Quantifying construction waste reduction through the application of prefabrication in China

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Abstract

Due to the fast development of urbanization in China, it has significant increase in new construction and the extension of building. According to the data from National Bureau of Statistics of China, the annual construction and demolition waste in China is about 1.55 to 2.4 billion tons now, accounting for approximate 30% to 40% of total solid waste. The landfill and burning are the main disposal methods of construction waste in China which lead to serious environmental pollution.

Reducing the waste at sources are the most efficient way to reduce its negative impacts. The prefabrication is a construction method to assemble building components in a factory or other manufacturing site, and transport complete assemblies or subassemblies to the construction site where the building is located. Prefabricated construction has less construction waste generation rate compared with the conventional cast-in-situ construction due to its industrialized production and it is promoted by the Chinese government. This paper aims to investigate the benefits of prefabrication and quantify the percentage of construction waste reduction through the application of prefabrication in China.

This study quantifying the benefit of prefabrication which can reduce construction waste reduction generation in China. This means that prefabricated construction could reduce the impacts of construction waste and decrease the cost related to construction waste management in China.

1. Introduction

1.1 Background

Due to the fast development of urbanization in China, it has a significant increase in newly constructed building area and accompanying construction waste. The annual construction and demolition waste in China is about 1.55 to 2.4 billion tons now, accounting for approximate 30% to 40% of total municipal waste [1], whose main disposal methods are landfill and incineration. However, these improper disposal methods do not only occupy a large area of land but also give rise to the environmental degradation, including serious pollution of water, land and air which diminishes the life quality of adjoining residents.

Alone with the seriously environmental problems caused by increased construction waste, how to minimize the effects of waste has attracted worldwide attention. Prefabrication has been regarded as an efficient method which reduce construction waste at its sources, during design and construction process. Prefabrication refers to assembling components of a structure in a factory or other manufacturing site, and transporting complete assemblies or subassemblies to the construction site where the structure is to be located. The industrial production process of prefabricated components can avoid the waste generation caused by improper operations during cast-in-situ process [2].

This research aims to quantify the amount of construction waste reduction by application of prefabrication. A 26-storey residential building in China with concrete-brick structure is analysed to estimate the amount of waste generation during construction and transportation processes. In addition, quantifying the potential construction waste reduction by using prefabricated construction for those replaceable building elements. This study illustrates the enormous potential of waste reduction of prefabrication for building construction compared with traditional construction method.

1.2 Aim and Objectives

The aim of this study is to investigate the benefits on waste reduction through application of prefabrication. To achieve the aim, the following objectives should be obtained:

- To conduct extensive literature review.
- To investigate the application of prefabrication in Chinese construction industry, and the whole process shall be understood including manufacture, transportation and installation.
- To quantify the amount of construction waste generation for a case project with conventional construction method and estimate its construction waste reduction by using prefabrication.

1.3 Significance of the Study

Prefabricated technology has been used in some construction projects in the 1950s in China, and the techniques for prefabricated construction have enormous development in the past 60 years. With the industrialization of building construction, Chinese government pays more attention to the prefabrication; China State Council aims to increase the percentage of floor area of prefabricated building to 30% in the next decade in order to optimize the construction speed, construction quality and construction waste generation [3]. This study aims to quantify the potential waste reduction by applying prefabrication into a case, whose results of this study could help public understand the benefits of prefabrication on construction waste reduction and enhance the development of market of prefabricated construction in China. In addition, this paper can provide the positive recommendations on prefabricated industry in China through detailed investigation.

2. Literature Review

2.1 Construction Waste

In the past thirty years, the number of new construction projects maintained a rapid growth with the process of urbanization and development. According to the data from the National Bureau of Statistics of China [3], the Fig 1 shows the completed floor space and construction floor space in China from 2006 to 2015. The annual construction area increased from 4.63 million square meters in 2006 to 12.92 million square meters in 2013, and annual completed area increased from 2.13 billion square meters to 3.51 billion square meters in 2013. Even though the increased trend of construction floor area and completed floor area has stopped during the period from 2013 to 2016, it still remained a large quantity, at about 13 billion square meters.

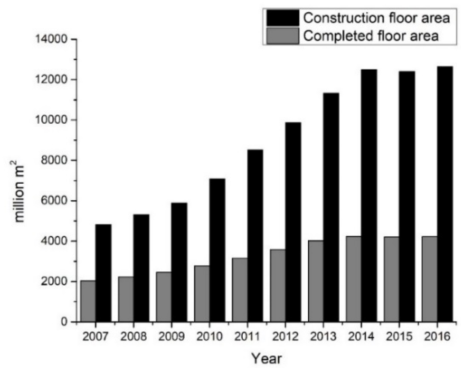

Fig 1 The Completed Floor Space and Floor space under construction in China from 2006 to 2015 [3]

As the construction quantities has increased significantly, the quantity of construction waste generation increases quickly as well. Some researchers have developed the estimated method of construction waste based on mathematical modelling in China and America. The waste produced during the construction process can be estimated from the following equation [4]:

$$p = Ai \qquad \text{Equation 1}$$

Where, P is the quantity of construction waste; A is the construction floor area; and i is the quantity of construction waste produced per square meter of construction floor area during construction process.

However, the index i shall be determined in this equation to calculate the estimated value of construction waste. Through the estimation of construction materials waste rate of cast-in-situ structure, 500-600 tones construction waste were generated during construction process. In addition, Lu et.al estimated the construction waste generation rate was 550 tons per 10,000m^2 according to the completed floor area from 2002-2006. Therefore, the value of index i were taken as 55kg/m^2 for the previous formula [5].

Camp, Dresser and McKee Inc investigated the quantity and composition of construction and demolition waste in Wisconsin. The major sources of construction are similar in commercial project and residential project. It is obvious that wood waste has occupied the largest proportion of construction waste, which is about 40% of total construction waste. Drywall contributed to 20% of construction waste generation in both of commercial and residential construction. However, compared with the commercial project, there are more type of construction waste for residential project though they are all less than 10% [6].

In Malaysia, Lau et.al conducted three separate case studies in three different locations to investigate the composition of construction waste. It basically conformed to the previous waste composition which were counted by Camp et.al in the US. The wood waste also contributed to the largest percentage of construction waste, which ranged from 35% to 69.5% in three separate projects. [7].

Based on the previous researches on composition of construction waste, it was wood that occupied the largest percentage of construction waste in most of the cast-in-situ projects, which can be explained by the results of survey questionnaire of Jaillon et.al. The timber formwork is the most waste producing components in traditional cast-in-situ project in Hongkong because all the timber formwork (100%) would be discarded as waste after several reuses [8,9].

Concrete is the second contributor for the waste generation. According to Poon's investigation, 80% of the work was made from ready-mix concrete. The 3-5% percentage wastage of concrete mainly caused by excessive material ordering, broken formwork and redoing due to poor concrete placement quality.

2.2 Prefabricated Construction

The prefabricated construction also can be called as industrialised Building, modular construction and off-site construction. It is a construction method that some or all the building components are manufactured in a controlled environment, transported and assembled in construction site. Prefabrication is not a new technology in China. In 1950s, Chinese construction industry began to use prefabricated construction method, but the most assemblies are produced on site in a temporary place of construction site and construction contractors were responsible for manufacturing assembling components [10]. The prefabricated construction has been developed rapidly in 1970s and the factory where producing prefabricated components replaced the on-site production as the main production method of assemblies. Some components of structure such as hollow slab has been used widely in industrial and civil construction. There are also some problems of prefabrication, such as low aseismic capacity, small span and low ductility due to backward production technology and the weak joint connection between prefabricated part and cast-in-situ part. Even though the prefabricated unit were widely used but the limitation low aseismic capacity of prefabricated structure gave rise to more casualties in the disaster of 1976 in China (Fig 2) . The Tangshan earthquake killed about 240, 000 people and people realized the risk of prefabricated components [11]. In addition, it caused safety risk that some inferior quality prefabricated components which were produced by small factory entered the construction market. The prefabricated components were even banded to use by governments of some cities in the late of 1990s.

With the development of prefabricated technology, it has obvious improvement on quality, types of component and construction period. Moreover, prefabricated construction even regarded as the first level of industrialization is popular in China and even the world. Fig 3 shows materials flows of prefabricated and traditional cast-in-situ construction. Compared with the conventional construction, the formwork, reinforcement, casting and curing work of prefabricated components have been finished in factory. Therefore, the prefabricated construction can provide the higher quality of building components, better working circumstance and faster construction speed [5].

The Chinese government also noticed the benefits of prefabrication. General Office of the State Council of the People's Republic of China issued 'Guidance on the development of prefabricated buildings' in 2016, which mentioned that popularizing the prefabricated construction of timber, steel and reinforced concrete in China and predicting to achieve the goal that 30% area of newly constructed building are prefabricated structure in a decade. Moreover, the corresponding standards and codes for prefabrication are published by Ministry of Housing and Urban-Rural Development, such as Technical code for assembled steel structure building, Technical code for precast concrete buildings and Technical code for prefabricated timber buildings.

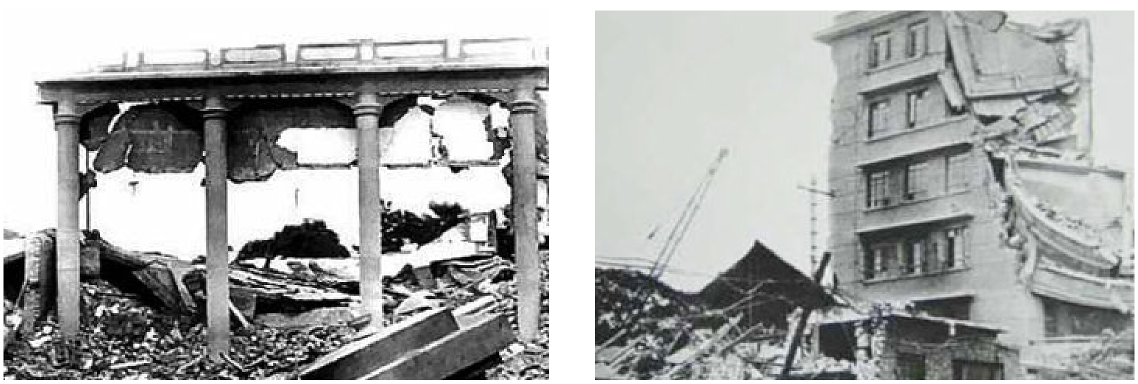

Fig 2 The building collapsed after Tangshan Earthquake [11]

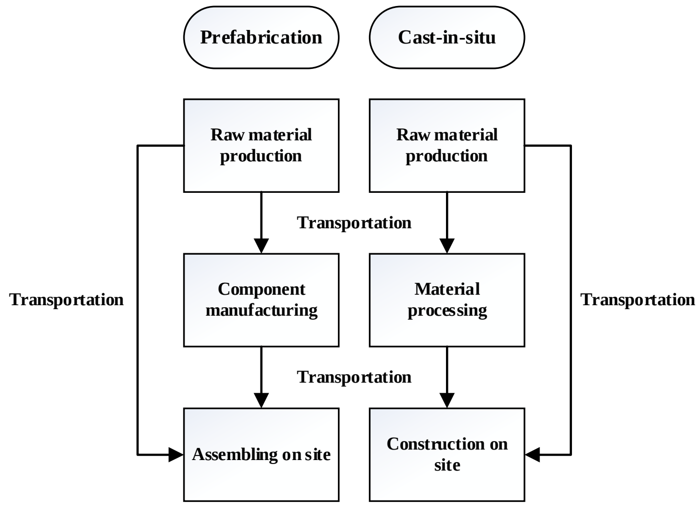

Fig 3 Materials flows of prefabricated and traditional cast-in-situ construction [12]

2.3 Waste Reduction through Prefabrication

As the problem of construction waste grown, studies related to waste management become hot spots. The prefabricated construction which is also a popular construction method recently in China due to encouragement of government, and it has obvious waste reduction potential compared with traditional cast-in-situ construction. Some studies explore the reasons why the prefabricated construction can reduce the construction waste through comparison of the manufacture process between these two construction methods. According to Jaillon and Poon's research, the formwork is the most waste producing components in all construction activities. In addition, The timber formwork is one of the main sources and contributors of construction waste as the previous mentioned [8].

The preceding part also shows the construction process of two methods, the characteristic of prefabricated construction which is integrating the formwork, reinforcement, casting and curing work in the manufacturing factory. The wood waste caused by the discarded timber formwork can be avoided by the application of prefabrication because metal formwork was commonly used in the manufacture of prefabricated components. Compared with timber formwork used in the conventional construction, there was nearly no waste produced due to formwork during the manufacture of prefabricated components because metal formwork can be reused and recycled. Jaillon et.al stated the results of their case studies that the average 70% waste reduction in timber formwork can be achieved through combination the application of prefabrication and metal formworks [8].

In order to quantify the impacts of application of prefabrication in building industry, there were two main investigation methods used by previous researchers, which are cases studies and survey questionnaires. Jaillon and Poon drawn drew conclusion that the construction waste reduction ranged from 14%-70% depending on how many prefabricated components were used in separate project. The results of their questionnaires illustrate 35% of the respondents thought the waste reduction through precast construction was about 10% - 20% based on their experience while some people believed that the waste reduction could reach at about 30% [8]. Vivian et.al also compared the wastage between cast-in-situ and prefabrication for each construction activities through survey questionnaires, the waste reduction for tilling can arrive at 100% and the figure for rebar fixing was 92% by using prefabrication. Waste emission was also evaluated by Cao in his study, a traditional residential building and a prefabricated residential building were investigated. The percentage of saving for mortar, heat insulation, steel, and concrete are 81.25%, 54.84%, 36.54% and 24.91 respectively [12].

3. Research Methodology

3.1 Overview of the Case Study

The case project analyzed in this paper is located at the city of Huaibei, Anhui province, which is a government-investing construction project. It is a 26-story high-rise residential building which is Special-shaped Column Frame Shear Wall Structure with total floor area with about 10697.3 m^2. In addition, all the design codes and standards used in this project are Chinese standards. The basic information for this case is shown in the Table 1. The design of this residential building has been completed in February of 2017 but the main structure is still under constructed. The major structure of this building consists of cast-in-situ reinforced concrete, which is molded by timber formwork. However, for those non-bearing walls in this project, hollow bricks are used.

Table 1 Project basic information

Project Name	Dongyueyayuan	**Construction Company**	Anhui Construction Engineering Group
Location	Huaibei, Anhui Province	**Seismic Fortification Intensity**	6
Total Floor Area	Total floor area on ground: 10697.3m including balcony area: 350.7m (1/2 area counted), roof machine room area, Site area: 395.9m		
Height	75.7m		
Structural System	Special-shaped column frame shear wall structure	**Building Story**	26 on ground, 0 underground

3.2 Data Collection Process

This paper mainly focusses on quantifying construction waste caused by construction work which could be affected by the application of prefabrication. Due to the poor connections between cast-in-situ concrete and precast concrete components, there is almost no application of prefabrication in the main structural member of buildings; the staircases, exterior and interior non-bearing walls are the principally serviceable range of prefabricated components in the concrete-frame structure buildings, which are also the sources of construction waste reduction if precast components are applied.

The quantity of construction waste would be estimated based on the construction quantity take-off for this case project and the potential construction waste reduction on site is affected by those construction works which can be replaced by the off-site prefabrication. Therefore, the reduction can be determined through assuming some parts are replaced by prefabricated components and the construction waste caused by those replaced parts is approximately equal to waste reduction.

Although the main sources of construction waste consist of reinforcement, concrete, timber formwork in cast-in-situ concrete frame structure, in addition, mortar and bricks if masonry structure is used for non-bearing walls. It shall be noted that the main scope for waste quantification in this paper are construction waste generated by timber formwork and masonry work. Concrete and reinforcement works are not included, because the premixed concrete is wildly applied in China so the waste of fresh concrete would be not occurred on site. In addition, the waste of reinforcement are mainly leftover materials which are caused by reinforcement processing; the quantity is not too large and it is easy to recycle due to its high value. Therefore, the issues related to concrete and reinforcement would not be included in this paper, but it pays more attention to the construction waste reduction caused by timber formwork and masonry structure when prefabricated components are applied.

<u>Construction Waste for Timber Formwork</u>

In order to quantify the waste reduction through prefabrication, the waste generation rates for this case shall be determined at first. Timber formwork is one of the major contributor to the construction waste due to its short service life, accounting for 20-30% of total construction waste [8]. The Fig 4 show the life cycle of the timber formwork. The standard formwork would be purchased by owners or contractors at first, however, it shall be processed on site or offsite based on the design and construction requirements. For example, the standard timber formworks with 1.83*0.915 m^2 size are not suitable for the casting of 0.6*0.6 m^2 rectangular columns. However, the waste generation are inevitable in this process due to leftover materials caused by improper operations and poor planning. For the typical cast-in-situ construction, the concrete for one floor is casted at the same time, therefore, the timber formworks for at least one floor have to be prepared during the construction process. Those formworks could be used to cast 5-8 floors depending on its level of deformation, because using formworks with too much deformation could cause the concrete cannot meet the design requirements.

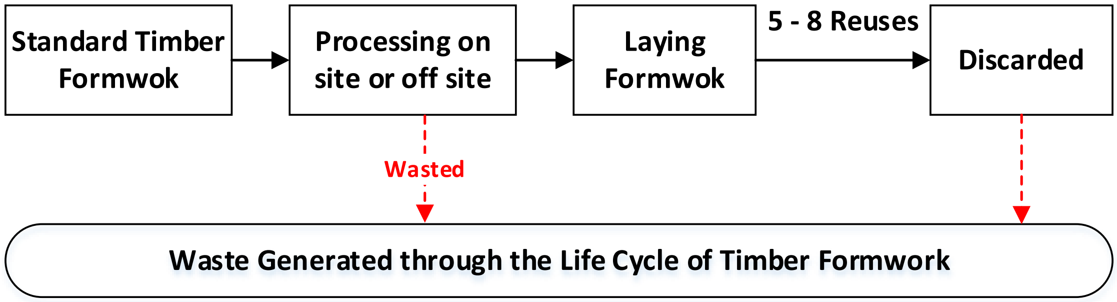

Fig 4 The generation process of timber formwork waste

The typical method for the construction waste take-off is through counting up the number of slag cars to estimate the quantity according to capacity of the truck. However, in practice, the different types of slag cars are used to transport construction waste, so the estimation could be very different from actual conditions. Apart from that, those wastes with low values are mixed up during transportation, which gives rise to the situation that the quantity for specific type of construction waste is hard to quantify.

The timber formwork is different with those materials which constitute the structure of buildings such as concrete, reinforcement and brick, all of formworks would be discarded in the end of project construction. Therefore, in this case project, the quantity of timber waste will be determined according to its sources, which means that estimate the timber waste generated through timber formworks quantities used in this project.

Construction Waste for Masonry Structure

Masonry structure is the major components of the second structure of reinforced-concrete frame structure, which composed of mortar and bricks. According to design requirements of different purposes, so many types of bricks could be applied in the construction site, including hollow brick, clay brick and aerated concrete block. Due to the large amount of quantity of masonry in brick-concrete structure, it is also a significant contributor to the construction waste, accounting for about 20% of total on-site waste generated. In order to estimate the waste quantity generated by masonry construction work, it shall be figured out that how the waste produced during this work flow.

According to the literature review and case study, the sources of waste generated on site due to construction of masonry structure are shown in the Fig 5. Some of bricks are damaged during the transportation process. The ready-mix mortar is not applied in this case project; therefore, the waste of mortar also could be produced when mixing the cement, fine aggregate and water. Both of them could be wasted due to the improper operations of workers during the construction process of masonry structure. The demolished waste of them at its end of life cycle would not be accounted because the stage of this research aims to quantify construction waste generation on site.

The method of quantity take-off for construction waste generation by masonry structure on site is not similar as the method for timber formwork, because the causes of this waste are damages during transportation process and improper operations of construction workers, which could be affected by the levels of project management significantly. The waste with low value such as bricks and mortar would not be recycled particularly and nobody record its quantity on site; it is impractical to estimate construction waste generation rate of brick and mortar at its ends. The purpose of this research is predicting the waste reduction on the macro level if prefabricated construction is applied widely by analysing specific case project. Therefore, the wastage from Chinese Construction Standards would be used to estimate the construction waste of masonry structure, whose results reflect the average level of waste generation rate in similar project, even though it could not be accurate for this case project.

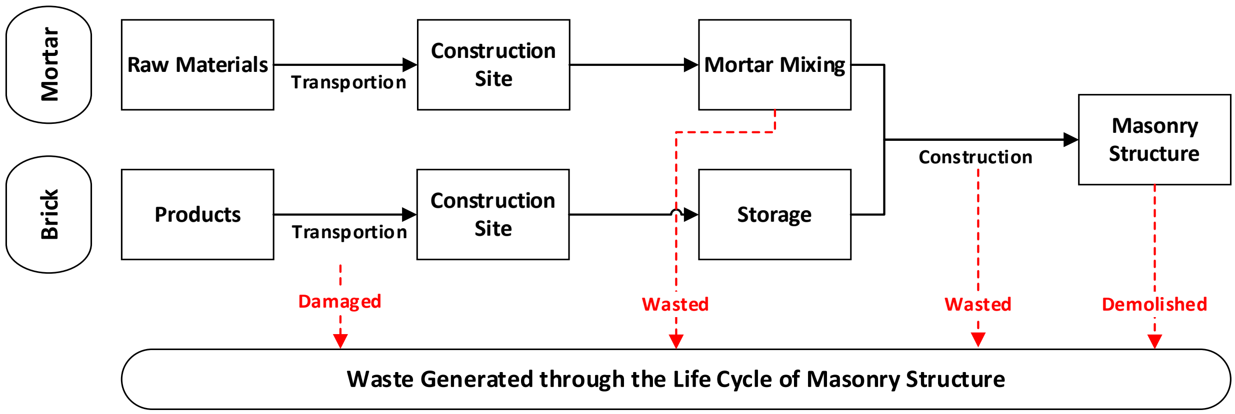

Fig 5 The generation process of masonry waste

4. Results and Analysis

4.1 Construction Waste Reduction for Timber Formwork

There are two types of potential construction waste reduction prevented by prefabrication analysed in this case project: 1) timber waste produced by timber formwork, and 2) mortar and brick waste produced by masonry structure. Since the owners and contractors do not record the amount of construction waste generation, the figure for each type of waste would be estimated by quantity take-off.

In term of timber formwork, the building elements are classified into column, wall, beam, and slab in order to quantify the quantities of formwork for each element respectively. The formwork quantity required for this project is estimated according their designs. The formwork could be lost or damaged during processes of manufacturing and reusing. The wastages during processing for each type of building component are diffident because they are differences in size for formwork applied in different types of building components. For instance, a number of formworks shall be connected when casting building elements with large area such as slab and shear walls. However, the standard formwork has to be cut when they are applied into the elements such as columns and beams so they have more wastage due to the cutting process. However, columns and shear walls are regarded as the same building elements in the calculation of formwork quantities because they are casted together in this case project. According to Shandong province's consumption standard for building construction, the quantity take-off can be calculated by the following Equation 2 [14].

$$Q_f = \mathrm{A} * (1 + w_c) * \left(1 + w_p\right)/\mathrm{T} \qquad \textbf{Equation 2}$$

Where, Q is the expected consumed quantity of timber formwork (m^2), A is concrete components contacted with formwork directly (m^2), w_c is wastage of timber formwork during construction (%), w_p is the wastage of timber formwork during processing (%) and T is the times of reuse of timber formwork (nr).

The wastages used to estimate the quantity are from consumption standards for building construction and fitting-out works as Table 2 shown [15]. Based on interview, the construction contractors mentioned that 4 sets of timber formwork would be used for the concrete casting of this 26-story building, therefore, the times of reuse used in the calculation is about 6.5. The total area of timber formworks used for this project are 5202.48 (4*1300.62) m^2 and the total volume is 78.04 m^3 due to the standard timber formwork with 15mm thickness used in this project (Table 2).

The square timbers are also consumable material which are applied to support the timber formwork during concrete casing. It also is determined based on the consumption coefficient and surface area contacted with formwork of concrete element. The times of reuse for supporting square timber is same with timber formwork which is 6.5. The Equation 3 show how to estimate quantity of supporting square timber [14]:

$$Q_t = \mathrm{A} * (1 + w_c) * k/\mathrm{T} \qquad \textbf{Equation 3}$$

Where, Q is the expected consumed quantity of timber formwork (m^2), A is concrete components contacted with formwork directly (m^2), w_c is wastage of timber formwork during construction (%), k is the consumption coefficient and T is the times of reuse of timber formwork (nr). The total volume of supporting square timber required for this project is shown in the Table 3, which is 98.17 m^3.

The construction waste caused by formwork is estimated based on the quantity take-off. The volume of timber formwork and square timber consumed during construction process has been determined, and the weight can be calculated through material densities. The total weight of construction waste generated from timber formwork and supporting square timber in this project is about 112,523.72 kg and the percentages of construction waste are also shown by categories of building components like columns and walls (41.7%), beams (25.88%), slabs (27.97%), tie columns (1.45%) and stair cases (3%), as shown in the Table 4. In addition, the timber formwork waste generation rate during constriction is 10.52 kg/m^2.

The prefabrication can reduce the construction waste of timber formwork through decreasing construction quantities of cast-in-situ concrete used on the construction site because they no longer need the formwork to wait strength development. However, the strength of joints between prefabricated component is not as good as cast-in-situ one; the building elements which can be replaced by precast components are limited at this stage. In this project, the possible building elements which could be replaced by the prefabricated components are slabs, staircases and tie columns. The potential construction waste reduction of timber formwork prevented by prefabrication is shown in Table 5. The waste volume reduction of timber formwork by replacing precast components of slabs, tie columns and staircases are 27.61%, 1.45% and 3.03% respectively, and the figures for waste weight reduction are similar, which are 27.97%, 1.45% and 3.00%. The construction waste generation rete of timber formwork can drop from 10.52 kg/m^2 to 7.11 kg/m^2 if replacing all these elements in this building into prefabricated components.

According to previous literature review, the construction waste reduction of timber formwork can range from 30% to 70% by combining of metal formwork and prefabrication. The weight and volume of construction waste reduction of timber formwork avoided by prefabrication can reach at 32.09% (56.55 m^3/176.21 m^3) and 32.42% (36,482.13 kg/112,523.73 kg) respectively.

Table 2 Timber formwork quantity take-off

Materials	Element	Contacted Area (m2)	Wastage During Constriction	Wastage During Processing	Times of Reuse (nr)	Quantity (m^3)
Timber Formwork	Columns and Walls	12391.68	5%	6.67%	6.5	2523.48
	Beams	6743.02		16.88%	6.5	1504.60
	Slabs	9021.73		7.87%	6.5	1857.88
	Tie Columns	359.42		28.07%	6.5	87.88
	Staircases	782.28		16.88%	6.5	174.55

Table 3 Supporting square timber quantity take-off

Materials	Element	Contacted Area (m2)	Wastage During Constriction	Consumption Coefficient	Turnover Rate	Quantity (m3)
Supporting Square Timber	Columns and Walls	12391.68	5%	0.0208	6.5	41.64
	Beams	6743.02		0.0247	6.5	26.90
	Slabs	9021.73		0.0172	6.5	25.07
	Tie Columns	359.42		0.0249	6.5	1.45
	Staircases	782.28		0.0247	6.5	3.12

Table 4 The amount of construction waste for timber formwork by categories of building elements

Element	Term	Material	Density (kg/m3)	Waste Volume (m3)	Waste Weight (kg)	Weight Percentage (%)
Columns and Walls	Timber formwork	Plywood	750	32.03	24021.55	21.35%
	square timber	Wood	550	41.64	22899.83	20.35%
	Total			**73.66**	**46921.38**	**41.70%**

Beams	Timber formwork	Plywood	750	19.10	14322.65	12.73%
	Square timber	Wood	550	26.90	14797.56	13.15%
	Total			**46.00**	**29120.21**	**25.88%**
Slabs	Timber formwork	Plywood	750	23.58	17685.56	15.72%
	Square timber	Wood	550	25.07	13786.59	12.25%
	Total			**48.65**	**31472.14**	**27.97%**
Tie Columns	Timber formwork	Plywood	750	1.12	836.53	0.74%
	Square timber	Wood	550	1.45	795.14	0.71%
	Total			**2.56**	**1631.68**	**1.45%**
Staircases	Timber formwork	Plywood	750	2.22	1661.61	1.48%
	Square timber	Wood	550	3.12	1716.70	1.53%
	Total			**5.34**	**3378.31**	**3.00%**
	Grand Total			**176.21**	**112523.72**	**100%**

Table 5 The amount of construction waste reduction for timber formwork by using prefabrication

Element	**Term**	**Volume Reduction (m3)**	**Weight Reduction (kg)**	**Percentage of Volume Reduction (%)**	**Percentage of Weight Reduction (%)**
Slabs	Timber formwork	23.58	17685.56	-13.38	-15.72
	Supporting square timber	25.07	13786.59	-14.23	-12.25
	Total	**48.65**	**31472.14**	**-27.61**	**-27.97**
Tie Columns	Timber formwork	1.12	836.53	-0.63	-0.74
	Supporting square timber	1.45	795.14	-0.82	-0.71
	Total	**2.56**	**1631.68**	**-1.45**	**-1.45**
Staircases	Timber formwork	2.22	1661.61	-1.26	-1.48
	Supporting square timber	3.12	1716.70	-1.77	-1.53
	Total	**5.34**	**3378.31**	**-3.03**	**-3.00**
	Grand Total	**56.55**	**36482.13**	**-32.09**	**-32.42**

4.2 Construction Waste Reduction for Masonry Structure

The masonry structure has occupied the large proportion of secondry structure in this project, which is also a main source of construction waste. The brick and mortar are constituent materials of masonry structure; the quantities of them are estimated in order to quantify the contruction waste genrated during their constrction process.

There are two size of brick walls used according to the design drawing and two types gangue hollow brick with different sizes are applied respectively in this project. The bulk density is same for all types of bricks, which is 900 kg/m^3. The bricks with size of 240*180*115 mm^3 are used to build the 200 mm brick wall with 180 mm birck and 20 mm plastering. The bricks with size of 240*115*115 mm^3 are used to build the 120 mm brick walls with 115 mm brick and 5 mm plastering. In addition, the depth of mortar joints is 10 mm in this project. The quantity take-off could be conducted through those information and Design AutoCAD Drawing provided by project mangement. The total 1112.25 m^3 bricks including 15.29 m^3 of type 1 brick and 1028.01 m^3 of type 2 brick. The quantity of mortar consists of plastering mortar and masonry mortar, which is 280.57 m^3 (Table 6).

The amount of construction waste generated by masonry structure is also estimated by the construction quantity of masonry work. The wastage of brick and mortar used in the estimation of construction waste quantities are from

Consumption Standard for building construction and fitting-out works in Fujian Province; therefore, the wastage for gangue hollow brick is 2%, the wastage for masonry mortar and plastering mortar is 10% and 2% respectively [15,16]. The bulk density for each types of materials in this project are provided by the manufacturer (Table 7). The amount of construction waste produced in this part can be calculated through the previous information. The total weight of construction waste generated by masonry work is 51,035.18 kg in this project, which is categorised into brick, joint mortar and plastering mortar. Their weight percentages are 39.23%, 51.88% and 8.89% respetively as Table 7 shown. The constrution waste generation for masonry work can also be determined, which is 4.77 kg/m^2 in this case project.

All the masonry structure in this building can be replaced by precast wall because the they are secondary structure which are not able to be load-bearing components. However, the prefabricated walls could also be wasted during transportation and installation as same as the masonry wall. The increased amount of waste of precast walls shall be counted when calculating the construction waste reduction of non-bearing walls. Compared with masonry walls, the wastage of precast components is much less due to the fewer construction processes. The wastage of precast components during different process are shown in the Table 8; only transportation and installation wastage are taken consideration into this section because this paper only focusses on the construction waste generation on-site. In addition, the quantities used for connection of prefabricated walls and its wastage used in the Table 9 are sources from consumption standards for building construction and fitting out works [16]. The Table 9 shows the construction waste reduction by using prefabricated walls instead of masonry structure. There are 53.6% (21.24 m^3/39.62 m^3) of the volume of construction waste reduction and 10.21% (52,211.39 kg/51,035.18 kg) of weight of construction waste reduction by replacing all the masonry walls by precast components in this project. In other words, the construction waste generation rate can decrease from 4.77kg/m^2 to 4.28 kg/m^2 by application of prefabrication.

Table 6 Quantity take-off of masonry structure

Wal Type	Brick Type	Design Volume (m3)	Volume of Brick (m3)	Volume of Mortar (m3)	
				Joint	Plastering
1	1	99.53	84.24	11.14	4.15
2	2	1293.29	1028.01	135.95	129.33

Table 7 The amount of Construction waste for masonry structure

Term		**Quantity (m3)**	**Wastage (%)**	**Waste Volume (m3)**	**Bulk Density (Kg/m3)**	**Waste Weight (Kg)**	**Weight Percentage (%)**
Brick		1112.25	2	22.25	900	20020.54	39.23
Mortar	Joint	147.09	10	14.71	1800	26476.44	51.88
	Plastering	133.48	2	2.67	1700	4538.19	8.89
Total		**1392.82**	**-**	**39.62**	**-**	**51035.18**	**100**

Table 8 The wastages of Precast components by process category

Manufacturing Wastage (%)	**Transportation Wastage (%)**	**Installation Wastage (%)**
0.20	0.80	0.50

Table 9 The amount of construction waste reduction for masonry structure by using prefabrication

Term	Materials	Wastage (%)	Bulk Density (Kg/m3)	Waste Volume (m3)	Waste Weight (Kg)	Percentage of Volume Reduction (%)	Percentage of Weight Reduction (%)
Masonry (-)	Brick	2.00	900.00	-22.25	-20020.54	-56.14	-39.23
	Joint Mortar	10.00	1800.00	-14.71	-26476.44	-37.12	-51.88
	Plastering Mortar	2.00	1700.00	-2.67	-4538.19	-6.74	-8.89
	Total	**-**	**-**	**-39.62**	**-51035.18**	**-100.00**	**-100.00**
Prefabrication (+)	Precast Walls	1.30	2500.00	18.11	45266.65	45.70	88.70
	Joint Mortar	2.00	2000.00	0.28	557.13	0.70	1.09
	Total	**-**	**-**	**18.39**	**45823.78**	**46.40**	**89.79**
	Grand Total	**-**	**-**	**-21.24**	**-5211.39**	**-53.60**	**-10.21**

5. Conclusion and Recommendations

This paper accesses the construction waste generation rate for a case project with concrete-brick structure and also illustrates the amount of potential construction waste reduction that could be achieved by application of prefabrication in this project through this project. The results gain from this study are shown in the following parts.

- The construction waste generated by timber formwork could be prevented by using prefabricated components. For this project, the construction waste generation rate for timber formwork is 10.52 kg/m^2 and the volume and weight of construction waste reduction of timber formwork can go up to about 30% by replacing the building elements into precast components. There could be higher percentage of reduction in timber formwork waste by increasing the uses of metal formwork.
- Compared with the masonry walls, the precast components can lead to the less amount of construction waste. For this case project, the construction waste generation rate for masonry structure is 4.77 kg/m^2; however, the construction generation rate can drop to 4.28 kg/m^2 and the volume of construction waste reduction can reach at 53.6% by using precast walls.

In summary, the amount of construction waste generated on site could be avoided efficiently by apply the prefabricated techniques in China. However, this study also has some limitations. One of them is that it only considers the construction waste related to formwork and masonry structure for this concrete-brick structure case. Other types of construction waste such as concrete and reinforcement are not mentioned though their construction waste generation also would be reduced by using prefabrication. In addition, even though this study only uses the wastage from Chinese construction standards to quantify the construction waste reduction which could differed with figures for actual situation, the results of this study reflect the average construction waste reduction for high-rise residential buildings prevented by prefabrication in China through this specific case project.

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