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Applying materials waste quantification to cement waste reduction in residential buildings of Tehran: A case study

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Abstract. The purpose of this research was twofold; first, it focused on developing quantitative wastage models for rebar, concrete, brick, and cement, as major traditional bulk building materials, used in Tehran residential buildings. The primary results indicated that multiple linear regression was an apt tool to model the effects of the studied variables on materials wastage. In every developed wastage model, subtractive or accumulative effect of each studied variable was recognized by its coefficient value and sign. The developed models resulted in adjusted R^2 values of 0.907, 0.875, 0.920, and 0.790, respectively, for rebar, cement, brick, and concrete waste. Cement, with average wastage of 8.57% by weight, was identified as the most wasted material verified by the case study. As the second objective of the study, the previously developed models as well as opinions of the project management experts were combined to propose a cement waste reduction guideline for traditional building construction, which is common in Tehran, Iran. With this purpose in mind, in the initial phase of the project, choosing lump-sum contract instead of cost-plus contract was considered. Moreover, a financial incentive reward scheme, with its economic viability and environment friendliness, was tested, which yielded positive results and hence, was proposed for the construction phase. Applicability of the proposed scheme was verified through a case study.

1. Introduction

Construction Waste (CW) as a crucial global concern is an important part of solid waste; it is a direct by-product of construction industry that unfavorably affects the environment [1-5]. Construction and Demolition Waste (C&DW) produces about one third of total landfill wastes [2] and has caused pressure on landfill sites [6]. Furthermore, construction industry is responsible for 30% of the global carbon emissions. It is expected that its share will be doubled during the next 20 years [7], which suggests CW as a culprit in global warming. Asthma attacks, premature deaths, and reduction in lung functionality in children are stemmed from CW Generation (CWG) as well as its accumulation in the ozone layer [8]. CWG quantification is a primary tool for serving other construction waste management policies, i.e., legislation or incentive proposals [9,10]. It fulfills data scarcity; alleviates determining, controlling, and managing CWG; facilitates CW management; and can be used to control CW

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environmental consequences [3,11], i.e., climate change, acidification, summer smog, and nitrification [12]. It provides contractors who are supposed to generate less CW with insight [13].

By a review of the literature, it is discernable that Kern et al. [9] conducted a Multiple Linear Regression (MLR) based study and evolved CWG model in high-rise buildings in Brazil. They deemed production system and design process salient influential parameters on CWG estimation. Sáez et al. [14] investigated project Floor Area (FA) and number of dwellings in several newly built residential building projects and proposed a quantification model in terms of volume and weight for CWG in the Mediterranean buildings. Ding and Xiao [15] quantified C&DW generation in buildings in Shanghai, China, by scrutinizing the outcomes of structure design and affiliated structure codes in several decades on CWG fluctuations. Based on mass balance principle for construction, Li et al. [16] generated a model for quantifying CWG per gross FA, which was applied to the construction of a residential building in Shenzhen, China. Won et al. [17] categorized design errors based on their causes and likelihood of detection in order to quantify the construction waste prevented. They studied two cases in South Korea with 381 and 136 design errors detected. By adopting BIM (Building Information Modeling)-based design validation, they could prevent 4.3-15.2% of construction waste. Ghosh et al. [18] quantified C&D waste generated in Kolkata, India, using building-specific and region-specific waste generation rates. The research was done between May 2015 and August 2015 on 5 ongoing demolition and renovation projects and ended up by optimizing the value of revenue that could be recovered by recycling C&D waste [18].

The most important weakness of these models is that they are true for specific cases and there is no single model for estimating waste generation that is applicable to each given situation [18]. Additionally, waste generation does not necessarily comply with the existing regressions and some developed models have significant error terms. To lessen the error terms, we need to increase the number of studied projects, which seems impractical due to time-consuming and difficult nature of gathering data. As well as being true for a limited number of buildings, they are generally applicable to a limited total amount of construction or demolition waste. They also do not consider contract type and locality, which seem to be important factors in construction waste generation. The present paper fills these gaps by developing quantitative models for each material and including contract type and locality in modeling process by studying 32 construction projects, which are significantly more than the numbers of studied projects in the previous studies (18 at most).

CW quantification provides useful models, which can be used to reduce waste. Waste reduction has been identified as a part of the 3R approach (reduction, reuse, and recycle) in order to make societies more sustainable [1]. In some Asian countries, several approaches have been taken to the development of 3R performance indicators [19]; all the same, no significant effort has been undertaken in Iran so far to develop approaches based on 3R policy to minimizing/managing CW:

- Although municipalities and the government highlight the importance of waste management, there is no practical action;
- There is no unique regulation of CW reduction, reuse, or recycling and the existing regulations merely aim at collection and disposal of solid waste;
- People and dignitaries are unaware of damages of CW.

Even though in recent years, municipalities have tried to lay down rules and legislations to manage CW, it is not clear when these actions will come into practice [20]. When there is no comprehensive plan to manage all wastes, the municipality can start the task of waste reduction with the most dominant type of waste. With this purpose in mind, managers can think about cement waste reduction. This is due to the fact that cement is one of the highly consumed Building Materials (BMs). Iran ranked fifth among cement producing countries in the world from 2003 to 2012. Annual cement production in Iran was 30.5, 32.6, 40.0, 56.3, 61.0, and 65.0 million tons in 2003, 2005, 2007, 2009, 2011, and 2012, respectively [21]. Table 1 represents average quantities of environmental

Table 1. The average quantities of some environmental indicators for 5 cement companies in Iran [22].

Indicator		Average	Unit
Raw materials consumption		1.64	t/t cement produced
Electrical energy consumption		99.79	kWh/t cement produced
Heat energy consumption		827.19	kcal/kg cement produced
Air pollutants emission	CO_2	933.80	kg/t cement produced
	NO_x	2.47	kg/t cement produced
	SO_2	522.40	kg/t cement produced
	SPM	99.60	kg/t cement produced

indicators of greenhouse gases production for 5 cement companies in Iran [22]. Currently, greenhouse gases emissions control is regarded as a highly outstanding environmental subject [23]. Researchers have proposed solutions to reducing production, usage, and wastage of BMs including cement. Tam and Tam [24] implemented a Financial Incentive (FI) reward program. Following a ladder approach, the reward was augmented as the wastes decreased. This scheme decreased CWG to 23% in Hong Kong. To reduce CO_2 emission, Oh et al. [21] proposed using demolished inorganic BMs instead of limestone in cement production. Ostad-Ahmad-Ghorabi and Attari [22] prioritized 15 indicators using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS, a multi-criteria decision making model that could be utilized for the purpose of prioritizing the indicators based on the quantities and relative importance achieved) and developed strategies to advance environmental evaluation of cement production industry in Iran. Chen et al. [25] developed a series of suggestions including replacing limestone with wastes to reduce detrimental effects of cement production.

In Tehran, CW constitutes approximately 10-30% of C&DW [2]. In 2009, in Tehran, 46,655 m^3/day (equivalent to: 14.70 million tons/year, 1300-1610 kg/m^2 built, 1694.35 kg/person/year, and about five times the household waste) C&DW was generated. This huge quantity is postulated to be mainly due to short lifetime of buildings, natural disasters, substandard safety codes, growing demands for modern construction projects, and poor maintenance. Other factors such as old construction methods, i.e., brick-based, dominancy of traditional demolition methods, low rate of reusing and recycling, and landfilling and illegal dumping could add up to such big amounts of C&DW. On the other hand, growing population is pushing housing demands that leads to more BMs usage and wastage [26]. In addition, Mehr Public Housing Project, which started 10 years ago, includes construction of about 350,000 low-cost condos and consumes tremendous amounts of CMs and generates huge amounts of CW all over Iran, and Tehran is not an exception.

Detrimental environmental effects of generating high amounts of CW/C&DW have obliged governments to make plans of CW management since several decades ago. The results are various regulations that have been devised and implemented all over the world. For instance, in Hong Kong, the following regulations control CW Generation (CWG): waste disposal ordinance, green manager scheme, waste reduction framework plan, practical note on the use of recycled aggregate, commissioning a pilot recycling plant to supply recycled aggregate, circulars of waste management, and public landfill levy scheme [24]. Besides these limiting regulations, incentive-based techniques and combined systems of bonus and penalty are posited to help in attaining more efficacy [24,25]. The required incentive can be provided by means of financial aid, upgrading certificates, etc.

The aim of the present study is to propose a construction waste reduction model valid in Tehran context. The following objectives are set for this study: determining influential parameters on materials wastage, quantifying the studied materials wastage, investigating applicability of FI reward programs to reducing materials wastage, and proposing a viable and environment friendly FI reward program in case its applicability is proven.

2. Theory and methodology

So far, possible effects of locality on CW generation have not been investigated by scholars, although some researchers are in favor of potential influence of the former on the latter. To evaluate the effect of locality on CW generation in practice, the authors narrowed down their research on residential buildings to Tehran, Iran. As a matter of fact, these buildings were a case study to initiate and conduct the investigation. The first part of the study focused on developing a building-level model to quantify rebar, concrete, brick, and cement wastages. These four materials are highly consumed in traditional residential projects. The average wastages (wasted material quantity over purchased material quantity) of rebar, concrete, brick, and cement in Tehran, Iran, are 1.358%, 3.793%, 6.049%, and 8.403%, respectively [2]. Other unstudied materials were either cheaper or less commonly utilized than the studied BMs in traditional construction projects. Variables of the study were derived from the available reviewed literature. The required data were obtained through the first questionnaire survey. After data treatment, MLR by IBM SPSS was identified as a proper tool for data analysis. Various combinations of the variables were evaluated. Finally, the models satisfying the acceptance criteria were derived from the most recent and relevant papers and statistical references, which are reported in this paper. The first part suggested that cement was highly wasted in the studied projects. Therefore, in the second part, using the results of the first part of the study and insights of project management experts gathered through the second questionnaire survey, a Cement Waste Reduction (CWR) guideline is suggested. Figure 1 illustrates the procedure of the present research.

2.1. The first questionnaire survey and sample characteristics

The required data for both parts were collected through the first questionnaire survey for 32 residential build-

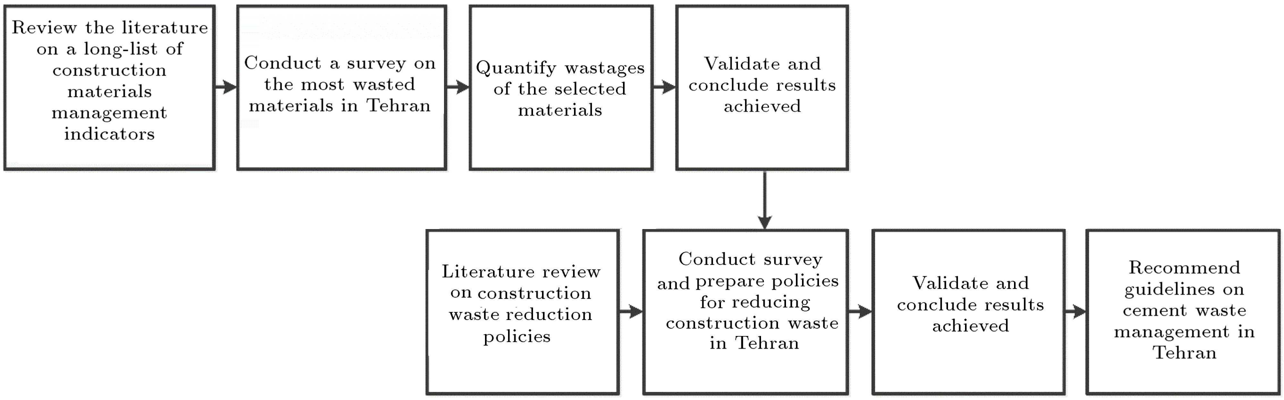

Figure 1. The research procedure diagram.

ings being built in Tehran, Iran. The respondents were contractors of the projects, who were supposed to declare/estimate the amounts of purchased and wasted materials in order to obtain the materials wastage percentage by weight.

2.1.1. Research variables

BMs Waste (BMW) is complicated enough to quantify, as it is a function of a set of variables [9,27]. In this paper, the dependent variable consists of the aforementioned four BMs wastage during construction in terms of weight percent. Parameter $Y_{\text{Site}}^{\text{Material}}$ generally represents these variables, so BMW weight percentages are presented as Y_{Site}^{Rebar}, $Y_{\text{Site}}^{\text{Concrete}}$, $Y_{\text{Site}}^{\text{Brick}}$, and $Y_{\text{Site}}^{\text{Cement}}$. The studied independent variables are the following:

- *Contract type:* There are a variety of contract types in construction industry, e.g., unit price, lump-sum, cost-plus, etc., of which content rules and regulations affect the way the contractor attempts to superintend CWG [28]. The focus of this study is on lump-sum and cost-plus contracts since they are widely used in residential building projects in Tehran. The contract type is a qualitative variable and needs to be in a numerical form in order to be analyzed [9]. Parameter X_1 presents this variable and equals 0 and 1 for cost-plus and lump-sum contracts, respectively.
- *FA*: FA affects the design of the building and BMs waste, because the more the FA, the more will be the purchased materials [29]. To make the coefficient of this variable in the same order of that of the other variables, a new parameter, A, which is defined as one hundredth of FA is used to develop the models:

$$A = \frac{FA(\text{m}^2)}{100}. \tag{1}$$

For the studied buildings:

$$50 \text{ m}^2 \leq FA \leq 235\text{m}^2, \tag{2}$$

$$0.50 \leq A \leq 2.35. \tag{3}$$

- *Locality:* Differences are climate conditions, training level of the local labor, and land prices. Such factors make locality an efficacious parameter in BMW. In this study, 7 different locations in Tehran were selected and 32 residential buildings were studied. These locations were selected in such a manner to cover the whole land price range in Tehran. Furthermore, each studied building was typical in order to represent a variety of buildings in the same location. The authors believe that the studied set of buildings is a good representative sample of residential buildings in Tehran. Similar to contract type variable, locality qualitative variable must be in numerical form [9] to be analyzed. For every residential building, the amount of the corresponding locality parameter is set to 1 and the rest of locality parameters are set to 0. Table 2 shows the characteristics of the studied locations.
- *Number of stories:* Building height restrictions are surmised to control the way pollutant dispersion and pedestrian ventilation are affected by building height [30]. A building's number of stories (S) is an

Table 2. Locations, their notations, and number of buildings in each location.

Location (Tehran, Iran)	Notation	Number of buildings in location
Imam Hosein	X_2	5
Saadat-Abad	X_3	7
Shohada	X_4	4
Shahran	X_5	4
Resalat	X_6	4
Tehran no.	X_7	4
Sepah	X_8	4
Total		32

indicator of its height and supposed to be one of the CWG quantification independent variables [9,11]. For the studied residential buildings:

$$S \in \{4, 5, 6, 7\}. \quad (4)$$

These independent variables are used in the first part of the study. In addition to these parameters, another parameter is to be defined to notate financial incentive and to conduct the second part of the study.

- *FI:* In Iran, there is no contrivance to control CWG. FIs are regarded as effective methods for compelling contractors to reduce the CW they generate as discussed in Section 1. Therefore, the authors decided to evaluate an FI-based program for controlling CWG in Tehran. This parameter is suggested to be calculated according to Eq. (5).

Moreover, the authors conducted the second questionnaire survey in Likert scale to evaluate dominance of FI over other CWG reduction methods, i.e., fining-based methods. A long list of indicators was first extracted from reviewed research efforts in the literature [21,25,31,32]. The final short list of indicators was then deduced from a set of meetings held with experts. The final questionnaire subsumed 17 indicators. Indicators no. 1 to 4, 9 to 11, and 14 to 17 were suggested by the experts with more than 20 years of experience in construction industry prior to designing the questionnaire. Other items were deduced from the following reviewed papers:

- Items no. 5, 7, and 12 from the paper of Tam and Tam, 2008 [24];
- Items no. 6, 8, and 13 from the paper of Chen et al., 2002 [25].

The indicators covered the preferences of construction industry experts (1- dominance of ethics over incentives, 2- dominance of incentives over penalizing, 3- effectiveness of incentives in all contracts, 4- influence of promoting ethical beliefs about waste reduction), legislative (5- imperativeness of assigning a budget to pay incentives, 6- effect of incentives on reduction in materials production, 7- relation of incentives with revenue of contractors, 8- relation of required budget with revenue of municipalities from rehabilitation projects), managerial (9- imperativeness of determining maximum allowed wastage of materials, 10- possibility of circumventing the rules requiring control, 11- dominance of incentives due to lower need for controlling mechanisms, 12- potential positive effects of trainings on waste reduction, 13- potential positive effects of ladder approach to designing incentives on waste reduction), and sustainable development related aspects of proposal (14- relation of the success of incentive plans with reduction in materials demand, 15- alignment of incentive plans with national benefits, 16- alignment of incentive plans with sustainable development, 17- incentives resulting in promotion of utilizing biodegradable materials by contractors).

Fifty-four experts took part in this survey and were supposed to assign a number from 1 (completely disagree) to 5 (completely agree) to each indicator. Table 3 shows characteristics of the respondents. To check the internal and overall consistency of indicators, Cronbach's alpha was calculated. Since $\alpha = 0.776 > 0.700$, favorable consistency was approved. Thus, the proposal was preferred to fining policies by respondents. Other results of the second questionnaire survey are the following:

- There is theoretical relationship between FI and materials waste reduction in Tehran residential building projects;
- In order to be applicable, the proposed FI programs must be feasible both economically and environmentally;
- Construction industry experts believe that FI reward programs are prioritized not only over fining policies but also over other materials waste reduction policies, e.g., legislation, regulating codes, increasing existing fines, etc., because lower supervision and control is required in implementing reward programs than in other mentioned methods;
- FI rewards inspire stakeholders of construction projects intuitively and trigger professional ethics more efficiently than other methods do;
- Even in projects employed by cost-plus contracts in which the contractor has the least apathy toward materials waste reduction, FI plans can convince them to reduce wasted materials to the possible extent;
- Demand for construction materials production and consumption will be reduced provided that FI reward programs are implemented in a big city with many construction projects like Tehran;
- FI reward programs are toward sustainable development, because in case of implementing these programs, less materials and resources will be wasted and more will be saved for future generations.

The authors proposed an initial amount of FI equal to demolition waste generation charge (Eq. (5)), hoping that it would persuade contractors more than fining policies. Since in case of defining a new taxing policy, instead of enforcing taxes on them, the contractors will be rewarded if the mentioned waste generation is either avoided or reduced:

$$DC = 0.2K.P.FA, \quad (5)$$

Table 3. Characteristics of respondents.

Property		**Number of respondents**	**Relative percentage**	**Sum**	
				Total	**Percent**
Gender	Male	39	72.22	54	100
	Female	15	27.78		
Age	0-25	2	3.70	54	100
	26-35	32	59.26		
	36-45	11	20.37		
	46-55	6	11.11		
	$\geq$ 56	3	5.56		
Work experience (years)	0-5	17	31.48	54	100
	6-10	16	29.63		
	11-15	8	14.81		
	16-20	5	9.26		
	21-25	3	5.56		
	$\geq$ 26	5	9.26		
Field of study	Civil and environmental engineering	42	77.78	54	100
	Industrial engineering	5	9.26		
	Architecture	6	11.11		
	Surveying and geospatial engineering	1	1.85		
Degree	Associate's	1	1.85	54	100
	BSc	19	35.19		
	MSc	29	53.70		
	PhD	5	9.26		

Table 4. Suggested quantities for the parameter K [33].

FA (m^2)	0-60	61-100	101-150	151-200	201-300	301-400	401-500	501-600	More than 600
K	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.5

where DC is demolition charge for a building in terms of USD ($ represents USD in all parts of the paper), K is correction coefficient presented in Table 4, FA is floor area in terms of m^2 [33], and P is "Last Trading Value" according to building location obtained from Table 5 in terms of $ [34].

All collected data in the first questionnaire survey as well as FI parameters are shown in Tables 5 and 6.

2.2. Statistical data treatment

Data treatment is of paramount importance for checking data set normality and choosing the proper data analysis method.

2.2.1. Dependent variable statistical analysis

MLR is feasible when data distribution is normal. Central limit theorem implies that distribution of the sample mean, the variables of which have normal distribution, is normal [9]. When sample size is greater than 25 (the sample size is 32 in this paper), chi-square statistical test can be used to check dependent variable normality and the data set is normal if Eq. (6) is satisfied [35,36]. The test procedure begins with arranging n observations into a set of k classes, and goodness of fit is accepted when [35]:

$$X_0^2 < X^2_{\alpha,k-s-1}, \tag{6}$$

Table 5. Collected data (independent variables) and calculated FI for each studied residential building.

Collected data					Calculated FI		
Contract type	**Building no.**	**FA (m^2)**	**Number of stories**	**Location**	K	P **(\$)***	**FI (k\$)**
Lump-sum	1	107	5	X_2	0.7	13.619	0.204
	2	132	5	X_2	0.7	13.578	0.251
	3	195	4	X_3	0.8	3.898	0.122
	4	235	7	X_3	0.9	0.445	0.019
	7	60	4	X_2	0.6	47.904	0.345
	9	140	5	X_4	0.7	1.622	0.032
	10	105	5	X_4	0.7	11.159	0.164
	11	210	5	X_6	0.9	10.247	0.387
	14	87	5	X_5	0.6	12.653	0.132
	15	75	4	X_4	0.6	11.214	0.101
	16	160	6	X_8	0.8	20.237	0.518
	18	140	6	X_7	0.7	0.346	0.007
	20	170	7	X_6	0.8	12.731	0.346
	24	150	6	X_8	0.8	18.281	0.439
	26	162	6	X_7	0.8	9.800	0.254
	28	155	6	X_6	0.8	13.547	0.336
	32	88	4	X_5	0.6	5.889	0.062
Cost-plus	5	80	5	X_4	0.6	28.823	0.277
	6	93	5	X_5	0.6	5.282	0.059
	8	50	4	X_2	0.5	62.994	0.315
	12	86	5	X_6	0.6	10.562	0.109
	13	110	5	X_5	0.7	5.321	0.082
	17	94	5	X_8	0.6	20.207	0.228
	19	97	5	X_7	0.6	9.798	0.114
	21	120	5	X_3	0.7	15.772	0.265
	22	113	5	X_3	0.7	10.974	0.174
	23	118	5	X_3	0.7	10.201	0.169
	25	74	4	X_8	0.6	34.166	0.303
	27	87	5	X_7	0.6	9.771	0.102
	29	125	5	X_3	0.7	15.767	0.276
	30	220	7	X_3	0.9	15.783	0.625
	31	123	5	X_2	0.7	13.586	0.234
Total	–	3961	–	–	–	–	8.016

* Rial (Iran's formal currency unit) is converted to Dollar; 35000 Rials is equivalent to 1 USD.

$$X_0^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}, \quad (7)$$

$$K\,(\text{integer}) \approx \sqrt{n} \geq 5, \quad (8)$$

where s is the number of estimated parameters (for normal distribution $s = 2$), O_i is accepted error level (0.05 in this paper), α_i is observed frequency in the ith class interval, $E_i = n.p_i$ is expected frequency in the ith class interval, and $p_i = 1/k$ is theoretical probability [35].

The normality test results are summarized in Table 7. Goodness of fit is approved since Eq. (6) is satisfied in all data sets. Therefore, all data

Table 6. Collected data (dependent variables), estimated amounts of wastage, end relative errors in the developed models for the studied materials.

Site no.	Rebar			Concrete			Brick			Cement				
	$Y_{\text{Site}}^{\text{Rebar}}$	$Y_{\text{Model\_1}}^{\text{Rebar}}$	$\lvert Error \rvert$*	$Y_{\text{Site}}^{\text{Concrete}}$	$Y_{\text{Model\_1}}^{\text{Concrete}}$	$\lvert Error \rvert$	$Y_{\text{Site}}^{\text{Brick}}$	$Y_{\text{Model\_1}}^{\text{Brick}}$	$\lvert Error \rvert$	$Y_{\text{Site}}^{\text{Cement}}$	$Y_{\text{Model\_1}}^{\text{Cement}}$	$\lvert Error \rvert$	$Y_{\text{Model\_2}}^{\text{Cement}}$	$\lvert Error \rvert$
1	1.000	0.973	0.027	2.500	2.818	0.127	5.800	6.407	0.105	5.660	5.600	0.011	5.885	0.040
2	1.300	0.973	0.252	2.670	2.492	0.067	5.600	6.407	0.144	7.400	7.594	0.026	5.581	0.246
3	1.200	1.302	0.085	2.250	1.672	0.257	6.800	6.407	0.058	16.670	16.868	0.012	6.519	0.609
4	1.100	1.098	0.002	1.220	1.151	0.056	8.000	6.407	0.199	14.500	14.343	0.011	6.885	0.525
5	1.500	1.352	0.099	6.470	5.068	0.217	5.000	5.049	0.010	6.670	7.880	0.181	8.663	0.299
6	1.600	1.823	0.139	3.350	4.074	0.216	5.700	5.140	0.098	6.670	6.446	0.034	10.074	0.510
7	1.300	1.041	0.199	2.700	3.430	0.270	6.800	6.407	0.058	3.330	3.757	0.128	5.072	0.523
8	1.750	1.630	0.069	5.450	5.459	0.002	No data			5.250	5.047	0.039	8.515	0.622
9	1.000	0.763	0.237	2.290	2.388	0.043	4.000	3.533	0.117	10.000	10.578	0.058	7.001	0.300
10	0.800	0.763	0.046	2.500	2.844	0.138	5.000	3.624	0.275	7.800	7.787	0.002	6.144	0.212
11	1.000	0.800	0.200	5.500	5.499	0.000	7.200	5.140	0.286	6.670	6.668	0.000	4.697	0.296
12	1.730	1.389	0.197	9.330	9.012	0.034	5.000	5.140	0.028	No data				
13	1.710	1.823	0.066	4.760	3.853	0.191	3.500	3.624	0.035	8.000	7.801	0.025	9.925	0.241
14	1.200	1.234	0.028	1.810	2.253	0.245	4.000	3.533	0.117	4.000	3.880	0.030	6.351	0.588
15	1.150	0.831	0.277	4.000	3.235	0.191	15.200	16.400	0.079	7.000	7.300	0.043	6.653	0.050
16	0.500	0.504	0.008	2.650	2.128	0.197	No data			7.000	7.130	0.019	3.750	0.464
17	1.000	1.161	0.161	3.950	4.886	0.237	11.110	11.703	0.053	5.830	5.860	0.005	8.979	0.540
18	1.140	1.166	0.023	2.480	2.388	0.037	5.100	3.624	0.289	10.000	8.673	0.133	7.063	0.294
19	2.000	1.823	0.089	4.170	4.847	0.162	10.000	7.923	0.208	9.670	9.236	0.045	9.717	0.005
20	0.900	0.664	0.262	6.060	6.020	0.007	7.500	7.923	0.056	No data				
21	1.790	1.823	0.018	3.960	4.548	0.148	7.000	7.923	0.132	10.000	11.070	0.107	8.739	0.126
22	1.800	1.823	0.013	3.750	4.639	0.237	17.600	16.400	0.068	13.330	10.512	0.211	9.331	0.300
23	2.000	1.823	0.089	4.050	4.574	0.129	10.000	10.187	0.019	13.330	10.910	0.182	9.364	0.298
24	0.700	0.504	0.280	2.650	2.258	0.148	No data			6.000	6.333	0.056	4.264	0.289
25	1.200	1.229	0.024	6.330	5.147	0.187	5.000	3.624	0.275	6.670	6.170	0.075	8.590	0.288
26	1.140	1.166	0.023	1.850	2.102	0.136	7.640	7.923	0.037	10.500	10.427	0.007	5.461	0.480
27	2.000	1.823	0.089	5.830	4.977	0.146	8.570	7.923	0.075	6.670	8.438	0.265	9.795	0.469
28	1.000	0.732	0.268	7.760	6.215	0.199	7.510	7.923	0.055	No data				
29	1.790	1.823	0.018	4.790	4.483	0.064	3.330	3.624	0.088	12.000	11.469	0.044	8.668	0.278
30	1.700	1.687	0.008	3.200	3.246	0.014	8.570	7.923	0.075	13.330	15.234	0.143	6.206	0.534
31	2.000	1.562	0.219	3.910	4.509	0.153	7.510	7.923	0.055	9.330	8.963	0.039	8.940	0.042
32	1.400	1.302	0.070	2.500	2.240	0.104	3.330	3.624	0.088	5.330	5.865	0.100	6.904	0.295

*All errors are in terms of relative percent.

Table 7. Checking normality test results for each accepted model.

Material	K	Mean	Standard deviation	O_i						X_0^2	$X_{\alpha,k-s-1}^2$	Is $X_0^2 < X_{\alpha,k-s-1}^2$?	Normality
				O_1	O_2	O_3	O_4	O_5	O_6				
Rebar	6	1.373	0.419	4	8	6	2	7	5	4.378	6.251	Yes	Accepted
Concrete	6	3.959	1.863	3	10	5	4	4	6	5.875	6.251	Yes	Accepted
Brick	6	7.151	3.289	3	9	4	6	4	3	5.552	6.251	Yes	Accepted
Cement	6	8.573	3.327	5	9	3	3	3	6	5.966	6.251	Yes	Accepted

sets are distributed normally and using MLR is allowed for quantification of all studied wasted materials [9,35,36].

3. Quantitative models

In the first part of the study, by means of IBM SPSS, dependent variable (BMW weight percent) and independent variables (contract type, locality, S, and FA) were analyzed for the studied BMs. Several combinations of the variables were examined, correlated variables were determined, and the best model satisfying acceptance criteria was found based on trial and error method. The general form of quantitative models based on MLR is as Eq. (9):

$$Y_{\text{Model}}^{\text{Material}} = \text{Const.} + \left(\sum_{i=1}^{8} \beta_i X_i \right) + E, \qquad (9)$$

where Const. is the constant, β_i is the coefficient of independent parameter X_i, and E is the error term.

3.1. Acceptance criteria

Acceptance criteria were derived from the most current and related papers and statistical references.

3.1.1. Validation

The following are the criteria of a valid model:

- Considering the sample size, parameters F and $|t|$ calculated by IBM SPSS for each model must be bigger than 2.15 and 2.03, respectively [36].
- P-value for the model must be equal to or less than 0.05 to find the best MLR for a significance level of $\alpha = 0.05$ [9,37].

3.1.2. Verification

Models must be felicitous for residential buildings, which are not studied in the conducted survey.

3.2. Valid and verified models

Validation and verification have to be performed separately for both parts of the study.

3.2.1. The first part of the study

Based on the delineated procedure, the following valid and verified models are developed to estimate BMW. The data used for this regression are presented in Table 5 (parameters FA (A), number of stories (S), contract type (X_1), and location (X_2 to X_8)) and Table 6 (amounts of wasted rebar, concrete, brick, and cement in sites ($Y_{\text{Site}}^{\text{Rebar}}$, $Y_{\text{Site}}^{\text{Concrete}}$, $Y_{\text{Site}}^{\text{Brick}}$, and $Y_{\text{Site}}^{\text{Cement}}$)).

$$Y_{\text{Model\_1}}^{\text{Rebar}} = 2.163 - 0.068S - 0.589X_1 - 0.261X_4 - 0.471X_5 - 0.434X_6 - 0.662X_8, \qquad (10)$$

$$Y_{\text{Model\_1}}^{\text{Concrete}} = 6.110 - 1.302A - 1.899X_1 - 0.825X_5 + 4.022X_6, \qquad (11)$$

$$Y_{\text{Model\_1}}^{\text{Brick}} = 7.923 - 1.516X_1 - 2.874X_4 - 2.783X_5 + 3.780X_7 + 8.477X_8, \qquad (12)$$

$$Y_{\text{Model\_1}}^{\text{Cement}} = 11.026 + 7.974A - 1.905S - 2.087X_1 - 2.346X_2 - 2.471X_5 - 9.491X_6 - 3.137X_8. \qquad (13)$$

3.2.2. Results of the previous researches

Kern et al. [9] conducted an analogous research in Brazil by studying 18 high-rise buildings and suggested Eq. (14) for C&DW generation:

$$\text{Waste (Ton)} = 5202.886 + 5138.519FR + 1.411FA + 22.968EIC + 375.155CS - 783.296WR + E, \qquad (14)$$

where FR is the number of on-ground floors to total number of floors ratio, WR is recycled materials percentage, CS is the construction system (1, 2, and 3 for conventional, ordinary, and industrial systems, respectively), and EIC is the economic index of compaction calculated by Eq. (15):

$$EIC = \frac{0.02 \times \sqrt{FA \times \pi}}{\left(\text{Plan perimeter} + \frac{\text{Number of edges}}{2}\right)}. \qquad (15)$$

Moreover, Ding and Xiao [15] suggested the wastage of concrete, brick, and rebar in 2013 in Shanghai to be 1, 5, and 3% by weight, respectively. Also, Cochran et al. [38] calculated the wastage of concrete, rebar, and wood equal to 22.9, 0.9, and 6.4 kg/m^2, respectively.

3.2.3. The second part of the study and theoretical soundness of the hypothesis

Incentive plans have already been implemented successfully in the Iranian agriculture industry (but not in construction industry yet) in order to compel farmers to cultivate substitute crops, i.e., corn instead of what they regularly grow, i.e., wheat. Based on the results of the conducted questionnaire survey, this method can potentially be helpful in reducing materials waste and might be an independent variable to explain building wastage. This is basically why the authors decided to test usefulness of this method and consider FI (C) in this part of study. To avoid duplication, parameters A and locality, which are involved in calculation of FI, are omitted. The data used for this regression are presented in Table 5 (parameters contract type (X_1) and FI or C). The following models are accepted after accomplishing the expounded procedure in the antecedent section:

$$Y^{\text{Rebar}}_{\text{Model\_2}} = 1.513 - 0.134X_1 - 0.575C, \tag{16}$$

$$Y^{\text{Concrete}}_{\text{Model\_2}} = 5.010 - 2.110X_1 - 2.535C, \tag{17}$$

$$Y^{\text{Brick}}_{\text{Model\_2}} = 7.615 - 2.438X_1 - 3.425C, \tag{18}$$

$$Y^{\text{Cement}}_{\text{Model\_2}} = 10.956 - 3.249X_1 - 0.100S - 6.480C. \tag{19}$$

3.2.4. Contract type quantitative effect

Quantitative effect of each independent variable, i.e., contract type, on BMW can be determined by analyzing its coefficient in Eqs. (10) to (13) and (16) to (19). Considering the values attributed to the parameter X_1, using cost-plus contract increases materials wastage, as depicted in Figure 2, for both scenarios of implementing or not implementing FI program.

3.2.5. Assigning FI to the most sensitive material and its evaluation in the second part of the study

According to the discussed characteristics of FI, it can be assigned to one of the BMs, and since its increase is a managerial tool for attain more reduction in waste, it should be attributed to the most sensitive material. This is the concept of elasticity analysis [2,39,40]. According to the definition of elasticity [26], the elasticity of BMW (Y) to FI (C) can be written as:

$$El_{YC} = \frac{\left(\frac{\partial Y}{Y}\right)}{\left(\frac{\partial C}{C}\right)} = \frac{\left(\frac{\Delta Y}{Y}\right)}{\left(\frac{\Delta C}{C}\right)} = \frac{\left(\frac{Y_2-Y_1}{Y_1}\right)}{\left(\frac{C_2-C_1}{C_1}\right)}. \tag{20}$$

The increase in elasticity of the studied BMW to FI is calculated for all buildings in Table 8. The average elasticity is used to calculate the total amount of BMW reduction after 1% increase in the initial incentive. The results are summarized in Table 9. If FI increases by up to 1%, the amount of cement waste will be reduced by up to 1.56%, which is more than the reduction in other materials wastage. Furthermore, cement is wasted more than other materials. As a corollary, attribution of the proposed FI to cement is legitimate.

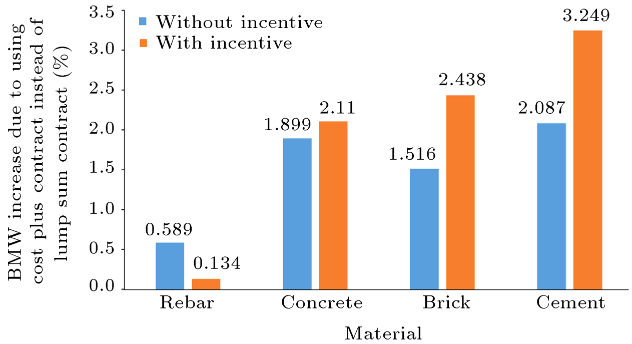

Figure 2. Quantitative effect of contract type on materials waste.

Benefit to cost ratio is used to evaluate the economic viability of the proposed FI. One unit of FI will result in 6.48% CWR according to Eq. (19). According to the last available data, annually, 3503 permits are issued for residential buildings construction, 4.7×10^6 m^2 residential building is constructed in Tehran, and the government allocates 100 kg cement per FA [41,42]. Furthermore, one ton of cement produced emits 933.80 kg CO_2 and avoiding emission of 1 ton of CO_2 using post combustion capture costs 107.4 € (about \$119) [43]. Therefore, cost and benefit (C_1 and B_1) of one unit of the proposed FI, \$1000, can be calculated:

$$C_1 = \frac{\text{unit cost (\$)} \times \text{permits number}}{\text{total constructed area (m}^2\text{)}} = \frac{1000 \times 3503}{4.7 \times 10^6} = 0.745 \left(\frac{\$}{\text{m}^2}\right), \tag{21}$$

$$B_1 = 6.48\% \times \frac{0.1\,\text{ton cement}}{1\,\text{m}^2\,FA} \times \frac{0.9338\,\text{ton CO}_2}{1\,\text{ton cement}} \times \frac{\$119}{1\,\text{ton avoided CO}_2} = 0.720 \left(\frac{\$}{\text{m}^2}\right). \tag{22}$$

The cost of increasing FI by x percent (ΔC) and benefit gained from corresponding CWR (cost saving, ΔB) should be considered too. According to Table 5, the average FI assigned to buildings equals $8.016 \times 1000/3961$ or \$2.023 per 1.0 m^2 FA and according to Table 9, 1% increase in FI results in 1.56% CWR:

$$\Delta C = \frac{x}{100} \times 2.023 = 0.020x \left(\frac{\$}{\text{m}^2}\right), \tag{23}$$

$$\Delta B = \frac{x}{100} \times 1.56 \times \frac{0.1\,\text{ton cement}}{1\,\text{m}^2\,FA} \times \frac{\$36.281}{1\,\text{ton cement}} = 0.057x \left(\frac{\$}{\text{m}^2}\right). \tag{24}$$

Cement costs \$36.281 per ton in Tehran [42]. Benefit to cost ratio equals:

$$\frac{\text{Benefit}}{\text{Cost}} = \frac{B_1 + \Delta B}{C_1 + \Delta C} = \frac{0.720 + 0.057x}{0.745 + 0.020x}, \tag{25}$$

$$1\%\ \text{increase in}\ FI \cong 1.56\% CWR \rightarrow \frac{\text{Benefit}}{\text{Cost}} = \frac{0.720 + 0.057x}{0.745 + 0.020x} \geq 1 \rightarrow x \geq 0.676\% \rightarrow CWR \geq 1.56 \times 0.676 = 1.055\%. \tag{26}$$

Table 8. Elasticity of studied BMs to one percent increase in the proposed FI.

Building no.	Rebar waste elasticity	Concrete waste elasticity	Brick waste elasticity	Cement waste elasticity
1	−0.117	−0.207	−0.120	−0.234
2	−0.111	−0.238	−0.154	−0.220
3	−0.141	−0.554	−0.248	−0.191
4	−0.349	−1.386	−0.286	−0.298
5	−0.123	−0.042	−0.073	−0.104
6	−0.021	−0.045	−0.035	−0.057
7	−0.043	−0.092	−0.049	−0.191
8	−0.022	−0.032	–	−0.084
9	−0.126	−0.242	−0.188	−0.142
10	−0.118	−0.166	−0.112	−0.136
11	−0.245	−0.196	−0.203	−0.414
12	−0.054	−0.044	−0.112	–
13	−0.028	−0.044	−0.080	−0.066
14	−0.026	−0.077	−0.047	−0.089
15	−0.051	−0.064	−0.023	−0.093
16	−0.596	−0.496	–	−0.480
17	−0.131	−0.146	−0.070	−0.253
18	−0.097	−0.196	−0.129	−0.124
19	−0.033	−0.069	−0.039	−0.076
20	−0.274	−0.179	−0.196	–
21	−0.085	−0.170	−0.130	−0.172
22	−0.080	−0.169	−0.049	−0.122
23	−0.075	−0.163	−0.089	−0.127
24	−0.398	−0.464	–	−0.524
25	−0.086	−0.072	−0.123	−0.175
26	−0.128	−0.348	−0.114	−0.157
27	−0.029	−0.044	−0.041	−0.099
28	−0.225	−0.128	−0.178	–
29	−0.089	−0.146	−0.284	−0.149
30	−0.211	−0.495	−0.250	−0.304
31	−0.067	−0.152	−0.107	−0.163
32	−0.081	−0.057	−0.058	−0.068
Average	−0.133	−0.216	−0.124	−0.183

Table 9. Total waste reduction of studied BMs per one percent increase in the proposed FI.

Material	Elasticity	Average wastage (%)	Total waste reduction (%)
Rebar	–0.133	1.32	0.18
Concrete	–0.216	3.96	0.86
Brick	–0.124	7.15	0.89
Cement	–0.183	8.57	1.56

Table 10. Annual reduction in raw materials as well as energy consumption and air pollutants emission per one percent increase in FI.

Indicator		Reduction	Unit
Raw materials consumption		12024.48	Ton
Electrical energy consumption		0.732	Million kWh
Heat energy consumption		6.065	Billion kcal
Air pollutants emission	CO_2	6846.622	Ton
	NO_x	18.110	Ton
	SO_2	3830.237	Ton
	SPM	730.267	Ton
Total air pollutants emission		11425.236	Ton

Thus, FI is economically viable when cement waste is reduced by more than 1.055%; therefore, the initial amount of FI can be increased proportional to this amount according to Eq. (27).

If $CWR \geq 1.055\%$ (1% increase in $FI \cong 1.56\% CWR$)

$$\rightarrow TFI=(1+x)\times DC=\left(1+\frac{CWR}{1.56\times 100}\right)\times DC=\left(1+\frac{CWR}{156}\right)\times 0.2\times K\times P\times FA, \quad (27)$$

where TFI is total FI in terms of $ and:

$$CWR=\%CW_1-\%CW_2, \quad (28)$$

where $\%CW_1$ is common cement waste weight percent asked of/estimated by project manager in projects without implementation of incentive based program, and $\%CW_2$ is cement waste weight percent after implementing FI based program.

On the other hand, when CWR is less than 1.055%, the contractor will be paid only the price of cement which is saved and not wasted according to Eq. (29):

$$\text{If } CWR<1.055\%\rightarrow TFI=\frac{CWR}{100}\times\frac{\$36.281}{1\,\text{ton cement}}\times\frac{0.1\,\text{ton cement}}{1\,\text{m}^2\,FA}\times FA\,(\text{m}^2)\times S=0.036\times CWR\times FA\times S. \quad (29)$$

Finally:

$$TFI=\begin{cases}(1+\frac{CWR}{156})\times 0.2\times K\times P\times FA & CWR\geq 1.055\%\\ 0.036\times CWR\times FA\times S & CWR<1.055\%\end{cases} \quad (30)$$

For environmental evaluation, considering 100 kg cement allocated per 1.0 m^2 FA and 4.7×10^6 m^2 annually constructed residential building in Tehran, 1.56% reduction in cement waste due to 1% increase in the amount of FI equals 7332 tons of CWR annually:

$$1.56\%\times\frac{0.1\,\text{ton cement}}{1\,\text{m}^2\,FA}\times 4.7\times 10^6\left(\frac{\text{m}^2\,FA}{\text{year}}\right)=7332\frac{\text{ton cement}}{\text{year}}. \quad (31)$$

Table 10 shows reductions in raw materials and energy consumption, and air pollutants emission per 1% increase in the proposed FI by multiplying 7332 tons of CWR by the environmental indicators in Table 1.

4. Checking models

4.1. Validation

All models are valid, because they satisfy the validation criteria (Tables 11 and 12). Parameters are defined in Table 13.

4.2. Verification

4.2.1. Verification of the models developed in the first part of the study

Thirty-two new residential buildings (equal to the primary sample size) were studied according to the described procedure in Section 2.1 and the BMs wastages in sites were calculated (Y_{Site}). Afterwards, Eqs. (10) to (13) were applied to the calculation of the estimated wastage of each material ($Y_{\text{Model\_1}}$). The relative errors of new residential buildings are presented in Table 14. All models have relative errors less than 30%, suggesting that the models are verified.

4.2.2. Verification of the models developed in the second part of the study

To implement the plan in public and private construction projects, it is necessary for the governmental organizations, i.e., municipalities and clients, to finance the program. To verify the models in the second

Table 11. Validation of the proposed models (part one).

	Equation number	Material	F	P-value	Is $F > 2.15$ and P-value≤ 0.05?	R^2	R^2_{Adjusted}
First part of study	11	Rebar	51.184	0.000	Yes	0.925	0.907
	12	Concrete	30.191	0.000	Yes	0.817	0.790
	13	Brick	65.108	0.000	Yes	0.934	0.920
	14	Cement	32.117	0.000	Yes	0.904	0.875
Second part of study	15	Rebar	27.393	0.000	Yes	0.763	0.735
	16	Concrete	42.018	0.000	Yes	0.832	0.812
	17	Brick	21.741	0.000	Yes	0.731	0.697
	18	Cement	64.685	0.000	Yes	0.791	0.741

Table 12. Validation of the proposed models (part two).

	Dependent variable	Constant or independent variables	P-value	t	Is $\|t\| > 2.03$ and P-value≤ 0.05?	Standard error	Beta
First part of study (without FI)	$Y^{\text{Rebar}}_{\text{Model\_1}}$	Constant	0.000	13.475	Yes	0.057	
		S	0.031	−2.280	Yes	0.030	−0.134
		X_1	0.000	−12.003	Yes	0.049	−0.699
		X_4	0.002	−3.448	Yes	0.076	−0.205
		X_5	0.000	−6.376	Yes	0.074	−0.370
		X_6	0.004	−3.166	Yes	0.137	−0.180
		X_8	0.000	−9.210	Yes	0.072	−0.520
	$Y^{\text{Concrete}}_{\text{Model\_1}}$	Constant	0.000	16.370	Yes	0.073	
		A	0.000	−4.360	Yes	0.099	−0.417
		X_1	0.000	−7.501	Yes	0.053	−0.666
		X_5	0.032	−2.256	Yes	0.066	−0.192
		X_6	0.000	5.615	Yes	0.076	0.492
	$Y^{\text{Brick}}_{\text{Model\_1}}$	Constant	0.000	24.291	Yes	0.026	
		X_1	0.001	−3.935	Yes	0.085	−0.223
		X_4	0.000	−5.147	Yes	0.058	−0.291
		X_5	0.000	−5.039	Yes	0.052	−0.282
		X_7	0.000	6.845	Yes	0.052	0.383
		X_8	0.000	11.058	Yes	0.067	0.632
	$Y^{\text{Cement}}_{\text{Model\_1}}$	Constant	0.000	7.365	Yes	0.097	
		A	0.000	10.220	Yes	0.076	−0.504
		S	0.000	−5.070	Yes	0.043	−0.331
		X_1	0.000	−4.709	Yes	0.025	−0.270
		X_2	0.001	−3.756	Yes	0.063	−0.259
		X_5	0.001	−3.727	Yes	0.039	−0.524
		X_6	0.000	−7.090	Yes	0.031	−0.329
		X_8	0.000	−4.973	Yes	0.080	0.154
Second part of study (with FI)	$Y^{\text{Rebar}}_{\text{Model\_2}}$	Constant	0.000	56.548	Yes	0.027	
		X_1	0.001	−4.219	Yes	0.032	−0.514
		C	0.000	−4.858	Yes	0.024	−0.592
	$Y^{\text{Concrete}}_{\text{Model\_2}}$	Constant	0.000	22.298	Yes	0.025	
		X_1	0.000	−7.908	Yes	0.067	−0.812
		C	0.021	−2.552	Yes	0.099	−0.262
	$Y^{\text{Brick}}_{\text{Model\_2}}$	Constant	0.000	19.981	Yes	0.081	
		X1	0.000	−5.640	Yes	0.032	−0.749
		C	0.050	−2.108	Yes	0.025	−0.280
	$Y^{\text{Cement}}_{\text{Model\_2}}$	Constant	0.020	6.981	Yes	0.037	
		X1	0.040	−6.155	Yes	0.021	−0.227
		C	0.010	−2.967	Yes	0.053	0.838
		S	0.050	−7.536	Yes	0.051	−0.284

Table 13. Verification and validation parameters definition.

Parameter	Definition
F	Distribution critical value with respect to the degrees of freedom related to numbers of buildings and variables
t	Distribution critical value with respect to the degrees of freedom related to number of buildings
P-value	The level of significance regarding the confidence level of 95%
R^2	Coefficient of determination
R^2_{Adjusted}	Adjusted coefficient of determination
Standard error	A measure of the statistical accuracy of an estimate
Beta	A measure of how strongly each predictor variable influences the dependent variable

Table 14. Verification of the proposed models in the first part of the study.

	Characteristics of buildings										Characteristics of materials											
				Locality							Rebar			Concrete			Brick			Cement		
Ref.	FA (m^2)	S	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	$Y_{\text{Model\_1}}$	Y_{Site}	$\lvert R_E \rvert$ (%)	$Y_{\text{Model\_1}}$	Y_{Site}	$\lvert R_E \rvert$ (%)	$Y_{\text{Model\_1}}$	Y_{Site}	$\lvert R_E \rvert$ (%)	$Y_{\text{Model\_1}}$	Y_{Site}	$\lvert R_E \rvert$ (%)
1	100	7	1	1	0	0	0	0	0	0	1.098	1.440	23.750	2.909	4.070	28.526	6.407	8.430	23.998	1.232	1.750	29.600
2	210	6	0	0	1	0	0	0	0	0	1.755	2.450	28.367	3.376	4.810	29.817	7.923	10.750	26.298	16.341	12.600	29.694
3	136	5	1	0	0	1	0	0	0	0	0.973	1.355	28.192	2.440	3.410	28.438	3.533	4.930	28.337	10.259	8.450	21.404
4	90	5	0	0	0	0	1	0	0	0	1.352	1.480	8.649	4.113	5.810	29.205	5.140	5.250	2.095	6.207	8.390	26.024
5	154	5	0	0	0	0	0	1	0	0	1.389	1.960	29.133	8.127	10.930	25.646	7.923	6.100	29.885	4.290	6.090	29.557
6	82	4	1	0	0	0	0	0	1	0	1.302	1.170	11.282	3.143	4.159	24.420	10.187	8.690	17.227	7.858	10.500	25.165
7	144	5	0	0	0	0	0	0	0	1	1.161	0.940	23.511	4.235	6.050	29.998	16.400	19.520	15.984	9.847	11.800	16.555
8	120	4	1	1	0	0	0	0	0	0	1.302	1.544	15.674	2.649	2.488	6.455	6.407	7.256	11.701	8.542	9.521	10.285
9	125	7	0	0	1	0	0	0	0	0	1.687	2.202	23.388	4.483	3.458	29.627	7.923	8.596	7.829	7.659	10.222	25.078
10	220	5	1	0	0	1	0	0	0	0	0.973	1.387	29.849	1.347	1.247	7.987	3.533	4.563	22.573	16.957	14.258	18.928
11	180	6	1	0	0	0	1	0	0	0	0.695	0.901	22.863	1.042	0.897	16.210	3.624	4.587	20.994	9.391	10.364	9.386
12	195	5	0	0	0	0	0	1	0	0	1.389	1.899	26.856	7.593	10.358	26.69 3	7.923	8.654	8.447	7.559	8.654	12.650
13	225	5	0	0	0	0	0	0	1	0	1.823	2.252	19.050	3.181	3.587	11.333	11.703	12.365	5.354	19.443	20.326	4.347
14	230	5	0	0	0	0	0	0	0	1	1.161	1.487	21.923	3.115	2.894	7.650	16.400	18.254	10.157	16.704	17.025	1.884
15	170	5	0	1	0	0	0	0	0	0	1.823	2.310	21.082	3.897	4.895	20.396	7.923	8.951	11.485	12.711	16.254	21.799
16	150	6	1	0	1	0	0	0	0	0	1.166	1.250	6.720	2.258	3.225	29.984	6.407	7.125	10.082	9.470	10.365	8.635
17	165	6	0	0	0	1	0	0	0	0	1.494	1.212	23.267	3.962	4.589	13.670	5.049	4.025	25.441	12.753	12.369	3.105
18	188	7	1	0	0	0	1	0	0	0	0.627	0.554	13.177	0.938	1.298	27.716	3.624	4.451	18.580	8.124	10.369	21.650
19	148	6	0	0	0	0	0	1	0	0	1.321	1.233	7.137	8.205	10.325	20.532	7.923	8.888	10.857	1.907	2.214	13.888
20	190	6	1	0	0	0	0	0	1	0	1.166	1.251	6.795	1.737	2.457	29.296	10.187	12.365	17.614	12.660	13.355	5.207
21	195	6	1	0	0	0	0	0	0	1	0.504	0.670	24.776	1.672	1.421	17.671	14.884	16.458	9.564	9.921	10.663	6.956
22	175	4	1	1	0	0	0	0	0	0	1.302	1.589	18.062	1.933	2.589	25.357	6.407	7.214	11.187	12.928	10.365	24.723
23	130	5	0	0	1	0	0	0	0	0	1.823	1.534	18.840	4.417	5.142	14.092	7.923	8.657	8.479	11.867	12.366	4.034
24	120	5	1	0	0	1	0	0	0	0	0.973	0.889	9.449	2.649	3.654	27.515	3.533	4.658	24.152	8.983	10.789	16.741
25	190	6	0	0	0	0	1	0	0	0	1.284	1.462	12.175	2.811	2.667	5.407	5.140	6.589	21.991	12.276	13.652	10.082
26	220	7	1	0	0	0	0	1	0	0	0.664	0.895	25.810	5.369	6.147	12.663	6.407	8.547	25.038	3.656	4.895	25.316
27	215	5	0	0	0	0	0	0	1	0	1.823	2.314	21.219	3.311	4.458	25.736	11.703	12.365	5.354	18.645	17.214	8.314
28	218	6	0	0	0	0	0	0	0	1	1.093	1.236	11.570	3.272	4.154	21.241	16.400	19.256	14.832	13.842	12.365	11.948
29	170	7	1	1	0	0	0	0	0	0	1.098	1.254	12.440	1.998	1.769	12.923	6.407	9.125	29.786	6.814	7.156	4.782
30	168	4	1	0	1	0	0	0	0	0	1.302	1.574	17.281	2.024	2.547	20.548	6.407	5.698	12.443	14.715	15.247	3.487
31	200	5	1	0	0	1	0	0	0	0	0.973	1.250	22.160	1.607	1.987	19.124	3.533	4.365	19.061	15.362	16.452	6.625
32	210	4	0	0	0	0	1	0	0	0	1.420	1.646	13.730	2.551	3.541	27.964	5.140	5.324	3.456	17.680	18.696	5.432

part of the study and the proposed reward program, a residential building project client (who was builder of his own projects too and is called builder in the rest of the paper) from private sector was contacted. The authors described the expected benefits of the proposed plan, namely reduction in purchased and wasted materials, environmental pollutions, and landfilled wastes, to persuade him to implement the FI based program during several consecutive meetings. Finally, he gave consent to implementing the plan in a current five-story residential building project with an FA of 285 m^2 in Tehran. This study lasted for 4 months. As a result of this reward program, the wasted and purchased amounts of cement were reduced. In this building, concrete was traditionally prepared in site rather than being bought from batching plants. To clarify:

$$\Delta Pc = P_{2,c} - P_{1,c}, \quad (32)$$

$$\Delta Wc = W_{2,c} - W_{1,c}, \quad (33)$$

where $P_{2,c}$ (or $W_{2,c}$) and $P_{1,c}$ (or $W_{1,c}$) are amounts of purchased (or wasted) cement after implementing FI program and before it, respectively. Amounts of $P_{2,c}$ and $W_{2,c}$ are calculated after finishing of the case study. Amounts of $P_{1,c}$ and $W_{1,c}$ are estimated according to the experience and judgment of the builder. The total benefit gained would be calculated according to Eq. (34):

$$\text{Total benefit gained} = -(\Delta Wc + \Delta Pc) \times \text{Price}_c, \quad (34)$$

where Price_c is unit cost of cement. According to Table 15, the benefit gained is \$472.234. Based on Eqs. (28)-(30):

$$CWR = \%CW_1 - \%CW_2 = 100 \times \left(\frac{W_{1,c}}{P_{1,c}} - \frac{W_{2,c}}{P_{2,c}}\right)$$

$$= \frac{810.7}{121000.0} - \frac{310.5}{108500.0} = 0.67\% - 0.28\%$$

$$= 0.39\%, \quad (35)$$

$$CWR = 0.39\% < 1.055\% \rightarrow TFI = 0.036 \times CWR$$

$$\times FA \times S = 0.036 \times 0.39 \times 285 \times 5$$

$$= \$20.01. \quad (36)$$

Based on the estimation of the builder, in his projects, usually 10% and 6.7% cement is wasted because of excessive purchase order and lack of supervision during construction, respectively. Therefore, according to Table 15, he ordered 108.5 tons of cement instead of his primary estimation of 121 tons (reducing excessive purchase order policy), because he was determined to reduce cement waste. Furthermore, at the beginning of the project, he assigned the task of reducing cement waste to the possible extent to one of the labor; also, we persuaded him by paying him a reward commensurate with cost savings at the end of the project (reducing avoidable waste policy). The labor avoided the wastage of cement by preventing other labor from discarding semi-filled cement packs and providing better storing conditions. As a result, 301.5 kg cement was wasted instead of the expected amount of 6.7% × 121 or 810.7 kg. Finally, the builder saved \$472.234 and paid the labor \$20.01 (see Eq. (36)), meaning that reducing avoidable cement waste per se saved a net value of \$452.224. Considering \$29429 as the total cost of purchased materials, \$452.224 reduction in cost of wasted cement accounts for 1.54% reduction in cost of purchased materials.

5. Results

The following results are derived from the first part of the study:

- Cement with average wastage of 8.57% by weight is the most wasted bulk material. Waste percentages for rebar, concrete, and brick are 1.32%, 3.96%, and 7.15%, respectively (Table 9);
- Locality and contract type variables are modeled in quantitative forms, concurrently;
- Building materials waste can be quantified rather than the total wasted materials to contrive plans for reduction in each building material waste;
- Effects of all studied variables on BMW are determined as follows:
  - In a specific model, the difference between two locality coefficients shows how much the wastage of the same material will be changed if a particular building is constructed in the second location instead of the first location;
  - The coefficient X_1 is negative in all models. Thus, materials are more waste-prone in projects with cost-plus contract than in those with lump-sum contracts. Considering the values of coefficient X_1 in the developed models, it is concluded that choosing cost-plus contract instead of lump-sum contract increases wastage by up to 0.589%, 1.899%, 1.516%, and 2.087% for rebar, concrete, brick, and cement, respectively (Figure 2). By dividing these values into corresponding average waste percentages from Table 9, 44.62%, 47.96%, 21.20%, and 24.35% relative waste increases for rebar, concrete, brick, and cement are resulted. This is an auspicious result, because cost-plus contract rules and regulations lead to contractor apathy toward heedful use of materials, which is opposed to CW reduction. Therefore, cost-plus contract, which is common in Iran for traditional

Table 15. Conducted case study results.

Material	Unit	Price_c (\$)	$P_{1,c}$	$P_{2,c}$	$W_{1,c}$	$W_{2,c}$	Benefit (\$)
Cement	kg	0.0363	121000.00	108500.00	810.7	301.5	472.234

residential buildings, is considered an improper contract type according to CW management policies.

- MLR is proved to be a pertinent tool to CWG quantification;
- Interpreting the values of independent variable S:
  - Rebar is mostly wasted due to uneconomical overlaps and cut-offs, which are intensified when more rebar is required. Forces and moments decrease in upper stories when less rebar is required. Therefore, the more the number of stories, the less the required rebar, overlaps, cut-offs, and waste will be. This makes the coefficient S in rebar waste model negative;
  - Cement is wasted due to poor transportation and storage conditions as well as discarding semi-filled sacks manually by the labor, which happens more in lower stories than in upper ones where cement sacks are lifted electro-mechanically. Hence, cement waste percent decreases as the number of stories increases. This makes the coefficient S in cement waste model negative;
  - Brick is wasted mostly during transportation. Bricks usually are lifted to upper stories by electro-mechanical lift, which is not supposed to damage bricks. Therefore, the number of stories has relatively no effect on brick waste;
  - Concrete is wasted by remaining in pumping tubes, which is not used elsewhere. The volume of tube is constant, meaning that the maximum amount of wasted concrete is limited to this volume. Therefore, the number of stories has relatively no effect of concrete waste.
- Interpreting the values of independent variable A:
  - As mentioned in the previous interpretation, the main culprit of brick waste is transportation. In construction sites, brick is lifted to stories and then carried by the labor. Brick wastage during this carriage is negligible in comparison with that during transportation. Thus, floor area does not affect brick waste;
  - Rebar is produced in 12-meter elements in Iran. Lengths of the beams are usually more than 12 m; therefore, less cut-offs and overlaps are required than columns, which are about 3 m. Thus, floor area does not affect rebar waste;
  - The more the floor area, the more concrete is required, while the wasted concrete volume cannot be more than the pumping tube volume. Therefore, weight percent of concrete waste decreases as the floor area increases and the coefficient A in concrete waste model is negative;
  - Cement on stories can be wasted due to reckless pulling of cement sacks on harsh ground by the labor, which hurts the sacks and results in cement waste. The bigger the plan area, the more the pulling distance and the cement waste are. Therefore, coefficient A in cement waste model is positive.
- For rebar, concrete, brick, and cement, adjusted coefficients of determination (R^2_{Adjusted}) equal 0.907, 0.790, 0.920, and 0.875, respectively, meaning that the studied variables approximately measure 90.70%, 79.00%, 92.00%, and 87.50% the factors involved in the BMs wastage.

The following are the results of the second part of the study, which lead to cement waste reduction:

- In Eq. (13), the values of coefficients A and S are +7.974 and -1.905, respectively, meaning that smaller buildings with more stories surpass bigger buildings with fewer stories in reducing cement wastage. This can be regarded by the municipality of Tehran in developing new public housing projects as well as residential building projects in northern Tehran in future, e.g., the studied location, i.e., Saadat-Abad, where construction of large one- or two-story buildings is commonplace;
- Elasticity concept along with MLR can be used in cement waste management;
- Reward based programs are preferred and proposed by construction industry experts to contrive BMW adeptly;
- The proposed FI works well in curtailing cement waste;
- The proposed FI program is justifiable both economically and environmentally. Table 16 summarizes the environmental and economic evaluations of this FI and its advantages;
- About 90% of permits for residential buildings are issued for 4- to 7-story buildings in Tehran [36]. This is why the authors chose these kinds of buildings. The locations were selected in a manner that covered nearly all locations of Tehran. In other words, design and construction methods of buildings in other locations were similar to those of the studied buildings. Hence, the chosen buildings were studied in such a manner that represented the majority of residential buildings in Tehran. This means that the proposed FI is applicable to approximately all residential buildings in Tehran with an acceptable error level;
- P-values for all derived models in Eqs. (10) to (13) and (16) to (19) are less than 0.05; all the same, the standard errors of some coefficients exceed 0.05. It means that the studied independent variables all together have a good correlation with the dependent

Table 16. Summarizing the proposed FI implementation advantages (per 1% FI increase).

Economic viability elements				Environmental justifiability					
C_1 (\$/m^2)	B_1 (\$/m^2)	ΔC (\$/m^2)	ΔB (\$/m^2)	Cement waste reduction		Reduction in resources consumption			Reduction in air pollutants emission (ton per year)
				Relative (%)	Total (ton per year)	Raw materials (ton per year)	Electrical energy (million kWh per year)	Heat energy (billion kcal per year)	
0.745	0.720	0.020	0.057	1.56	7332	12024.48	0.732	6.065	11425.236

variable, but a single independent variable does not necessarily correlate with the corresponding dependent variable. In other words, wastage of a specific studied material is a function of a set of independent variables rather than a sole independent variable. This result is very close to the result for a current MLR conducted by Kern et al., 2015 [9];

- Linear property makes the models less time-consuming to analyze. This advantage accelerated designing, evaluating, and finalizing the financial incentive-based proposal in the second part of the research;
- There is theoretical relationship between FI and CWR in the residential building projects of Tehran;
- Part of cost savings due to reducing avoidable wastes and excessive purchased materials can be used to persuade the labor into reducing wasted materials to the possible extent;
- According to the results for the case study, the proposed FI program reduced cement waste from 0.67% to 0.28%, which equaled 0.39% CWR (Eq. (35));
- Saving of implementing the proposed financial reward system is \$452.224 and regarding \$29429 as the total cost of purchased materials, this saving in cost of wasted cement accounts for 1.54% reduction in cost of purchased materials.

6. Conclusions

The authors used trial-and-error method to select a regression method for quantification. In trial-and-error method, the first trial can be the simplest and most available one [44] and if this trial does not lead to satisfactory results, the process has to be repeated with another trial. After that Kern et al. (2015) in a recent research used MLR to quantify waste generation in Brazil, the authors were persuaded to choose MLR as the first trial. After applying this method, the results would be analyzed. In this study, fortunately, MLR as the first trial led to suitable results. In other words, the adjusted coefficients of determination (R^2_{Adjusted}) for the developed models were in the acceptable range in the review of the literature [9,36]. As a result, no other regression method was tested to quantify wastages.

Regarding research limitations, in the first part of the study, models were developed to engender a good database for BMW in residential building projects of Tehran by determining quantitative effects of different variables, e.g., contract type. The result was in a good agreement with the reviewed literature and contractual origin of CWG was identified as a rudimentary one directly influencing other origins (purchase, storage, on-site carriage, etc.) [2].

The second part of the study focused on finding solutions to reducing cement as the most wasted material. Selecting a proper contract type would prevent wasteful utilization of cement. Considering regulations of the studied contracts from the CW management viewpoint, lump-sum contract was suggested instead of cost-plus contract generally made in traditional residential buildings construction in Tehran. Furthermore, the suggested FI, of which viability and environmental friendliness were confirmed, was a proper managerial tool to persuade contractors into reducing cement wastage.

The results of this paper are a testimony to the fact that CWG quantification alleviates devising unique solutions to BMW, i.e., reducing cement waste, recycling rebar and concrete, reusing brick, etc., which is incumbent upon urban managers. In this study, an FI program reduced the quantity of wasted cement in residential buildings, but did not eliminated it completely. It is suggested that future researchers work on methods of zero waste buildings, which previously targeted zero-killed and zero-accident construction projects. In addition, it may be asserted that although the studied case was residential buildings of Tehran, it is possible to generalize and apply the model to other locations. To do this, the following modifications have to be made:

1. Determining the major contract types of the new location;
2. Selecting a state and dividing it to smaller locations in the study;

3. Developing a new financial incentive based scheme compatible with local regulations; and
4. Identifying the major construction materials of the new location.

In summary, contributions of this paper, compared to previous similar studies, include:

- Proposing quantification as an apt tool for CW management and planning;
- Introducing MLR as a suitable mathematical tool of CW quantification;
- Simultaneous inclusion of contract type and locality as qualitative factors;
- Suggesting financial incentive as a new method for cement waste management;
- Quantifying the influence of financial incentive on cement waste; and
- Identifying environmental evaluation as an important factor in designing financial incentive based plans besides the previously proposed criterion (economic parameter [24,45-48]).

Finally, the following are the research limitations, which might be addressed in the future academic studies:

- Concentration on residential buildings with concrete structure, which have a great share among construction projects in Tehran;
- Disregarding the effects of parameters like skill, training, and education level of the labor; and
- Concentration on four BMs only.

The future scholars may use other quantification methods such as binomial regression, polynomial regression, etc. and compare their results with those of the present paper.

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Acronyms

BM	Building Material
BMW	Building Material(s) Waste
C&DW	Construction and Demolition Waste
CW	Construction Waste
CWG	Construction Waste Generation
CWR	Cement Waste Reduction
FA	Floor Area
FI	Financial Incentive
MLR	Multiple Linear Regression

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Biographies

Amirreza Mahpour received his BSc degree in 2014 from Amirkabir University of Technology, Tehran, Iran, and his MSc degree in Construction Engineering and Management in 2016 from Sharif University of Technology, Tehran, Iran, with honors during all the 6 years of studies. His research is within the field of construction and demolition waste management and devising policies to manage this kind of solid waste. He started his PhD program at the University of Toronto in September 2018.

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Mohammad Mehdi Mortaheb received his PhD in 1990 in Construction Materials and Management from University of Kentucky, Lexington, KY, USA. He has been a member of the scientific committees of several national and international conferences related to project and construction management and supervised many graduate students doing their MSc degrees at Sharif University of Technology (SUT) and other universities. He has been active in directing and managing different real projects, especially in pipe line as well as oil, gas, and petrochemical industries of Iran over the last 42 years.