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Article

Analysis of Influencing Factors on Solid Waste Generation of Public Buildings in Tropical Monsoon Climate Region

Tingwei Meng [1], Xiaofang Shan [1,2], Zhigang Ren [1,2] and Qinli Deng [1,2,*]

1 School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China; tingweimeng@whut.edu.cn (T.M.); xfshan@whut.edu.cn (X.S.); renzg@whut.edu.cn (Z.R.)
2 Hainan Institute, Wuhan University of Technology, No. 5 Chuangxin Road, Sanya 572024, China
* Correspondence: deng4213@whut.edu.cn

Abstract: Environmental problems including the depletion of natural resources and energy have drawn a lot of attention from all sectors of society in the context of high-quality global development, and solid waste generated by the construction industry accounts for 36% of the total amount of municipal waste. The generation of large amounts of construction waste not only causes a waste of resources, but also causes great damage to the environment. Reducing the quantity of solid waste produced during a building's new construction period can be greatly aided by construction site solid waste statistics and forecasts. Based on the statistical data of 61 public construction projects in Hainan Province, China, this study uses the Random Forest algorithm to rank the importance of possible factors affecting the amount of solid waste generated, and linearly fits the data to achieve the prediction of solid waste at construction sites. The findings indicate that building area, building height, concrete usage, steel usage and assembly rate are the main factors affecting solid waste in construction sites. In office buildings and exhibition buildings, an increase in ground area, building height, concrete usage, and steel usage increases the generation of each type of solid waste (inorganic non-metallic solid waste, metallic solid waste), with the exception of an increase in concrete usage, which results in a decrease in the generation of metallic solid waste. Furthermore, a higher assembly rate can substantially lower the production of all waste types. These results offer a theoretical foundation for the implementation of assembly construction to support the high-quality development of the construction industry, as well as partial design inspiration for the architectural design stage.

Keywords: construction site; solid waste; random forest; prediction

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1. Introduction

The building area in China has been steadily increasing during the "13th Five-Year Plan" period, indicating the rapid development of the country's construction industry. By 2020, the country's housing construction area is expected to reach 14.947 billion square meters [1]. China is the largest nation in the field of new construction, and Zhu et al. noted that the country produces a significant amount of construction solid waste, which makes up 30–40% of all municipal waste [2]. China's rapid urbanization over the past few decades has resulted in the generation of a significant amount of solid waste from construction sites [3,4]. As the construction industry becomes more important as the country's pillar industry, the quantity of solid waste produced at construction sites will unavoidably rise along with the number of new buildings that are constructed.

Landfills are used to dispose of a lot of solid waste currently [5], but in most places, the amount of landfill material generated exceeds the landfill's capacity [4]. The random stacking of a large amount of solid waste not only causes a large amount of material waste, but also leads to air and soil pollution, seriously harming the ecosystem [6–8]. Recycling solid garbage can significantly lessen its environmental impact [9]. Nonetheless, compared to the 76% recycling rate in the United States and the average 90% recycling rate in the

28 nations that make up the European Union, China's recycling percentage for construction solid waste is extremely low [10–12]; it is only about 5% [13].

Many academics have previously studied the topic of recycling construction solid waste (hereinafter referred to as solid waste). China and the United States have made exceptional contributions in this area [14] and have investigated a variety of recycling techniques for it. In place of natural aggregate resources, recycled aggregates from construction solid waste are added to cement and concrete [15–19]. Strategies to improve their performance are also investigated. Some scholars use solid waste as recycled aggregates as sub-base materials in road construction [20–22].

Reducing the generation of solid waste from construction sites is the best strategy to manage it for new buildings, yet scholars have paid relatively little attention to this aspect of research [23–25]. A portion of the academics used software simulation and the project construction personnel questionnaire to analyze the current solid waste management conundrum, propose fundamental guidelines for the development and management of solid waste at construction sites, and offer initiatives and suggestions to minimize construction solid waste during the construction phase [24–29]. Other scholars have analyzed different solid waste treatment methods in the whole life cycle from both economic and environmental aspects, and provided suggestions for policy makers and practitioners on how to improve waste management through the analysis of research findings [30]. Duan et al. anticipated a significant increase in the generation of medical waste during the COVID-19 public health crisis, and predicted that the treatment system of this medical waste had serious challenges, so they conducted research to improve its treatment efficiency. Their findings not only reveal the changes brought about by the outbreak, but also provide effective measures to improve the efficiency of medical waste management in emergencies, which can provide guidance for policy makers and practitioners on how to improve management during public health crises [31]. In an effort to reduce the quantity of solid waste that may be produced during building construction from the design stage, several academics have also investigated the influence of various influencing factors on the amount of construction solid waste generated. Many elements, such as floor area, building type, building height, assembly rate, and construction environment influence the quantity of solid waste generated during a building's construction phase [32]. Prefabricated structures have been shown to significantly reduce the generation of solid waste [33,34].

China's Hainan Province has a tropical monsoon climate, which means that there are increased demands for building materials due to the region's high seasonal temperatures, high humidity, and high salinity levels. High-performance materials mean that their cost is higher than that of ordinary building materials, and the solid waste generated at the construction site will lead to more serious economic losses and environmental pollution. Therefore, under such climate conditions, It is very important to study the influencing factors of the generation rate of solid waste at the construction site of public buildings and their action rules for the future development of the construction industry, which can avoid environmental pollution and resource waste caused by construction solid waste from the source. In order to achieve this goal, this paper made accurate data collection of 61 public buildings in Hainan Province in the construction stage, to a certain extent, to make up for the lack of data in the current research. At the same time, the influence of various factors on the production of solid waste in the construction site of new buildings is studied, and the importance of each factor is analyzed by the Random Forest algorithm. According to the results of the importance analysis, the main influencing factors of solid waste production rate were determined, and the correlation analysis was carried out with the measured data to explore the connotation between the changes of influencing factors and the solid waste production rate.

2. Research Objectives and Methods

2.1. Research Objects

China has not provided a precise definition of construction solid waste. Construction waste disposal technical standards will be defined as: engineering residue, engineering slurry, engineering rubbish, demolition waste, decoration waste, etc., including new construction, expansion, alteration and demolition of all kinds of buildings, structures, pipe networks, etc., as well as residents to decorate the process of house decoration of the discarded soil, discarded materials and other waste, excluding the inspection, identification of hazardous waste construction waste [35]. Considering the different contents of the study, this paper defines construction solid waste as follows: the generic term for engineering sludge, engineering mud, engineering rubbish, and decorating garbage, including new construction, expansion, alteration and demolition of all kinds of buildings, structures, pipe networks, etc., as well as residents to decorate the process of house decoration of the discarded soil, discarded materials and other waste, including solid waste tested as hazardous waste. This paper focuses on the solid waste generated at the construction site of the main stage of the building, so the solid waste mentioned below refers to all of the solid waste generated at the construction site of the main stage of the building.

It is necessary to classify the solid waste in order to better analyze the solid waste generated during the construction site of the main stage of the building [7]. The source classification method, the physical composition classification method, the chemical composition classification method, and other methods are currently used to classify solid waste. The classification method of Chen Lei et al. [36] is cited in this paper. It divided construction solid waste into five categories: inorganic non-metallic solid waste (INSW), organic non-metallic solid waste (ONSW), metallic solid waste (MSW), composite solid waste (CSW) and hazardous solid waste (HSW). The specific classification is as follows Table 1.

Table 1. Classification of new construction solid waste.

Sort	Description and Contained Component
INSW	Stands for inorganic non-metallic solid waste, including natural stone, burnt earth products, cement, concrete and silicate products, etc.
ONSW	Stands for inorganic non-metallic solid waste, including waste plastic, waste paint, waste adhesive and other plant materials, synthetic polymer materials and asphalt materials, etc.
MSW	Stands for metallic solid waste, including scrap steel bars, scrap copper pipes and other ferrous and non-ferrous materials, etc.
CSW	Stands for composite solid waste, including lightweight metal sandwich board, gypsum board, etc.
HSW	Stands for hazardous solid waste, including rock wool, asbestos, glass glue, etc.

2.2. Research Boundary

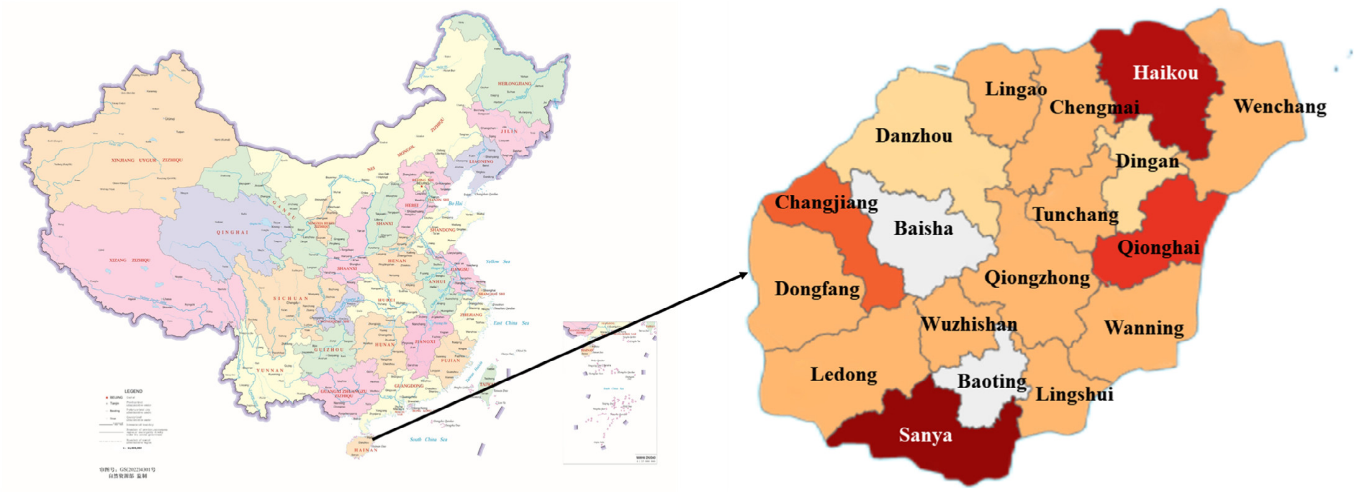
Determining reasonable research boundaries plays a crucial role in determining the accuracy of conclusions [37]. This study focuses on the production of solid waste at construction sites. In order to more precisely quantify the solid waste, this document gives defined parameters for the study scope, such as time boundaries, object boundaries, field pair boundaries, element boundaries, and other requirements [38]. Table 2 shows the methodology used to determine the exact limitations.

Table 2. Research Boundary Delineation Table.

Boundary Name	Boundary Range
Time boundaries	From the beginning of construction to the completion and acceptance of the entire construction project.
Object boundaries	Take the buildings in the project as the research object, only the solid waste generated in the underground, main, decoration and electromechanical stages of the new building is calculated, and the solid waste generated in any other construction stage is not included in the calculation.
Site boundaries	All kinds of building materials start to be calculated when they enter the boundary of the construction site, and solid waste generated by transport and processing outside the site is not calculated.
Element boundaries	Solid waste generated from the daily lives of construction workers is not counted.
Other provisions	Materials that can be reused directly, such as waste soil, are not counted as solid waste, and materials that need to be processed before they can be used, such as waste steel pipes, need to be counted.

2.3. Data Sources

Data collection is a very important part of the whole research. In order to better complete the data collection during the study and ensure the accuracy of the data, data collection was carried out around a certain construction phase of 61 public buildings in Hainan Province, including 29 office buildings and 32 exhibition buildings. The classification outlined in 1.1 is used to statistically weigh the solid trash produced at the construction site. Figure 1: Project Distribution Map displays the projects' distribution.



Place	Total	Exhibition Buildings	Office Buildings	Place	Total	Exhibition Buildings	Office Buildings	Place	Total	Exhibition Buildings	Office Buildings
Baisha	1	1	0	Ledong	2	2	0	Wenchang	3	1	2
Danzhou	1	0	1	Wanning	3	2	1	Changjiang	4	2	2
Dingan	1	0	1	Chengmai	3	2	1	Qionghai	6	4	2
Wuzhishan	2	2	0	Lingao	3	1	2	Haikou	9	4	5
Dongfang	2	0	2	Lingshui	3	2	1	Sanya	13	7	6
Tunchang	2	0	2	Qiongzhong	3	2	1				

Figure 1. Project distribution map.

2.4. Random Forest

Random Forest is a classifier containing many decision trees proposed by Leo Breiman, which is a non-parametric machine learning method. Random Forest is an effective method for handling regression and classification issues, and it may also be used to evaluate the relative significance of explanatory factors. Random Forest works effectively, and provides precise variable importance prediction even when there are a lot of features and few data.

The algorithm of Random Forest consists of the following steps: 1. Use sampling method with put-back to draw n samples from the sample set as a training set. 2. Randomly draw M (M is less than the total number of features) features from the sampled samples as inputs to the training decision tree, to find the optimal delineation of features, and to construct the decision tree. 3. Repeat the steps 1–2 for K times, to generate K decision trees that constitute a random forest. 4. Finally, the classification results of the K decision trees are integrated, and the samples are predicted and analyzed. By quantifying each feature's contribution to the classification performance of the K decision tree construction process, Random Forest evaluates the importance of features. The evaluation index used in this general calculation is the out-of-bag error rate. Feature importance measures (FIM) are the measures used to assess the importance of features.

Defining Indicator Functions $I(x, y)$.

$$I(x,y) = \begin{cases} 1, x = y \\ 0, x \neq y \end{cases} \tag{1}$$

The $FIM_{km}^{(OOB)}$ of the mth feature Fm in the kth tree is

$$FIM_{km}^{(OOB)} = \frac{\sum_{p=1}^{n_0^k} I(Y_p, Y_p^k)}{n_0^k} - \frac{\sum_{p=1}^{n_0^k} I(Y_p, Y_{p,\pi_m}^k)}{n_0^k} \tag{2}$$

In this equation: n_0^k is a sample of observations from the kth tree, Y_p is the true classification label corresponding to the Pth sample, and Y_{p,π_m}^k is the classification result of the Kth decision tree for the Pth sample after the ensuing replacement Fm, where the Kth decision tree after the replacement Fm needs to be retrained. When the feature F does not appear in the kth bare tree, $FIM_{km}^{(OOB)} = 0$.

The importance score of feature F in the whole random forest is defined as follows:

$$FIM_{m}^{(OOB)} = \frac{\sum_{p=1}^{K} FIM_{km}^{(OOB)}}{K\sigma} \tag{3}$$

where K denotes the number of decision trees in the random forest and σ denotes the standard deviation of $FIM_{km}^{(OOB)}$. The importance score $FIM_{m}^{(OOB)}$ of feature Fm characterizes the contribution of Fm to the correct classification rate.

3. Results

3.1. Influence Factor Screening

Pre-processing the data is necessary to make better use of the sample data. There are instances of missing data in the samples that were gathered for the study. In a statistical sample, a missing value can be filled in using techniques like mean replacement and predictive simulation filling. However, the total amount of measured data in this study is rather small, so adopting this type of data cleaning method will have a greater impact on the subsequent impact analysis; so we choose to delete the statistical sample. Furthermore, the gathered data samples suffer from significant variations in the dataset's characteristic interval range. As a result, the data must be normalized to ensure that the influencing elements with varying scales are measured on the same scale.

Following the preprocessing of the data, the importance of each factor that might have an impact on the rate of solid waste generation during the construction phase was determined. The findings indicated that certain factors, including pile diameter ratio, pit support and structural type, had very little bearing on the rate of solid waste generation. Based on this, Random Forest was used to analyze the major factors influencing the rate of solid waste generation during the main phase and explore the importance of each factor (importance is measured on a scale of 0 to 1, with 1 representing the highest level of importance for a feature). The specific findings are displayed in Figure 2.

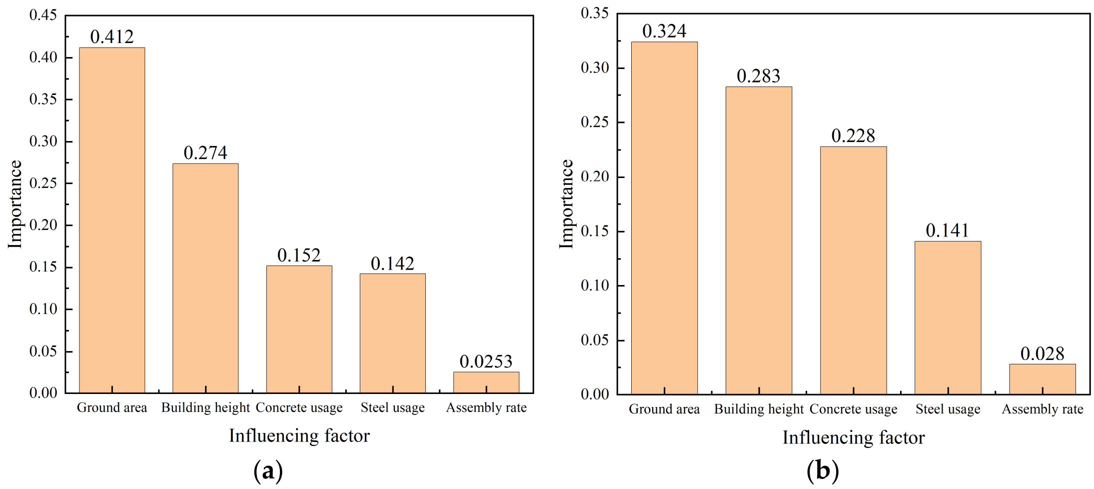


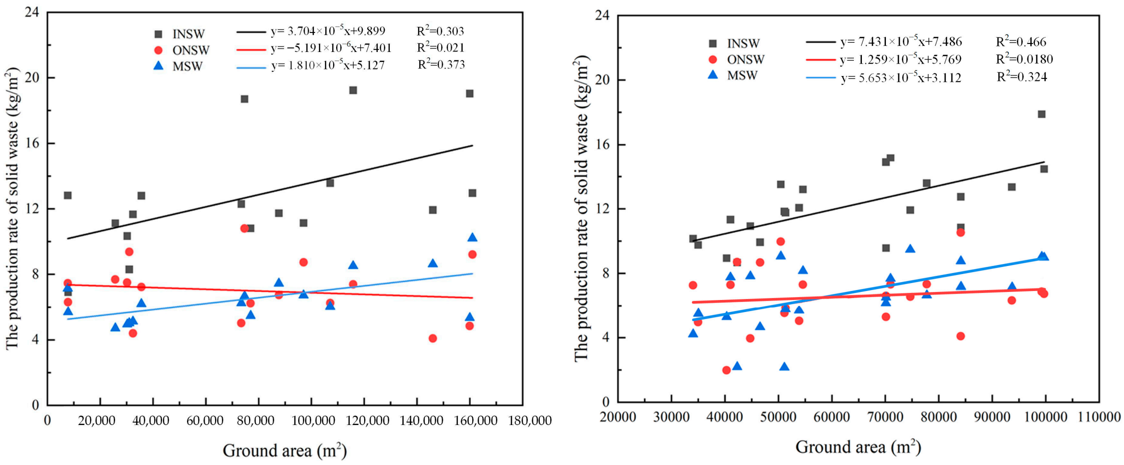
Figure 2. Importance analysis of factors affecting solid waste generation rate at construction sites. (**a**) Office buildings; (**b**) Exhibition buildings.

A number of influencing elements, including ground area, building height, concrete usage, steel usage, and assembly rate, were chosen for the importance analysis of influencing factors. The above figure shows that ground area (0.412) and building height (importance factor: 0.274) have the greatest effects on the construction site solid waste generation rate in the new construction phase of office buildings. There is not much difference in the influence of the amount of concrete usage and steel usage, with an influence factor of 0.152 and 0.142, respectively. With only 0.0253, the assembly rate has the least significant influence. When it comes to exhibition buildings, several influencing factors on the production rate of solid waste on the construction site are, in order of importance, ground area, building height, concrete usage, steel usage and assembly rate, and their influencing factors are 0.324, 0.283, 0.228, 0.141 and 0.028, respectively.

In addition to the assembly rate, the results are basically consistent with the conclusions of Hu et al., that is, that the construction area and building height are the main factors affecting the solid waste generation rate at the construction site; but Hu et al. paid more attention to the impact of the process on the average solid waste generation rate [32]. The construction stage assembly rate for various types of construction solid waste generation rate is not large in the results of the analysis of the importance of the impact factors. This is because the sample data's assembly rate distribution is more centralized, and there are only a few sample data points where the assembly rate is different. As a result, the assembly rate's impact on the analysis of the impact is smaller. Analyzing the gathered samples further demonstrates that in real projects, the solid waste generation rate of buildings with assembled components is significantly lower than that of buildings without assembled components. This has been amply demonstrated by other researchers.

3.2. Influence of Ground Area

The building area had the biggest influence on solid waste at the building construction site, based on the Random Forest analysis results. According to the type of building use, the sample data from the main stage is divided into office buildings and exhibition buildings. The more concentrated portion of the data is then chosen, a scatter plot is created, and it is linearly fitted to yield a fitting curve and the correlation coefficient R^2 value. The results are shown in Figure 3.



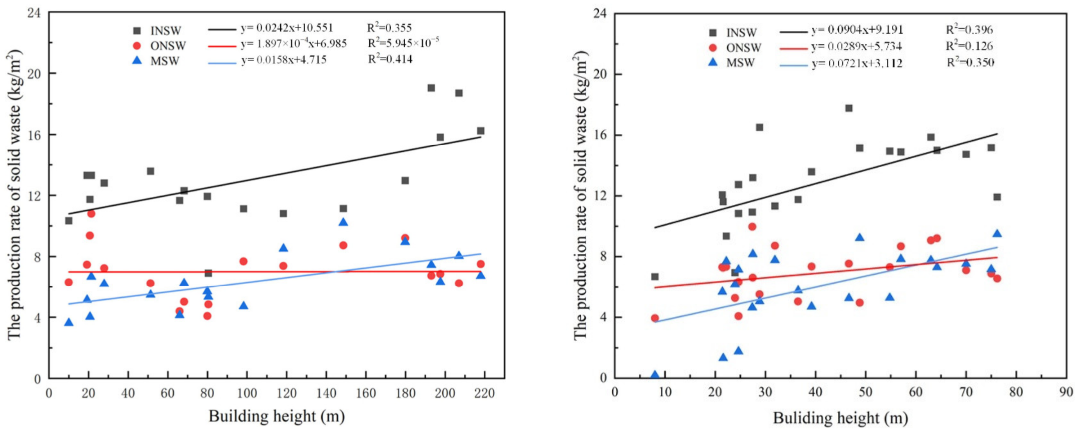
(**a**) (**b**)

Figure 3. Effect of ground area on solid waste generation rate. (**a**) Office buildings; (**b**) Exhibition buildings.

While ONSW was fitted poorly, INSW and MSW were fitted better. As ground area increases, there is a trend toward an increase in the generation rate of INSW and MSW at construction sites. In office buildings, the generation rate of INSW and MSW increases by 0.370 kg/m^2 and 0.181 kg/m^2, respectively, for every 10,000 m^2 increase in ground area. As for exhibition buildings, the generation rate of INSW and MSW increases by 0.743 kg/m^2 and 0.565 kg/m^2, respectively, for every 10,000 m^2 increase in ground area.

3.3. Influence of Building Height

The height of the building has a large impact on the solid waste of the construction site. The same method in Section 3.2 was followed to fit the curve. The results are shown in Figure 4.



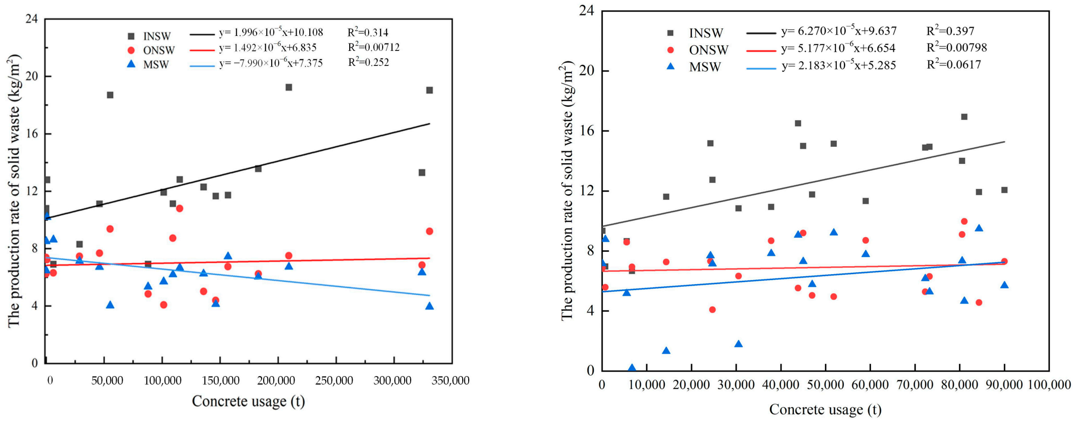
(**a**) (**b**)

Figure 4. Effect of building height on solid waste generation rate. (**a**) Office buildings; (**b**) Exhibition buildings.

The results showed that the goodness of fit was equally high for INSW and MSW, and poorer for ONSW. The generation rate of all types of solid waste in the construction stage of new buildings shows an increasing trend with the increase of building height. For office buildings, every 10 m increase in building height, the generation rate of INSW and MSW increases by 0.242 kg/m^2 and 0.158 kg/m^2, respectively. As for exhibition buildings, the generation rate of INSW and MSW increases by 0.904 kg/m^2 and 0.721 kg/m^2, respectively, for every 10 m increase in building height.

3.4. Influence of the Amount of Concrete Usage

The amount of concrete usage has a large impact on the solid waste generation rate of the building construction site. The results are shown in Figure 5.



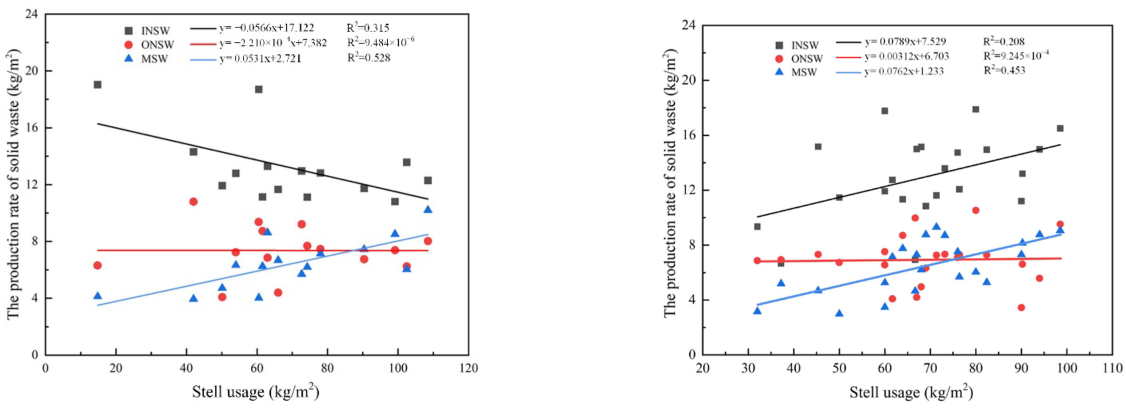
(**a**) (**b**)

Figure 5. Effect of the amount of concrete usage on solid waste generation rate. (**a**) Office buildings; (**b**) Exhibition buildings.

The fitting results show that the generation rate of ONSW is not affected by the amount of concrete usage, but the amount of concrete usage and the generation rate of INSW and MSW in the construction stage of office buildings show a certain correlation. For office buildings, for every 10,000 t increase in the amount of concrete usage, INSW increases by 0.199 kg/m^2, and MSW generation rate decreases by 0.0799 kg/m^2. As for exhibition buildings, for every 10,000 t increase in the amount of concrete usage, INSW and MSW generation rate increases by 0.627 kg/m^2 and 0.218 kg/m^2, respectively.

3.5. Influence of the Amount of Steel Usage

The amount of steel usage is also one of the main influencing factors of the solid waste generation rate. The results are shown in Figure 6.



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

Figure 6. Effect of the amount of steel usage on solid waste generation rate. (**a**) Office buildings; (**b**) Exhibition buildings.

The fitting findings indicate that the amount of steel usage has a significant effect on the generation rate of MSW, and also influences the generation rate of INSW; however, the amount of steel usage has no effect on the generation rate of ONSW. In office buildings, for every 10 kg/m^2 increase in the amount of steel used, MSW increases by 0.531 kg/m^2, and the generation rate of INSW decreases by 0.566 kg/m^2. While exhibition buildings, the use of steel increased by 10 kg/m^2, INSW and MSW generation rate increases by 0.789 kg/m^2 and 0.762 kg/m^2, respectively.

3.6. The Impact of Assembly Rate

Because the data samples of the assembly rate are more concentrated, the typical values of measured data under different assembly rates are selected to make the fitting curve of solid waste generation under different assembly rates, and the values of the fitting curve and the correlation coefficient R^2 are found. Specific results are shown in Figure 7.

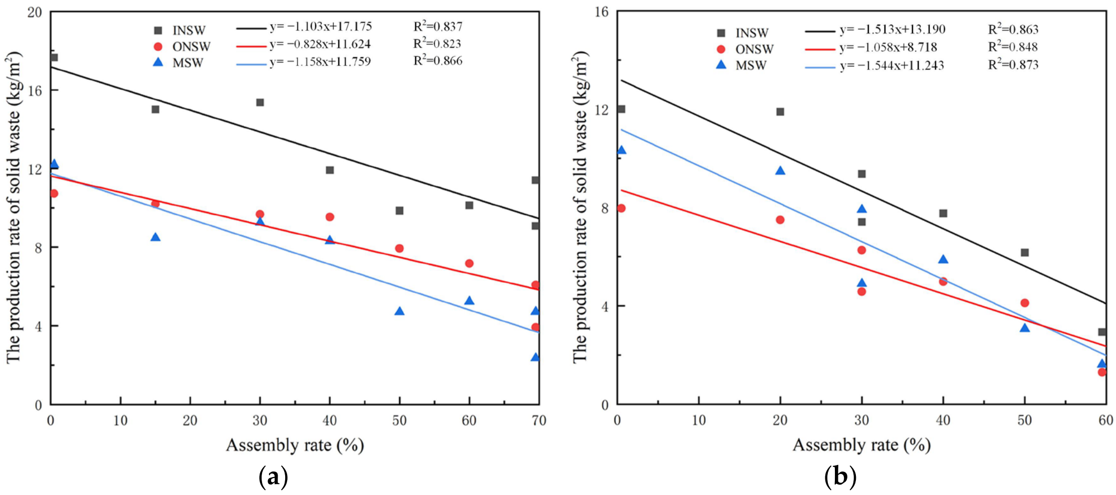


Figure 7. Effect of the assembly rate on solid waste generation rate. (**a**) Office buildings; (**b**) Exhibition buildings.

Analyzing the fitted curves shows that an increase in the assembly rate during the construction phase of new buildings leads to a decrease in the generation rate of each type of waste. For office buildings, for every 10% increase in the assembly rate, the generation rates of INSW, ONSW and MSW are reduced by 1.103 kg/m^2, 0.828 kg/m^2 and 1.158 kg/m^2, respectively. And for every 10% increase in the assembly rate of exhibition buildings, the generation rates of INSW, ONSW and MSW decreased by 1.513 kg/m^2, 1.058 kg/m^2 and 1.544 kg/m^2, respectively.

4. Conclusions and Perspective

By measuring the amount of solid waste generated during the construction stage of 61 projects in Hainan Province, this paper uses the Random Forest algorithm to explore the relationship between influencing factors and solid waste generation rate. The following conclusions are summed up based on the examination of the project's assessed data processing:

(1) The impact of building area: in office buildings, the generation rate of INSW and MSW increases by 0.370 kg/m^2 and 0.181 kg/m^2, respectively, for every 10,000 m^2 increase in building area. For exhibition buildings, every increase of 10,000 m^2 in building area, the generation rate of INSW and MSW increases by 0.743 kg/m^2 and 0.565 kg/m^2, respectively.

(2) The impact of building height: in office buildings, every 10 m increase in building height, INSW and MSW generation rate increases by 0.242 kg/m^2 and 0.158 kg/m^2, respectively. For exhibition buildings, for every 10 m increase in building height, the generation rate of INSW and MSW increases by 0.904 kg/m^2 and 0.721 kg/m^2, respectively.

(3) The impact of concrete usage: for office buildings, the rate of MSW generation decreases by 0.0799 kg/m^2 and INSW increases by 0.199 kg/m^2 for every 10,000 t increase in concrete usage. For exhibition buildings, the rate of MSW and INSW

generation increases by 0.218 kg/m^2 and 0.627 kg/m^2 for every 10,000 t increase in concrete usage.

(4) The impact of steel usage: for office buildings, the steel usage increases by 10 kg/m^2, MSW increases by 0.531 kg/m^2, and INSW generation rate decreases by 0.566 kg/m^2. For exhibition buildings, for every kg/m^2 increase in steel usage, the generation rate of INSW and MSW increases by 0.789 kg/m^2 and 0.762 kg/m^2, respectively.

(5) The impact of assembly rate: for office buildings, assembly rate increases by 10%, and INSW, ONSW and MSW generation rate decreases by 1.103 kg/m^2, 0.828 kg/m^2 and 1.158 kg/m^2, respectively. For exhibition buildings, for every 10% increase in the assembly rate, the generation rate of INSW ONSW and MSW decreases by 1.513 kg/m^2, 1.058 kg/m^2 and 1.544 kg/m^2, respectively.

After summarizing the article, the following suggestions are made:

(1) For all types of buildings, increasing the rate of assembly and controlling the building height and floor area during design can reduce the generation of solid waste.

(2) For visiting buildings, increasing the rate of assembly has a significant impact on reducing the rate of solid waste generation. The design of these buildings ought to prioritize the highest possible rate of assembly.

(3) Construction contractors ought to fortify their oversight and management protocols, enhance the caliber of their workforce, and ameliorate the construction site's environmental conditions to curtail the production of solid waste.

The production of a large amount of solid waste will not only cause economic waste, but also have a huge impact on the environment. In the process of data collection, we found that developers and construction teams are reluctant to pay attention to solid waste recycling. On the one hand, solid waste recycling will occupy a large part of human resources, but on the other hand, solid waste recycling cannot bring economic benefits to the construction side. In further studies, we expect to explore the relationship between solid waste production rates and influencing factors in other climate types. Following this study, it is expected to investigate the suggestions of major participants in the construction site on solid waste management by issuing on-site questionnaires, explore feasible solid waste management schemes for construction sites, and provide suggestions for decision makers.

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