EMPIRICAL MODEL TO CALCULATE THE WASTE GENERATED IN RESIDENTIAL BUILDING CONSTRUCTIONS

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ABSTRACT

There are numerous studies developing quantification models of construction and demolition waste (CDW) in building works. Currently, knowing the amount of CDW generated in a construction site is essential to optimize its management. Therefore, any tool, which can estimate in advance the waste generated, should be considered a strategy to propose real solutions in the field of sustainability.

However, the developed models up to now, offer indicators taking into consideration only the gross floor area (GFA) of the project. In general, GFA has been widely used for CDW estimation worldwide and mainly in high density urban areas such as China or Hong Kong where dwellings are sold by GFA. However, regions such as Europe, U.S or Australia may need to consider other parameters such as the numbers of dwellings as houses are usually sold by units.

Also, previous research highlight that masonry work is the main activity generating CDW. Considering this issue, the amount of waste generated during masonry works in two different projects --with the same floor area—but one designed with big surface dwellings and the other with small studios, will differ --as the latter has more brick interior partitions--.

Consequently, the main aim of this research is to establish a model to estimate the waste generated, both in weight and volume, considering the GFA and the number of dwellings of the project. To do this, several construction works built in the Community of Madrid have been analyzed. The results obtained offer some formulas to know in advance the amount, both in weight and volume of the total waste that will be generated in newly built construction works.

In short, the methodology developed in this paper can help to optimize and systematize the management of the CDW generated in residential construction and can help building agents in the development of CDW management Plans and Reports in agreement with the legislation in force.

Keywords: construction and demolition waste; quantification; estimation tools; residential buildings.

1.- Introduction

In 2012 Spain generated around 26 million tonnes of CDW [1]. Although now the activity has entered in a phase of decline, due to the change of the economic cycle, the quantity of CDW generated has decreased since the beginning of the crises, but its management has gone worse as illegal dumping has increased around 20% **[2]**.

Aware of this situation, the European Countries are implementing national policies as well as different measures to prevent the waste that can be avoidable and to promote measures to increase recycling and recovering [3]. In particular, the Royal Decree 105/2008 regulates the production and management of the CDW in Spain. This Law, forces to draw up a CDW management Report – during the design phase—and CDW management Plan –during the planning of the construction work-- for each project. The CDW management Plan document is specific for the construction work and it is based on the CDW management Report included in the design project and should necessarily include the following information:

- An estimated approach of the amount, in tons and volume of the C&D waste to be generated in the construction work.
- The operations of reuse, valorization or final disposal of the waste.
- The drawings of the installations provided for CDW storage, handling or any other management activity.
- The descriptions to include in the technical specifications of the design project, regarding storage, handling or any other managing operation of the CDW to be carried out on the working site.
- An assessment of the predicted cost for the correct management of CDW, which should be stated in the project budget in a separate section.
- CDW should be classified in fractions when a certain volume of generated. If this volume is reached or surpassed and onsite segregation is not possible due the lack of physical space, an authorized external CDW manager needs to be subcontracted.

Thus, the new Reports and Plans promote waste minimization, selective removal and recycling of the inevitable waste, favoring the reduction of the environmental impact of the building [4].

Despite the high potential of CDW valuation, and the existence of different management models, today, professionals continue prioritizing elimination as opposed to recycling or reuse [5]. According to the 2nd National Plan of CDW 2007-2015 (II PNCDW), in Spain the percentage of CDW recycled, did not reach, even in the best of cases, 18% of the total waste produced [6].

This situation is mainly due to the type of waste collection system used in the construction of buildings, as it is decentralized by each subcontracted company in the construction work [7]. This means that the principle of waste reduction is not applied in practice, since it is not considered as an activity in the planning of the work. There is therefore, an important lack of planning and implementation on site best practices to minimize waste and promote recycling [8, 9].

Nevertheless, the main construction companies are slowly considering environmental issues by implementing Environmental Management Systems (EMS), not being limited to the current legislation, and seeking the implementation of good environmental measures in their works [10]. However, while this fact is a reality for large construction companies, still the vast majority of construction companies (small and medium enterprises) need to accept this trend [11]. Therefore, current EMS should go a step further and include not only procedures for managing CDW, but also tools for estimating CDW waste which will help to plan a proper CDW management in order to achieve building construction works with zero waste generation.

In this sense, the concern to establish indicators describing the waste generated -- both in new construction and demolition works-- has increased in recent years [12-15]. In general, the vast majority of these analyses estimate the total amount of waste generated considering the built up area of the project [16]. However, the number of dwellings in the project should also be a factor to be considered when estimating CDW generation. Therefore, the main aim of this research is to establish a formula to estimate, both in weight and volume, CDW generation considering two variables: the total built area of the project and the number of dwellings. The results of this research will help develop the CDW Management Plans and Reports.

2.- Material and methods

The study focused on obtaining the total waste generated from seven newly built buildings carried out by a Spanish construction company with similar construction features among them (table 1).

All the projects follow a traditional Mediterranean building construction: deep foundations with concrete piles, one-way slabs, flat roofs, brick façades insulated with polyurethane foam and interior partitions made of ceramic hollow bricks or plasterboard [17]. The construction works were ordered, showing work site O32 as the smallest in size (32 dwellings) and O226 as the largest (226 dwellings). Projects with the same number of dwellings have been distinguished by including an "A" or "B" at the end (table 1).

Work site code	Nº dwellings	m^2 per dwelling	Total built area (m^2)	Interior partition
O226	226	67	23,569.00	Ceramic brick
O192	192	89	17,617.00	Plasterboard
O156	156	119	30,759.68	Plasterboard
O105	105	105	20,435.24	Ceramic brick
O59	59	59	11,045.30	Plasterboard
O32A	32	111	5,983.46	Ceramic brick
O32B	32	111	5,983.46	Ceramic brick

Table 1 "Characteristics of the works analyzed".

In sum, four projects were built using traditional ceramic partitions and four with drywall plasterboard, containing 32–226 dwellings, with five to eight floors above ground and two to three underground levels. Moreover, the relation between the total floor area and the number of dwellings ranged from 104.29 and 197.18 m^2/dwelling, in all the projects analyzed.

With the selected works, an experimental data collection has been performed using the delivery notes corresponding to when the work containers left the site (service delivery), as well as the delivery notes issued by the waste manager once the heavy containers arrived at the recycling plant (receipt of admission).The pilot study allowed to identify, through the actual on-site data, the volume and the weight of the total waste generated daily in each work. In total, more than 8000 data of CDW generation were collected, and they have been statistically processed.

Moreover, a preliminary analysis of CDW generation data obtained for each work was performed first, analyzing the CDW generation and each variable studied: number of dwellings and total floor area (individually). The results are displayed in four XY graphs relating such amounts with each variable.

2.1.- Development of the formula for CDW estimation considering two variables
In order to compare both variables on the same value scale, weighting of variables is needed [18]. To this end, it is necessary to obtain, for each analyzed work, weighted factors for both variables: number of dwellings (a) and total built area (b). The weighting factor is determined by using equation 1.

$$\mathbf{VP}_{x_n} = \frac{Vx_n}{\sum V\,x_n} \tag{1}$$

Where,
- x is x the analyzed variable (number of dwellings "a" or built area "b").
- n is one of the works analyzed (n = 1, 2, 3, 4, 5, 6 and 7).
- Vx_n is the value of the variable x for the analyzed work "n".
- $\mathbf{VP}_{x_n}$ is the weighted value of each variable x for the analyzed work "n".

Seven weighting factors are calculated for each variable of study. In total 14 weighting factors are obtained. Finally, the relationship between the calculated weighted values and the amount of CDW generated (in weight and volume) is calculated. To do so, an analysis of polynomial regression between CDW kg vs weighted value, is performed, and another between CDW m^3 vs weighted value.
Subsequently, it is necessary to establish the importance value each variable will have at the end of the formula. To do so, a multiple regression analysis is carried out with the data obtained from the seven selected construction works, considering as the only independent variables, the weighted number of dwellings ($\mathbf{VP}_{a_i}$) and the weighted built surface ($\mathbf{VP}_{b_i}$).
With the regression analysis the determination coefficients values (R^2) are obtained showing the correlation between the data and the proposed model. In this sense, given a random series of data population, corresponding to the seven tested construction works, the parameter estimations of the resulting linear regression model are described with equation 2:

$$y_i = \beta_o + \beta_1 x_{1i} + \beta_2 x_{2i} + e_i \tag{2}$$

- y is the amount of CDW estimated for the particular work "i".
- β represents the parameters of the model indicating how changes in each of the independent variables "x" ($VP_{a_i}\ and\ VP_{b_i}$) influence on the dependent variable "y".
- e_i is the residual error, being the difference between the observed values (y_i) and those estimated by the model of the dependent variable ($\hat{y}_i$) (Equation 3).

$$e_i = y_i - \hat{y}_i \tag{3}$$

The value of the non-standardized coefficients of the equation (β) cannot be used to determine the relative influence of each variable on the amount of CDW, since they are measured on different scales. However, it is possible to use the standardized coefficients, allowing to set the relative importance of the input variables (number of dwellings and total built area).
Thus, the result obtained in regression analysis allows to statistically determining the variables influencing the estimate of the generated CDW in residential building

construction, quantifying the influence of each independent variable in the final formula for the waste estimation and obtaining the corrected weighted factors (FP_c).

Finally, a polynomial regression was performed to analyze the relationship between corrected weighted factor (FP_c) and the CDW generation, using the SPSS statistical program. The equation of the curve closest to the data used is obtained. The efficiency of the proposed adjustment curve has been tested with a confidence level of 95% ($p < 0.05$).

This equation allows estimating the amount of CDW generated once the fixed weighted factor of the works is known. Likewise, the existing deviation between the values obtained with the model and those obtained in other Mediterranean studies or projects were checked in order to test the validity of the model and show its usefulness in contrast to other studies. Results are not compared with data from other countries because construction characteristics will differ from one region to another.

3.- Results and discussion

All studied homes have a total built m^2/ housing m^2 comprised between 1.29 and 1.31. The proposed adjustment equation is designed for projects meeting these conditions, or with similar characteristics to the analyzed works. The CDW amounts obtained with the experimental analysis are displayed in figure 1.
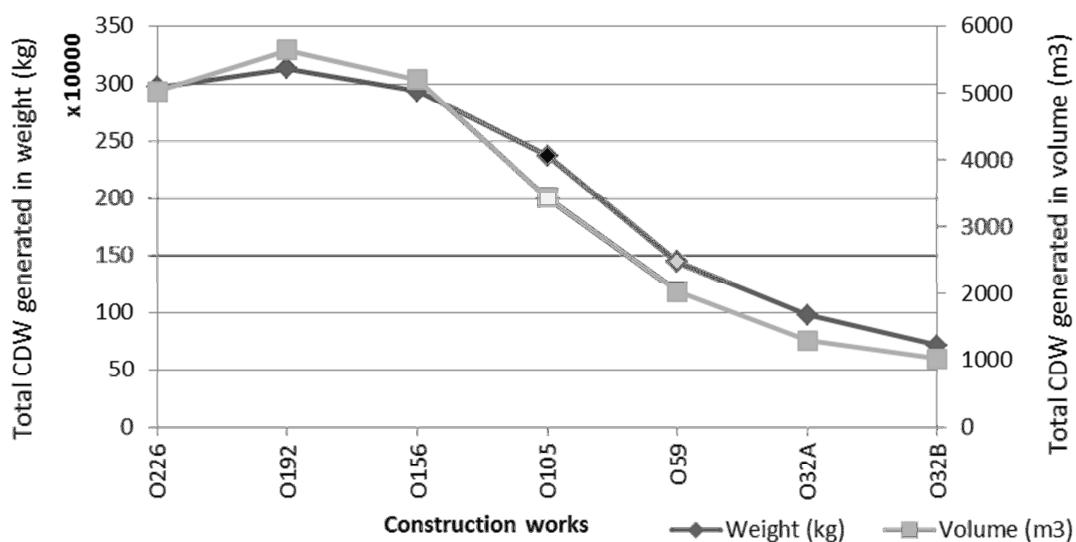

Fig 1 "Amount of CDW generated, in weight and volume, for each of the analyzed works"

In general, there is a decrease in the total CDW generated, both in weight and volume, as the number of dwellings decreases. A small deviation was found between projects O32A and O32B (around 21% less in weight), built with exactly the same characteristics but with different construction teams/subcontractors and locations. In this sense, a deviation of around 21% can be reached depending on the management carried out by the construction team. This factor can also explain the other small deviation found (around 11%) when comparing site O226 and O192.

As can be seen from the results in Fig 2, as the number of dwellings and the total floor area of the project increases, greater quantities of waste are generated. Figure 2 shows an irregular trend of CDW generation. In particular, sites O226 and O156 generate less waste despite having the greatest number of dwellings and total floor area, respectively. This irregularity can be due to their relation between the total floor area and the number of dwellings. Site O226 has the lowest ratio of all the projects analyzed (situated at 104.29 m^2/ dwelling) and site O156 the maximum (197.18 m^2/

dwelling). Therefore, the proposed model can be limited to: projects up to 226 dwellings, 30759.68m^2 of total floor area and the ratios should be ranged from 104.29 m^2/ dwelling to 197.18 m^2/ dwelling.

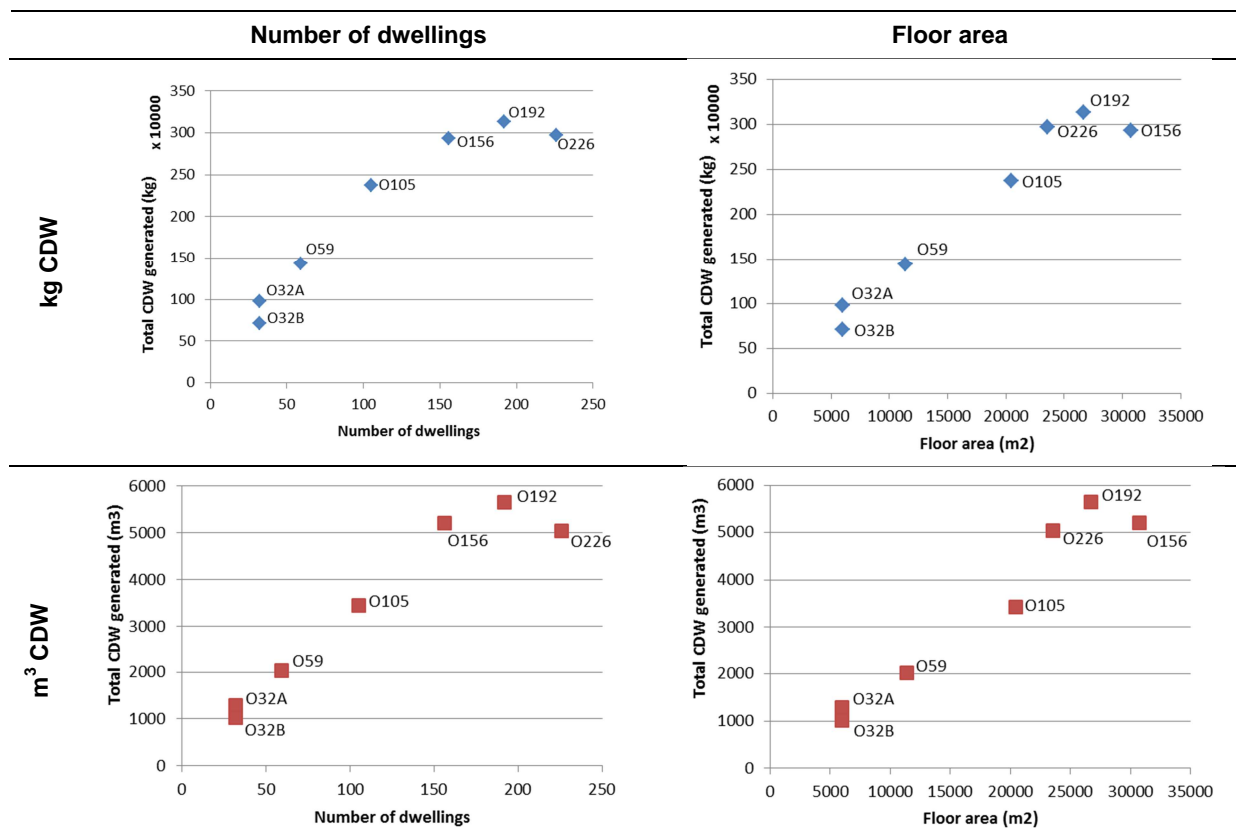| Number of dwellings	Floor area

Fig 2 "Total CDW generated, in weight and volume, for each variable analyzed".

3.1. Formula development for the estimation of the generated CDW

Table 2 displays the values of the two independent variables of the seven works analyzed (Va_n y Vb_n), as well as their respective weighted values --calculated with the equation 1-. These weighted factors allow comparing both independent variables, using the same scale of values.

Site (n)	Va_n [und]	Vb_n [m^2]	Weighted factors (VP$_n$)		Corrected weighting factor (FP$_c$)	
			VP$_{a_n}$	VP$_{b_n}$	Weight	Volume
O226	226	23569.01	0.282	0.189	0.176	0.182
O192	192	26691.63	0.239	0.214	0.181	0.183
O156	156	30759.68	0.195	0.246	0.188	0.185
O105	105	20435.24	0.131	0.164	0.133	0.131
O59	59	11395.71	0.074	0.091	0.079	0.078
O32	32	5983.46	0.040	0.048	0.044	0.043
O32	32	5983.46	0.040	0.048	0.044	0.043
Total Vx_i	802	124818.19				

Table 2 "Weighted factors and corrected weighting factors obtained for each construction site".

Based on the results of table 2, an equation is established to calculate the weighted value of each variable in one work (i), once the number of dwellings is known (equation 4) and the total built area (equation 5).

$$\text{VP}_{a_i} = \frac{Va_i}{\sum Va_n + Va_i} = \frac{Va_i}{802 + Va_i} \tag{4}$$

$$VP_{b_i} = \frac{Vb_i}{\sum Vb_n + Vb_i} = \frac{Vb_i}{124818.19 + Vb_i} \tag{5}$$

Where,

Va_i is the number of dwellings of the building work

Vb_i is the surface built in m2 of the work

VP_{a_i} is the weighting factor corresponding to the number of dwellings.

VP_{b_i} is the weighting factor corresponding to the built surface

3.1.1. Corrected weighting factors

The results of the performed multiple linear regression model with data from the seven studied works show a strong correlation between the quantities of CDW and the weighted values of the independent variables, since the determination coefficient (R^2) values obtained are: 0.990 for weight estimation, and 0.997 for volume. On the other hand, the obtained p-values for the estimation by weight and volume, are less than 0.05. This confirms that, with a confidence level of 95%, the variation explained by the model is not due to chance. Ultimately, these values are sufficiently high to consider the influence of both variables in the estimation of the CDW proven.

At the same time, table 3 shows the standardized coefficients and the results of the significance test to check the validity of the multiple linear regression models. In every case, as can be observed in table 3, in order to estimate the amount of generated CDW, variable *b* "total floor area" presents greater influence than variable *a* "number of dwellings" (greater standardized coefficients).

Model		CDW estimation (kg)		CDW estimation (m^3)	
Variables		**Nº dwellings**	**Built surface**	**Nº dwellings**	**Built surface**
Standardized coef.	β	0.289	0.711	0.375	0,625
p-value		0,090	0.008	0.009	0.001

Table 3 "Coefficients and p-values of the multiple linear regression models of the 7 residential construction works analyzed".

The influence of variable b is much greater when estimating the waste weight, since a standardized coefficient of 0.711 is obtained, in contrast with the one obtained for the variable of the number of dwellings (0.289). In the case of the estimation per volume (m3), the number of dwellings has a greater importance than for the estimation per weight. However, the built surface keeps as the most influential variable obtaining a standardized coefficient equal to 0.625. In addition, the "t" test results show that all the variables are significant at a 90% confidence level (p-value < 0.1) and cannot be removed from the model.

The previous results validate the proposed regression model and, therefore, the standardized coefficients will be used to calculate the corrected weighted factors, which are significant to each variable in the final formula of the waste estimation (equations 6 and 7). In short, the corrected weighting factor of a work can be calculated with the weighted values, once the built surface and the number of dwellings in the project are known.

Volume:
$$FP_c = (VP_{a_i} * 0.375) + \left(VP_{b_i} * 0.625\right) \tag{6}$$

Weight:
$$FP_c = (VP_{a_i} * 0.289) + \left(VP_{b_i} * 0.711\right) \tag{7}$$

Where,
FP_c is the corrected weighting factor

3.1.2. Formula development for CDW estimation
The corrected weighted factor will allow establishing the final formula to estimate the kg or m^3 of CDW generated (Q_{CDW}) (equations 8 and 9).

Volume:
$$Q_{CDW} = 628657.10 FP_c{}^3 - 130041.95\ FP_c{}^2 + 32460.93\ FP_c \qquad \text{R}^2\text{=0.998} \qquad (8)$$

Weight:
$$Q_{CDW} = -175190710.21 FP_c{}^3 + 24517298.88\ FP_c{}^2 + 17863852.57 FP_c \quad \text{R}^2\text{=0.998} \qquad (9)$$

The proposed adjustment equations are designed for projects with similar characteristics to the ones analyzed here (table 1), following the Mediterranean conventional construction style for residential premises and with FP_c up to 0.188 (table 2). If other factors were incorporated into the model – e.g. the type of materials, the use of prefabrication systems, the construction quality level, etc. – the efficiency of the model for CDW estimation might be further enhanced. However, the methodology shown can definitely help to obtain new quantification models in other countries or even in projects with different characteristics to the ones analyzed here.
Finally, the deviation between the CDW quantities obtained with the proposed model and those generated in other previous studies and projects are shown in table 4. Despite the lack of data specifying the needed information to be used with the model proposed a total of nine projects were used to validate the model: two from previous Spanish researches and seven from data provided by a different construction company.

Other studies	Real CDW generation		Parameters		CDW estimation model					
					kg			m^3		
	(kg)	(m^3)	Va_n[und]	Vb_n [m^2]	FP_c	Q_{CDW}	Error (%)	FP_c	Q_{CDW}	Error (%)
Project 1	3388798	6182	177	36477	0.213	3224546.7	-4.85	0.209	7092.1	10.84
Project 2	No Data	3438	139	18433	0.134	2415110.9	-	0.136	3532.9	4.27
Project 3	1953920	2457	91	14170	0.102	1890184.1	-3.26	0.102	2623.6	6.78
Project 4	1944274	3856	83	19088	0.121	2216757.3	14.01	0.118	3149.3	-20.78
Project 5	1786240	2745	72	13406	0.093	1728001.5	-3.26	0.091	2393.7	-13.92
Project 6	1555850	2463	56	13288	0.087	1629331.8	4.72	0.085	2260.4	-10.82
Project 7	846420	1429	26	5360	0.038	711217.7	-15.97	0.038	1089.0	-25.28
Llatas [19]	No Data	1208	26	2882	0.025	461453.9	-	0.026	743.4	-38.48
Solís-Guzmán [14]	No Data	492.2	16	1600	0.015	266444.6	-	0.015	449.7	-5.14
Mean Deviation							-1.43			-10.28

Table 4 "Deviation of the amount of CDW obtained with the proposed model and the real CDW generated"

The results obtained with the model (equations 8 and 9) show a mean deviation of around -0.75% in weight and -10.28% in volume, as opposed to the amount of CDW generated in other projects. In addition, the maximum deviation is located around -38.48% in volume and -15.97% in weight. Also, Project 1 slightly exceeds the range of total floor area and FP_c determined in the model. However, an error of around 7.50% is obtained. Moreover, figures 3 and 4 graphically show the existing deviation between the model proposed for CDW estimation and the one generated in other

projects (table 4). These deviations may be due to the management performed by the working team. This would demonstrate the importance of the on-site management carried out and the good practices implemented to minimize the waste generated.
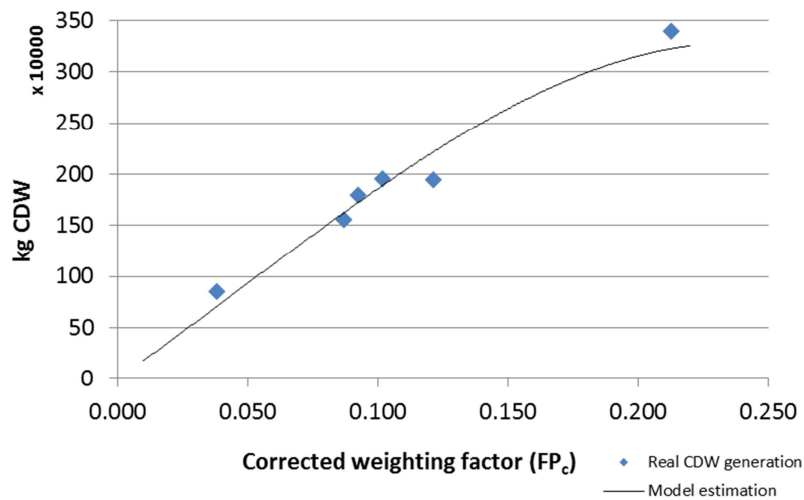

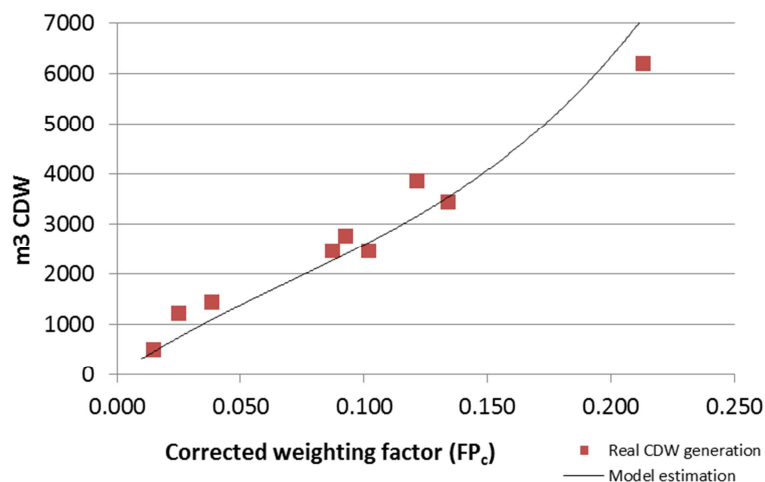Fig 3 "Weight of CDW estimated with the proposed model vs the CDW generated in the 7 works analyzed"

Fig 4 "Volume of CDW estimated with the proposed model vs CDW generated in the 7 works studied"

In short, by introducing the number of dwellings and the total floor area of a newly built project– with similar characteristics to the ones studied in this research (table 3)--, construction agents can obtain its weighting factor using equations 4 or 5. Further, they can estimate ahead of time the total waste that will be generated by using equations 7 and 9 (weight estimation) or 6 and 8 (volume estimation).

4.- Conclusions

The model reached in this paper estimates CDW generation, both in volume and weight, in newly built residential buildings is shown, considering two variables: number of dwellings and total built area. The methodology followed can serve to obtain new quantification models in other areas or even other types of building constructions. Also, considering other factors influencing CDW generation in the final formula, will definitely improve the model's efficiency.

In general, the proposed estimation model differs around 1% to 10% from the data collected in other projects or published in previous research works (both for weight and volume). Also, other variables such as the management carried out by the work team or good practices implemented to minimize CDW generation may result in maximum deviations of the model.

In short, the model developed in this article can be included in the Environmental Management Systems of construction companies, helping construction agents to only to optimize and systematize the management of the CDW generated in residential constructions, but also to develop the CDW management Plans and Reports in agreement with the legislation in force.

ACKNOWLEDGEMENTS

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