085	χ^2 = 3.814; p = 0.432	χ^2 = 2.97; p = 0.563	χ^2 = 7.361; p = 0.118
3	Training of employees in the field of management	χ^2 = 4.188; p = 0.381	χ^2 = 4.657; p = 0.324	χ^2 = 9.60; p = 0.048	χ^2 = 7.313; p = 0.12	χ^2 = 8.028; p = 0.091
4	Use of monitoring systems	χ^2 = 13.751; p = 0.008	χ^2 = 11.272; p = 0.024	χ^2 = 13.754; p = 0.008	χ^2 = 16.369; p = 0.003	χ^2 = 14.996; p = 0.005
5	Proper transport and storage	χ^2 = 7.197; p = 0.126	χ^2 = 6.023; p = 0.197	χ^2 = 10.777; p = 0.029	χ^2 = 8.1; p = 0.088	χ^2 = 5.072; p = 0.28
6	Appropriate involvement of subcontractors	χ^2 = 10.671; p = 0.031	χ^2 = 8.144; p = 0.086	χ^2 = 17.855; p = 0.001	χ^2 = 8.977; p = 0.062	χ^2 = 11.495; p = 0.022
7	Site security	χ^2 = 1.899; p = 0.754	χ^2 = 3.2; p = 0.525	χ^2 = 8.113; p = 0.088	χ^2 = 3.869; p = 0.424	χ^2 = 4.308; p = 0.366
8	Use of prefabricated elements	χ^2 = 13.259; p = 0.01	χ^2 = 5.687; p = 0.224	χ^2 = 12.315; p = 0.015	χ^2 = 7.825; p = 0.098	χ^2 = 2.693; p = 0.611
9	Waste segregation on site	χ^2 = 4.546; p = 0.337	χ^2 = 1.702; p = 0.79	χ^2 = 3.525; p = 0.474	χ^2 = 2.385; p = 0.665	χ^2 = 5.971; p = 0.201
10	Designation of a place for waste segregation	χ^2 = 4.299; p = 0.367	χ^2 = 1.005; p = 0.909	χ^2 = 2.963; p = 0.564	χ^2 = 1.655; p = 0.799	χ^2 = 0.767; p = 0.943
11	Reuse of products within the construction	χ^2 = 6.871; p = 0.143	χ^2 = 9.862; p = 0.043	χ^2 = 14.825; p = 0.005	χ^2 = 11.056; p = 0.026	χ^2 = 13.027; p = 0.011
12	Timely delivery of products	χ^2 = 5.707; p = 0.222	χ^2 = 1.682; p = 0.794	χ^2 = 5.063; p = 0.281	χ^2 = 4.082; p = 0.395	χ^2 = 2.284; p = 0.684
13	Having a waste management plan	χ^2 = 5.211; p = 0.266	χ^2 = 2.346; p = 0.672	χ^2 = 2.631; p = 0.621	χ^2 = 1.733; p = 0.785	χ^2 = 2.937; p = 0.568

Statistically significant results marked in gray.

Based on the analysis of the results presented in Table 3, it can be concluded that in each group of products waste reduction methods are used, and their frequency of application in a company either depends on its size ($p \leq 0.05$) or there is no such relationship ($p > 0.05$). For comparison purposes, the frequency charts of the "Use of monitoring systems" method and the "Timely delivery" method for the five analyzed products groups and five sizes of construction companies are shown in Figure 6.

Figure 6a shows a graph illustrating the frequency of applying the "Use of monitoring systems" method in companies of various sizes. The height of the bars for all groups of products indicates increasing trend of used methods along with the size of companies. In turn, Figure 6b shows a diagram illustrating the frequency of using the "Timely delivery" method in companies of various sizes. In this case, the height of the bars does not show an unequivocal growing trend of used methods along with the size of companies. However, a much higher frequency of using this method can be noticed in companies of all sizes for wood products when compared to other product groups.

Table 4 presents the methods of waste reduction for five examined groups of building products for which the frequency of use depends on the size of a company.



(**a**) (**b**)

Figure 6. (**a**) Graph illustrating the frequency of using the "Use of monitoring systems" method in companies of various sizes. (**b**) Graph illustrating the frequency of using the "Timely delivery of products" method in companies of various sizes.

Table 4. Statistically significant relationships between the frequency of construction waste reduction methods usage in relation to five groups of construction products and the size of a company.

Building Product	Waste Reduction Methods
Steel	(4) use of monitoring systems, (6) involvement of subcontractors, (8) use of prefabricated elements
Concrete	(4) use of monitoring systems and (11) reuse of products within the construction
Masonry products	(1) adequate storage, (3) training of employees in waste management, (4) use of monitoring systems, (5) proper transport and storage, (6) involvement of subcontractors, (8) use of prefabricated elements, (11) reuse of products within the construction
Finishing products	(1) adequate storage, (4) use of monitoring systems, (8) use of prefabricated elements, (11) reuse of products within the construction
Timber	(1) adequate storage, (4) use of monitoring systems, (6) involvement of subcontractors, (8) use of prefabricated elements, (11) reuse of products within the construction

5. Discussion of Results

The classification of waste reduction methods in terms of the frequency of their use, in relation to the five groups of building products, made it possible to determine how often individual methods are used in construction companies. It can be seen that more attention is focused on construction products such as concrete, steel, and wood and less on masonry and finishing products. This is due to the fact that concrete, steel, and wood products are bigger and more costly than masonry and finishing products. This is evident in the number and type of used waste reduction methods and their frequency of use. Thus, among the 13 analyzed methods of reducing waste, in the groups of products of steel, concrete, and wood, the following methods are very often (in over 71% of companies) used: (7) site security, (5) proper transport and unloading, (3) waste management training for employees, (10) adequate storage, and (12) the timely delivery of products. In these groups of products, the following reduction methods are often (from 42% to 71% of companies) used: (4) use of monitoring systems, (6) appropriate involvement of subcontractors, (9) waste segregation at the construction site, and (10) allocation of a place for waste segregation. In turn, (8) the use of prefabricated elements was rarely (less than 42% of companies) used.

Methods such as: (1) adequate storage, (2) ordering products as per size and in the right quantity, (12) the timely delivery of products, (11) reuse of products, and (13) having a waste management plan are used with varying degrees of intensity, which results from the specificity of the product. For example, in the case of wood, (11) "reusing of products" is very often used, and in the case of concrete (including a concrete mix and precast elements) it is (12) "timely delivery" that is very common.

In the case of masonry products, as well as ceramic and stone tiles, two methods are very often used, namely, (7) site security and (5) proper transport and unloading. In turn, the following methods are often used: (10) adequate storage, (2) ordering products as per size and in the right quantity, (3) training of employees in waste management, (4) use of monitoring systems, (6) appropriate involvement of subcontractors, and (12) delivery of products in a timely manner. However, methods such as (8) use of prefabricated elements, (9) waste segregation on site, (10) designation of a place for waste segregation, (11) reuse of products on site, and (13) having a waste management plan are rarely used.

The results of the current research are partially confirmed by the studies conducted by Al-Hajj and Hamani [25]. The authors indicate that construction companies in the United Arab Emirates mainly use methods to prevent the formation of construction waste such as: (i) appropriate storage of products, (ii) ordering products in the right amount, and also (iii) training and raising awareness of staff. In the present research, these three basic methods have also been classified as being used very often in construction companies. In turn, according to the research carried out by Nalanie Mithrarante [27], the most important techniques used to minimize construction waste include training of construction personnel, training of employees in product management, improved supervision, good coordination between the supplier's personnel and the construction personnel in order to avoid over-ordering, and proper storage and use of products on site.

One of the analyzed methods of reducing construction waste is the use of prefabricated elements. This method is included in the set of methods that are rarely used, possibly due to the structural characteristics of local buildings. The research conducted by Luo and Shahzad [28] emphasized that prefabrication technology offers many benefits, such as lower costs, shorter project duration, better quality of workmanship, and the minimization of waste. However, in order to minimize the amount of waste in construction projects, there is a need to constantly raise the awareness of employees by increasing the amount of management training.

Special consideration should be also given to methods such as (9) waste segregation on site, (10) designation of a place for waste segregation, and (11) reuse of products within the construction. These methods are primarily applicable to concrete, masonry, and ceramic waste. Many studies have been conducted on the possibility of reusing aggregate obtained from such waste. Researchers from China investigated the use of recycled sand, instead of natural sand, in the production of the concrete suitable for 3D printers [29]. The use of recycled sand in the 3D printer concrete mix is believed to significantly improve the durability of 3D printed concrete structures. Furthermore, researchers from Portugal examined the possibilities of using recycled fine-grained construction and demolition waste as a backfill material for geosynthetic reinforced slopes [30,31]. The crushed concrete can also be used in geotechnical projects, e.g., the use of very irregular concrete fractions for the formation of stone columns in weak soils [32]. The benefits of reusing concrete waste on construction sites are related to the possibility of using it locally without incurring significant transport and storage costs. This is of great importance for the protection of the environment and the sustainable development of construction.

The chi-square test results show that for all of the groups of building products, the frequency of using construction site monitoring systems (method 4) depends on the size of the company, i.e., the frequency of usage of the method increases along with the size of the company.

A significant statistical relationship was found between the size of a company and the use of the following seven methods of reducing construction waste: use of monitoring systems, use of prefabricated elements, reuse of products on the construction site, appropriate involvement of subcontractors, adequate storage, training of employees in waste management, and proper transport and unloading. These methods are used more frequently as the company expands in size, which shows that the larger the company, the more committed employees are to reducing waste. Moreover, the number and type of a method that meets the above condition vary depending on the type of construction product.

For the remaining six methods of decreasing construction waste, there was no correlation between frequency of use and company size in particular product groupings, notably: ordering products as per size and in the right quantity, site security, waste segregation at the construction site, designation of a place for waste segregation at the construction site, timely delivery of products, and having a waste management plan.

6. Summary

The development of civilization brings positive and negative effects that directly or indirectly affect the environment. One of the areas that has a huge impact on environmental changes is the construction industry, which is the source of a large amount of waste. The amount of produced construction waste can be minimized by appropriate management. The effectiveness of construction waste management depends on many factors, such as the correct identification of sources and factors that influence the production of waste and the appropriate selection of methods in order to minimize waste.

This article presented the research that aimed to find out about:

1. which waste reduction methods are most often used in the construction industry in relation to: steel, concrete, masonry products, finishing products, and wood.
2. whether the used waste reduction methods depend on the size of the construction company.

Surveys conducted among construction site managers were used to perform the research and analysis. The research was carried out in 140 construction companies of five different sizes which build residential and mixed-used buildings. Studies covered 13 methods of reducing construction waste. Pearson's χ^2 (chi-square) test of independence and the SPSS-26 statistical software were used in the analyses.

The following methods of reducing construction waste were found to be the most frequently used:

- for steel products: (1) adequate storage, (2) ordering products as per size and in the right quantity, (3) training of employees in waste management, (5) proper transport and unloading of products, (7) site security, (12) timely delivery;
- for concrete products: (3) training of employees in waste management, (5) proper transport and unloading of products, (7) site security;
- for masonry and finishing products: (7) site security, (5) proper transport and unloading of products;
- for wood products: (1) adequate storage, (3) training of employees in waste management, (5) proper transport and unloading of products, (7) site security, (11) reuse of products within the construction.

It was also found that waste reduction methods are also used in each group of products, with the frequency of their use varying depending on the size of the company. These methods include (for all groups of materials): use of monitoring systems, use of prefabricated elements, reuse of products on the construction site, appropriate involvement of subcontractors, adequate storage, training of employees in waste management, and proper transport and unloading. As the company grows in size, these methods are used more frequently. In the case of other methods that were not mentioned above, no dependence of their use on the size of the company was found.

By identifying methods of reducing construction waste used in companies of various sizes for each product group, it is possible to easily plan activities preventing the cultivation of bad construction practice by, for example, conducting trainings and directing dedicated requirements to companies of different sizes. This knowledge can definitely facilitate the management of construction waste on the scale of individual companies and on a national scale by adjusting the aid in the field of training and promotion of the benefits resulting from waste reduction. The presented analysis of the research results may have a definite positive impact on the protection of the natural environment by minimizing construction waste and increasing the amount of recyclable waste.

Authors plan to conduct further research related to the financial benefits of construction waste management.

Author Contributions: Conceptualization, M.B.; methodology, M.T.; software, Z.W.; validation, M.B., B.H., and M.T.; formal analysis, M.T.; investigation, M.B.; resources, M.B.; data curation, M.B. and Z.W.; writing—original draft preparation, M.B., B.H. and M.T.; writing—review and editing, B.H.; visualization, Z.W.; supervision, B.H.; project administration, M.B. and B.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bougdah, H.; Sharples, S. *Environment Technology and Sustainability*; Technologies of Architecture; Taylor & Francis: Abingdon, UK, 2009; p. 2, ISBN 978-0-415-40379-5.
2. Eurostat, Waste Statistics. 2021. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation (accessed on 18 March 2022).
3. Bayanat-Official Data Portal of the UAE Government. 2021. Collected-Dumps Managed Non-Hazardous Wastes by Source—Disposing Method. 2016. Available online: https://admin.bayanat.ae/Home/DatasetInfo?dID=hY4a8nA59DTBOGbpPRCvy2vNFlGzgd-G6ObWDtesokA&langKey=en (accessed on 28 December 2021).
4. Zhang, C.; Hu, M.; di Maio, F.; Sprecher, B.; Yang, X.; Tukker, A. An overview of the waste hierarchy framework for analysing the circularity in construction and demolition waste management in Europe. *Sci. Total Environ.* **2022**, *803*, 149892. [CrossRef] [PubMed]
5. Yeheyis, M.; Hewage, K.; Shahria, A.M.; Eskicioglu, C.; Sadiq, R. An overview of construction and demolition waste management in Canada: A lifecycle analysis approach to sustainability. *Clean Technol. Environ. Policy* **2013**, *15*, 81–91. [CrossRef]
6. Silva Souza, F.; Castro Mendes, J.; Barbosa Morais, L.J.; Santos Silva, J.; Fiorotti Peixoto, R.A. Mapping and recycling proposal for the construction and demolition waste generated in the Brazilian Amazon. *Resour. Conserv. Recycl.* **2022**, *176*, 2022. [CrossRef]
7. Dania, A.; Kehinde, J.; Bala, K. A Study of Construction Material Waste Management Practices by Construction Firms in Nijeria. In Proceedings of the 3rd Scottish Conference for Postgraduate Research of the Built and Natural Environment, Glasgow, Ireland, 20–22 November 2007; pp. 121–129.
8. US Environmental Protection Agency. 2017. Available online: https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials (accessed on 24 January 2022).
9. Adamczyk, J.; Dylewski, R. The importance of local waste collection points in the construction waste management system. *Support Syst. Prod. Eng.* **2013**, *3*, 9–16.
10. Dz. Of Laws. Item 1923 from December 29 2014, Regulation of the Minister of the Environment on the Waste Catalog.
11. MOCCAE. Federal Law No. 12 of 2018 Issued on 18/12/2018 on the Integrated Waste Management. Available online: https://www.moccae.gov.ae/assets/download/c5e9ee5b/L12-18%20Eng.pdf.aspx?view=true (accessed on 29 December 2021).
12. EAD (Environment Agency—Abu Dhabi), Waste Classification Technical Guideline. 2016. Available online: https://www.ead.gov.ae/en (accessed on 31 January 2022).
13. Dubai Municipality. *Waste Management Department Technical Guideline No.1. Waste Collection and Transportation Services*; Government of Dubai: Dubai, United Arab Emirates, 2009.
14. Symonds Group Ltd.; ARGUS; COWI; PRC Bouwcentrum. *Raport for DGXI, European Commission, Construction and Demolition Waste Management Practices, and Their Economic Impacts*; European Commission: Brussels, Gelgium, 1999.
15. Li, J.; Ding, Z.; Mi, X.; Wang, J. A model for estimating construction waste generation index for building project in China. *Resour. Conserv. Recycl.* **2013**, *74*, 20–26. [CrossRef]
16. Notice from the Commission Concerning Technical Guidelines Regarding the Classification of Waste. *J. Law Eur. Union* **2018**, *C 124*, 1–134.
17. Bee'ah (Sharjah Environment Company). Available online: https://beeahgroup.com/ (accessed on 2 January 2022).
18. European Commission; Directorate-General for Environment. Resource Efficient Use of Mixed Wastes Improving Management of Construction and Demolition Waste: Final Report. Publications Office. Available online: https://op.europa.eu/en/publication-detail/-/publication/78e42e6c-d8a6-11e7-a506-01aa75ed71a1/language-en (accessed on 2 January 2022).

19. Bao, Z.; Lu, W. A decision-support framework for planning construction waste recycling: A case study of Shenzhen, China. *J. Clean. Prod.* **2021**, *309*, 127449. [CrossRef]
20. Ramos, M.; Martinho, G. Influence of construction company size on the determining factors for construction and demolition waste management. *Waste Manag.* **2021**, *136*, 295–302. [CrossRef] [PubMed]
21. Crawford, R.H.; Mathur, D.; Gerritsen, R. Barriers to improving the environmental performance of construction waste management in remote communities. *Procedia Eng.* **2017**, *196*, 830–837. [CrossRef]
22. Ekanayake, L.L.; Ofori, G. Building waste assessment score: Design-based tool. *Build. Environ.* **2004**, *39*, 851–861. [CrossRef]
23. Bossink, B.A.G.; Brouwers, H.J.H. Construction waste: Quantification and source evaluation. *J. Constr. Eng. Manag.* **1996**, *122*, 55–60. [CrossRef]
24. Al-Hajj, A.; Hamani, K. Material waste in the UAE construction industry: Main causes and minimization practices. *Arch. Eng. Des. Manag.* **2011**, *7*, 221–235. [CrossRef]
25. Białko, M.; Hoła, B. The investment process in the United Arab Emirates on the example of the Emirate of Sharjah. *Mater. Bud.* **2016**, 143–144, 151. [CrossRef]
26. Pearson, K. On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling. *Philos. Mag.* **1900**, *50*, 157–172. [CrossRef]
27. Mithraratne, N. Measures to Minimise Construction Waste. In Proceedings of the Construction & Deconstruction Conference 'Building Today—Saving Tomorrow', Auckland, New Zealand, 15–17 July 2015.
28. Luo, O.; Shahzad, W. Prefabrication and Waste Minimisation in Construction Projects: Perspectives from New Zealand. In *The 10th International Conference on Engineering, Project, and Production Management*; Lecture Notes in Mechanical Engineering; Panuwatwanich, K., Ko, C.H., Eds.; Springer: Singapore, 2020. [CrossRef]
29. Ding, T.; Xiao, J.; Zou, S.; Wang, Y. Hardened properties of layered 3D printed concrete with recycled sand. *Cem. Concr. Compos.* **2020**, *113*, 103724. [CrossRef]
30. Vieira, C.S.; Pereira, P.M. Influence of the geosynthetic type and compaction conditions on the pullout behaviour of geosynthetics embedded in recycled construction and demolition materials. *Sustainability* **2022**, *14*, 1207. [CrossRef]
31. Ferreira, B.F.; Pereira, P.; Vieira, S.C.; Lopes, L.M. Long-term tensile behavior of a high-strength geotextile after exposure to recycled construction and demolition materials. *J. Mater. Civ. Eng.* **2022**, *34*, 04022046. [CrossRef]
32. Kawalec, J.; Kwiecien, S.; Pilipenko, A.; Rybak, J. Application of Crushed Concrete in Geotechnical Engineering—Selected Issues. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2017; Volume 95, p. 022057.