Journal of Engineering Sciences and Information Technology
Volume (5), Issue (3) : 30 Sep 2021
P: 149 - 172

AJSRP
ISSN: 2522- 3321

مجلة العلوم الهندسية وتكنولوجيا المعلومات
المجلد (5)، العدد (3) : 30 سبتمبر 2021م
ص: 149 - 172

SUSTAINABLE PREFORMANCE CRITERIA FOR INDUSTRIAL BUILDINGS CONSTRUCTION METHOD IN EGYPT

Mahmoud Ezzat Elkotb salem
Khaled Mohmed Mohmed Heiza
Kamel Sayed Ahmed Kandeel
Faculty of Engineering || Menoufia University || Egypt

Abstract: As for factories, they are always divided into two main parts, which are the administrative part and the part in which the industrial process takes place, which is the industrial part. The two parts may be located in one building or a building dedicated to each part may be built, depending largely on the requirements of the industry and the size of the factory. There are large differences between the use of each part and thus, resulting in large differences in the characteristics of each building. The ways of choosing the construction method for industrial building in Egypt still depend to a large extent on anecdotal evidence or simply cost- based evaluation when comparing different construction methods for industrial buildings. Therefore, there is an urgent need for holistic criteria to assist in the method of choosing the appropriate construction method for industrial buildings during the early stages (design and planning stage) of the project. By reviewing the previous literature and the requirements of the various stakeholders in the project, reviewing the Egyptian laws, whether building laws or environmental laws, as well as labor laws, and making comprehensive comparisons between the different construction methods, especially the on- site construction method and the off- site construction method, a set of 30 Sustainable Performance criteria (SPC) based on the Trip Bottom Line (TBL) were determined. A questionnaire was designed and a survey was conducted for Egyptian practitioners who have experience in either the industrial building construction industry or in off- site construction methods. The survey included contractors, consultants and owners of industrial buildings. The survey was conducted to determine their perceptions of the importance of the selected criteria. The ranking analysis of the survey results showed that there is still a low importance for social and environmental standards compared to economic criteria in the method of choosing methods for constructing industrial buildings in Egypt.

Keywords: industrial buildings; construction method; prefabrication; Sustainable Performance criteria (SPCs)

معايير الاداء المستدام لطريقة تشييد المنشآت الصناعية فى مصر

محمود عزت القطب
خالد محمد محمد حيزه
كامل سيد أحمد قنديل
كلية الهندسة || جامعة المنوفية || مصر

المستخلص: في الغالب تنقسم المباني الصناعية إلى قسمين راسيين وهما الجزء الإداري (المبنى الذي يتم فيه ادارة المصنع وتتم ايضا فيه العمليات الإدارية) والجزء الصناعي (المبنى التي تتم فيه العملية الصناعية). قد يقع الجزآن في مبنى واحد أو قد يتم بناء مبنى منفصل

لكل جزء (غالبا ما يحدث ذلك لاختلاف خصائص كل عملية اختلاف العملية الادارية عن العملية الصناعية). وفي هذا البحث تم مناقشة المبنى الخاص بالعملية الصناعية وأطلق عليه المبنى الصناعي. لا تزال طرق اختيار طريقة البناء للمباني الصناعية في مصر تعتمد إلى حد كبير على الأدلة القصصية أو ببساطة التقييم القائم على التكلفة عند مقارنة طرق البناء المختلفة للمباني الصناعية. لذلك، هناك حاجة ماسة لمعايير شاملة للمساعدة في طريقة اختيار طريقة البناء المناسبة للمباني الصناعية خلال المراحل الأولى (مرحلة التصميم ومرحلة التخطيط) من المشروع. من خلال مراجعة الأدبيات السابقة ومتطلبات المشاركين في المشروع سواء كان مهندسين مالك أو مقاول أو استشاري، ومراجعة القوانين المصرية سواء قوانين البناء أو قوانين البيئة، وكذلك قوانين العمل، وإجراء مقارنات شاملة بين طرق البناء المختلفة، وخاصة طريقة البناء في الموقع وطريقة البناء خارج الموقع، تم تحديد مجموعة من 30 معيارًا للأداء المستدام (SPC) بناءً على خط الرحلة السفلي (TBL). تم تصميم استبيان وإجراء مسح للممارسين المصريين الذين لديهم خبرة في صناعة البناء الصناعي أو في طرق البناء خارج الموقع. وشمل المسح المقاولين والاستشاريين وأصحاب المباني الصناعية (مهندسين المالك). تم إجراء الاستبيان لتحديد تصوراتهم لأهمية المعايير المختارة. أظهر تحليل الترتيب لنتائج المسح أنه لا تزال هناك أهمية منخفضة للمعايير الاجتماعية والبيئية مقارنة بالمعايير الاقتصادية في طريقة اختيار طرق إنشاء المباني الصناعية في مصر.

الكلمات المفتاحية: المباني الصناعية، طريقة التشييد، معايير الاداء المستدامة، سابقة التصنيع.

Introduction.

Sustainable development and sustainable construction around the world has become a growing concern due to the risk of environmental pollution, lack of natural resources، and negative social impacts associated with the project. Buildings are among the most resource- intensive buildings and represent a significant part of greenhouse gas emissions [1].

Sustainability consists of three categories: social, environmental, and economic categories. Often referred to as the triple bottom line is used to measure the success of a particular development program in order to ensure a sustainable result. This balance becomes clear when each category is defined as follow [2]:

- The economic dimension: Increase income while maintaining a constant or growing stock of capital.
- The environmental dimension: Not to negatively affect the resilience and robustness of biological and physical systems.
- The social dimension: Not to negatively affect the stability of the cultural and social systems surrounding the project.

In fact, sustainable construction aims to achieve a balance between the three dimensions of sustainability by analyzing and addressing the criteria associated with the dimensions throughout the life cycle of the construction project. There is a significant impact of the built environment and its associated activities on the dimensions of sustainability [3].

The engineers, whether architects, constructors, or other engineering professions, must take into account the surrounding environment while conducting their daily work. These professionals must know that an environmental and other community- based assessment of construction cannot be ignored when designing and constructing buildings. They must also know and learn the tools that can help them know the effects of the impact on their work as well as help 9them in making decisions to produce a final building that is not harmful to the surrounding environment or the associated community (projects more environmentally friendly) [4]. As stated by new research by the construction blog Bimhow, the construction industry provides 23% to air pollution, 50% to climate change, 40% to drinking water pollution and 50% to landfill waste. In another research by the US Green Building Council (USGBC), the construction sector provides 40% of energy use worldwide, with considers that by 2030 emissions from commercial buildings will grow 1.8% [5].

Due to the new and continuous growth of the construction sector, it will have many negative impacts on the surrounding environment. According to the UK Green Building Council, the construction sector consumes more than 400 million tons of materials annually in UK, many of which have many negative impacts on the surrounding environment [6].

During the past few years, alternative construction methods have emerged to the on- site construction method (also called the traditional method), such as the off- site construction method [7]. By reviewing many studies, there are many benefits that result when using off- site construction methods compared to on- site construction methods, which can result from that sustainable construction [8,9, 10, 11, 12].

No progress has been made in residential construction, in general, in the process of designing industrial buildings, the characteristics of which make them completely different. It can be said that the definition of sustainable aspects does not exist in the field of industrial plant construction, however a sustainable industrial building must be dealt with in the same way as residential buildings or buildings [13].

The relationship between industry and sustainability represents a rich and interesting field of research, given the complexity and number of fields of study, not to mention the importance of identifying factors to make industrial architectural requirements compatible and in line with sustainability goals [14].

In the current period, Egypt is heading towards a major economic reform. This period is witnessing the establishment of many factories, but new industrial areas, but this should not affect both the surrounding environment and the social situation. These areas should therefore be established on the principles of sustainability.

INDUSTRIAL BUILDING `

In fact, an industrial building is an isolated container in which a specific productive activity takes place. The aspects of sustainable industrial construction that are being considered today mainly refer to the production process that is done in- house. Attention is focused on factors such as pollution from the production process or activity throughout the life cycle of a building (air, noise, water, etc.) and treatment of waste deposition or recycling with very few resources devoted to research on the building itself. A more sustainable vision is the same architectural component that permanently interacts with sustainability requirements. (See Figure 1)

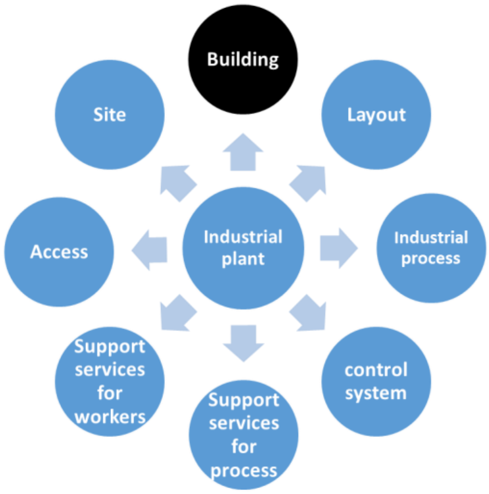

Figure (1) Components of a factory

An industrial building can also be defined as a building designed to be a place where industrial operations take place, taking into account the provision of suitable conditions for workers inside the building, as well as providing places that bear the operation of industrial equipment. The classification of an industrial building should be adapted into the production process and the necessary auxiliary services. Each process has its own characteristics, and there are endless processes. In other words, a group of industries should be placed in a state of kind that have similar properties with respect to materials, building shapes, spans between columns, more types of lighting and areas of ventilation or storage [15].

There are many distinctive features of industrial buildings from other buildings, and among those features are the following [16]:

1- A total of great variety: - There are various possibilities in the shapes and styles of the industrial building, as the final solution depends on the planning and distribution of the different activities to be performed, as well as on the great variety of operations that can take place in its internal space. However, in residential buildings, activities in indoor space always focus on providing its residents with stable room conditions
2- Higher loads: - Usually the loads associated with production processes that take place in industrial buildings, as well as the loads resulting from large quantities of raw materials, as well as the weights of large equipment, are much greater than the loads found in residential buildings.
3- Flexibility for future: - Industries characterized by rapid technological change today, which means that the industrial building must be allowed the flexibility to adapt to the future with the new allocations or the needs of the industrial expansion of the plant. Thus, the flexibility of the facilities is also important feature to consider when designing these models.

4- The possibility of mobility: - In industrial buildings, access and mobility of raw materials as well as manufactured products must be taken into account when designing. The volume of raw materials as well as manufactured materials and the length of production lines are a constraint on the design of spaces in industrial buildings.
5- Air conditions in the indoor space: - Unlike residential buildings and their use, where the type of housing is the only effect on energy use, but for industrial buildings, energy consumption depends on the available machinery. Therefore, there are many methods available to save energy. For example, the energy generated from one production stage inside the factory can be reused in another production stage. On the other hand, due to the difference between industrial and residential buildings, the air conditions of the interior spaces in the industrial buildings differ from those of the residential buildings.
6- The social aspect: - The industrial buildings have a great return on investment as they create a lot of job opportunities in the community, develop the neighborhood and enhance commercial activities.
7- Aesthetic form: - In some cases, as a result of the brand image of some companies, industrial buildings have a high aesthetic value that contributes to increasing the architectural heritage of the surrounding area.

RESEARCH METHODOLOGY

The methodology chosen for this research included designing a questionnaire, conducting a survey, interviewing Egyptian professionals involved in the Egyptian construction industry, and a statistical analysis of the collected data. (see figure 2)

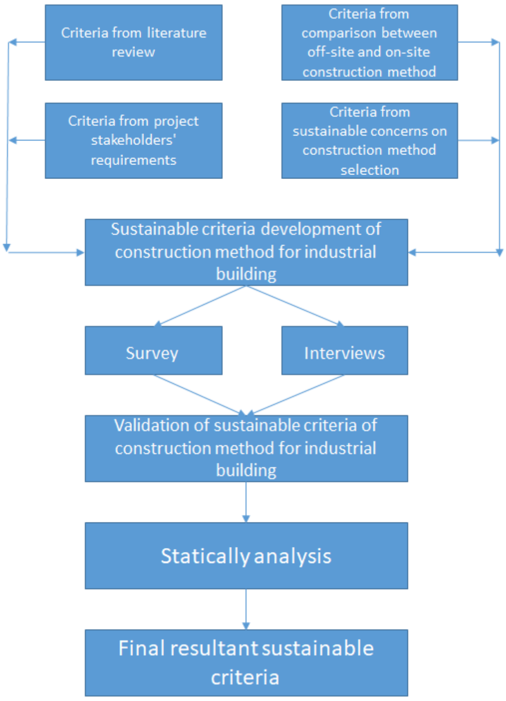

Figure (2) research framework and methodology

SUISTAINABLE CRITERIA DEVELPOMENT FOR INDUSRIAL BUILDING CONSTRUCTION METHOD

As mentioned earlier in the methodology, in order to deduce and develop sustainable performance criteria for the construction method for industrial buildings, a comprehensive and extensively extensive review of relevant previous studies has also been conducted, and ten interviews were conducted with Egyptian professionals to be used in reviewing the standards collected from previous studies.

- Criteria from Literature Review

There are many off- site construction methods such as prefabrication, pre- assembly, modularity and off- site fabrication, modular construction, HCC (Hybrid Concrete Construction), Prestressed / Precast Concrete Construction, Prefab Components, etc...

Industrial facilities are considered buildings of a special character, as mentioned before, as they differ in their characteristics from residential or commercial buildings, and this does not mean that all previous methods cannot be used in industrial buildings. However, the decision- makers' choice of method will change due to the different type of structure and also the different building activity.

So, an extensive literature review has been conducted in related areas including off- site construction methods.

The criteria were collected from some studies used in choosing the method of construction, but in residential buildings. It is not practical to mention all criteria in this paper due to space constraints. Instead, the reference, the criteria type based on triple bottom line method and the type of constriction of all the criteria is explained in it. (see **Appendix 1**)

- Comparisons between off- site and traditional construction method

Traditional construction methods (on- site construction method) consist of the casting and fabrication activities of large- scale on- site construction elements that are in widespread use. These activities are characterized by being labor- intensive and overlapping with each other on the site, which leads to overcrowding of the site and consequently this negatively affects the safety of workers and the time plan as well as generates large quantities of waste. Therefore, the use of construction methods outside the site results in less congestion and thus a cleaner site It is more arranged compared to the traditional methods, it also produces less waste and can save a lot of time in the construction period of the project. In research, the evaluation criteria for choosing a construction method should have the ability to clearly distinguish the off- site and on- site construction method from the established criteria. Hence, there is a need for a comprehensive comparison between the two construction methods. It is not practical to compare all differences between the off- site and on- site construction method in this paper due to space constraints. Instead, Economic Standards 'Construction Phases' was taken as an example, and provide figures to show the time savings due to the use of off- site construction methods. (See Figures 2,3)

Thus, also, Table 2 illustrates and summarizes briefly the main advantages and disadvantages of the off- site construction method compared to the traditional construction methods (the on- site construction method).

THE SURVEY AND INTERVIEWS

- Designing the Questionnaire

In order to arrive at a questionnaire that achieves its purpose, seven steps were taken to develop and design the questionnaire.

These steps are as follows: -

- Determine the information required from the survey
- Develop a list of questions required to collect information
- Review and revise the questions
- Determine the response format for each question
- Put the questions in a logical order
- The final design of the questionnaire
- Test the questionnaire and its final review

A comprehensive review of relevant previous studies indicated that there is no comprehensive list of sustainability performance criteria used in the method of choosing the method of construction for industrial buildings in Egypt. To develop this list, many related previous research has been studied. (see table 1)

To make sure that off- site and on- site construction methods can be clearly distinguished by the collected criteria, a rigorous comparison of the two methods was explored. Alongside the sustainable concerns and requirements of project stakeholders regarding the choice of construction method, a list of initial criteria was drawn up.

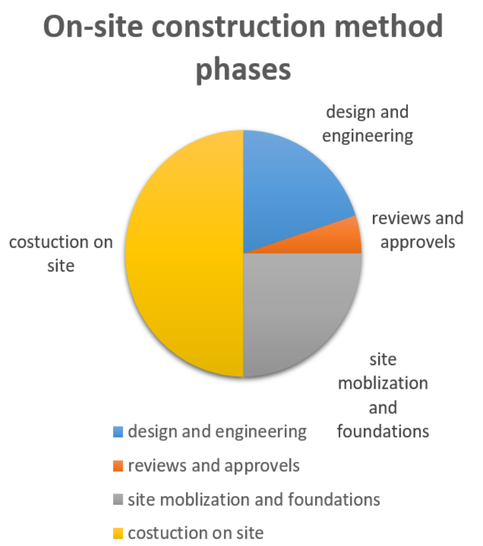

Figure (3) on- site construction method phases

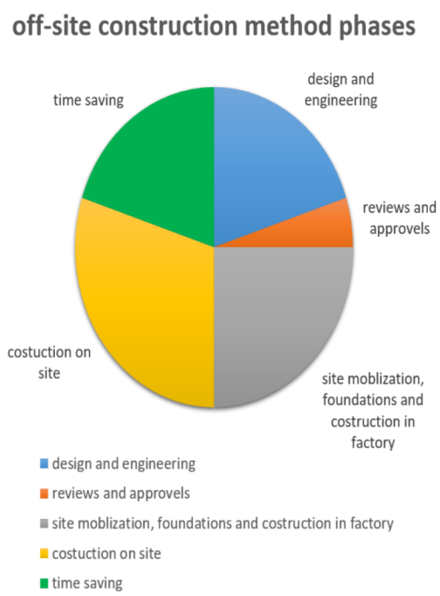

Figure (4) off- site construction method phases

Table (1) criteria selected from studies

Dimension	Indicator	Shen et al., [17]	Jeong Et al., [18]	Peter Op 't Veld [19]	Heravi Et al., [20]	O'Neill Et al., [21]	Omid Et al., [22]	Kamali Et al., [23]	LENKA Et al., [24]
Economic dimension	construction time	√	√	√	√	√	√	√	√
	initial construction costs	√	√					√	√
	maintenance costs	√	√	√	√	√	√	√	√
	disposal costs		√	√		√	√	√	√
	defects and damages		√	√	√	√	√	√	√
	Durability					√			√
	Investment and related risks		√	√	√	√			√
	flexibility (adaptability)			√	√	√			√
	loading capacity	√	√	√	√	√			√
	lead- times						√	√	√
	material costs	√			√	√	√	√	√
	labor costs	√			√	√	√	√	√
	constructability (buildability)	√			√	√	√	√	√
	integration of supply chains (logistics)	√	√	√	√	√	√	√	√
	Effects on national economic								√
	use of national/regional resources								√
Environmental criteria	site disruption			√	√	√	√	√	√
	recyclable/ renewable contents			√	√	√	√	√	√
	energy efficiency in building use (thermal mass)			√	√	√	√	√	√
	reusable/recyclable elements	√	√	√	√	√	√	√	√
	material consumption			√	√	√	√	√	√
	energy consumption in design and			√	√	√	√	√	√

Dimension	Indicator	Shen et al., [17]	Jeong Et al., [18]	Peter Op 't Veld [19]	Heravi Et al., [20]	O'Neill Et al., [21]	Omid Et al., [22]	Kamali Et al., [23]	LENKA Et al., [24]
	construction								
	waste			√	√	√	√	√	√
	pollution generation			√	√	√	√	√	√
	water consumption			√	√	√	√	√	√
	Air pollution		√	√	√	√	√	√	√
	Climate change					√	√	√	√
	Reuse of process water	√	√	√	√	√	√	√	√
Social dimension	health of occupants (indoor air quality)				√	√	√	√	√
	influence on job market					√	√	√	√
	aesthetic options	√	√	√	√	√	√	√	√
	workers' health and safety		√	√		√	√	√	√
	labor availability		√	√		√	√	√	√
	community disturbance		√	√		√	√	√	√
	traffic congestion	√	√	√	√	√	√	√	√

Using the criteria that were selected from the previous studies and developed by conducting interviews, the questionnaire was designed using a program. This program allows its users to create interactive and dynamic forms that enable the target audience of the questionnaire to fill out the questionnaire via the computer and resend it again. Some questionnaires have also been printed for a group of professionals to fill in manually. In the survey, which consists of two main parts, it aims to investigate the construction industry's perspective on the importance of criteria. The first part sought to obtain basic information about the respondents and their institutions, such as the respondent's experience in the construction industry, the number of industrial projects, and the number of projects using prefabrication in which the respondent was involved. In the second part, respondents were asked to rate the level of significance of the derived criteria based on a scale of 1- 5, where 1 is "least important", 2 "fairly important", 3 "important", 4 "very important" and 5 "extremely important. ". To ensure a better understanding of the criteria, the definition of each criterion is clarified and guidance on completion is provided in the questionnaire.

At the same time, and at the end of the questionnaire, professionals were encouraged to mention any complementary criteria to the criteria mentioned in the questionnaire, and they considered them important in the method of choosing factory construction methods.

- Questionnaire survey

It has also been mentioned previously that the questionnaire needs to be tested before sending it to the professionals. Therefore, the questionnaire was conducted face to face with 5 contracting engineers and 5 consultant engineers with experience in constructing industrial buildings, in order to finally verify the validity of the questionnaire. After verifying the validity of the questionnaire, it was sent to 215 professionals selected from the construction industry professionals in Egypt. The Egyptian professionals were chosen to include owner engineers, contracting engineers and consultant engineers as well as manufacturers of pre- fabricated concrete. Each of them has a different view of the criteria affecting the method of choosing a construction method (a view that achieves the most benefit to him). Acquiring the differing perspectives of these professionals ensures that comprehensive criteria are set for how to choose a construction method.

To conduct the survey, two pre- fabricated concrete manufacturers were interviewed, and the questionnaire was filled out face to face. In addition, 100 questionnaires were sent to contracting engineers, 100 questionnaires for consulting engineers, and 15 questionnaires sent to owner engineers. Contact information about the engineers to whom the questionnaires were sent was collected by using social media sites and also using the LinkedIn application. The questionnaire was also sent by using the WhatsApp application or by using e- mail, depending on the availability of contact information.

- Interviews

Egyptian construction industry professionals with previous experience in industrial buildings as well as pre- fabricated concrete were selected. After receiving the questionnaire from the professionals, a group of five professionals who have great experience in the industrial building construction industry were selected and interviewed and asked about the reasons for their choice, such as the fact that standards are more important than other criteria. The previous step was taken to further understand the results of the questionnaire.

Table (2) A summary of the most important advantages and disadvantages of off- site construction methods [8,9, 10, 11, 12].

		Main criteria	Description
Advantages	Economic advantages	time	The construction process can be speeded up by the mass production of precast components in factories. Removal of in- situ construction activities from the critical path of the overall construction process. Clear site construction activities from the critical path in the full construction plan. Prefabrication and site preparation can occur simultaneously, and the erection process is fast .The bad weather does not significantly affect the construction progress A lot of time can be saved by using more than one pre- made component manufacturer at the same time.
		Quality	All quality assurance tests can be performed in the factory before the items are transported to the factory. Small samples can be made for loading tests before starting the manufacturing process. Any level of finish of the concrete surface can be reached in the factory.
		Cost	less timber formwork due to prefabricated elements. Obtaining discounts on the price of the materials, because they are requested in a bulk form. Saving costs of labor transportation machinery transportation reduction Less number of theft from the site due to the speed of construction Fewer accidents due to less traffic at the site Saving in the cost of the margin of financing due to the speed of construction Avoid fines for delay due to bad weather or severe conditions on the site. Improved productivity.
	Environmental advantages	Pollution	Fewer activities on site, thus less water pollution and less consumption. The noise produced is much less due to the reduced number of activities. reduction in greenhouse gas (GHG) emissions
		Waste	A certain amount of solid waste generated from On- site construction. prefabrication leads to significant reduction in solid waste. the ability to waste management efficient land resources use
	Social advantages	Safety	Fewer site activities result in fewer workers on site. reduce the elevated work and dangerous activities.

Disadvantages	Economic disadvantages	Time	a longer timeout is required in the design and production processes. Extra time is required to approval procedures.
		Quality	Quality control and procurement problems may be found if the precast units are not fabricated locally but internationally.
		Cost	Higher investment cost is imposed on contractors especially when there is an insufficient volume of work to sustain running costs. changes will cost at late time in design as it will expensive changes to both existing and new precast units. prefabrication is not cost effective for small projects because the extra cost of manufacturing the modeling cannot be recovered on a satisfactory unit cost basis. prefabrication is not suitable for small construction sites as a larger site area than normal is required for storage of the units and maneuvering of handling vehicles and cranes. If site area is not available, off- site storage can be considered but in this case extra cost should be allowed for storage and delivery of precast elements. Areas for the storage of units must be hard and level and may need strengthening to enable the units to be safely stored and easily handled and this is cost. Special equipment may be required e.g. lifting beam, crane, lifting hooks to lift prefabricated elements. lifting equipment may need well trained persons to operate and incur extra labor costs. The whole project development phase is shifted towards the start of the project and that result higher initial cost.

DATA ANALYSIS METHODS

The next step, according to the methodology established for the research, is to analyze the data collected from the completed questionnaires.

But first, the reliability of the questionnaire must be checked before analyzing the data to ensure the reliability of the questionnaire. To ensure the reliability of the questionnaire, the Cronbach alpha measure (reliability coefficient) was used. It was used to verify the extent to which the Sustainability Performance Criteria (SPC) derived and used in the questionnaire were related to each other. The range of values for Alpha Cronbach ranges from 0 to 1, as the closer the values are to 1, this indicates a higher internal consistency of the Sustainability Performance Criteria (SPC). The Statistical Package for Social Sciences (SPSS) version 23 was used to calculate Cronbach's alpha values. Reliability coefficients greater than 0.7 are considered acceptable according to Nunnaly (1978) [25].

After that, to classify the SPC in the questionnaire, the ranking analysis was used to analyze the collected data. As previously mentioned in the study, a 5- point Likert scale was used to rank the importance of SPC. The scoring of the ordinal scales depends on the order of the criteria, and it is not possible to determine the exact difference between the two points. For example, point 4 is more important than point 3, but the difference in importance cannot be determined precisely. According to Johnson and Bhattacharya (1977), when using descriptive statistics (for example, Likert scales), nonparametric methods of ordering elements (here SPIs) should be used instead of parametric statistics (means, standard deviations, etc.) [26].

Therefore, an index method was used. Severity (SI) to classify SPC criteria according to applicability (significance) since the scoring system was ordinal in nature. The SI is calculated as follows (Idrus and Newman, 2002):

$$servisity\ index\ (SI) = \frac{(\sum_{i=1}^{5} Wi \times \frac{fi}{n} \times 100\%)}{a} \quad (1)$$

where i i is each SPC's score (1- 5) assigned by the questionnaire respondents; Wi is the weight of the assigned score (1 is the least important and 5 is the extremely important); fi is the total frequency of the score i; n is the total number of the completed questionnaires; and a is the highest weight which is 5 in this study. Severity index values ranged between 0 and 100%. In this procedure, the frequency analysis was first carried out to obtain the percentage ratings of the different selection factors. This was done with the help of SPSS. The percentage ratings (given as "valid percentage" by SPSS) were then used to calculate the severity indices via the above formula. The term fi. 100%/n is the valid percentage as calculated by SPSS. All the SPCs were ranked (based on their severity index values) under the overall TBL SPCs (i.e., all the 30 SPCs) as well as within each associated sustainability dimension categories, i.e., the economic category, the environmental category and the social category. Subsequently, each SPC was assigned an importance level according to the following severity scale:

- Extremely high (EH): SI ≥ 95.00 %
- Very high (VH): 85.00 % ≤ SI < 95.00 %
- High (H): 75.00 % ≤ SI < 85.00 %
- Medium (M): 65.00 % ≤ SI < 75.00 %
- Low (L): 55.00 % ≤ SI < 65.00 %
- Very low (VL): 45.00 % ≤ SI < 55.00 %
- Extremely low (EL): SI < 45.00 %

Those SPCs that were assigned as either "extremely high", "very high", or "high" importance level are the critical sustainability criteria. In other words, they can be considered as applicable SPCs that are capable of making a considerable difference between the sustainability of in site and off site industrial buildings construction methods from the research participants' points of view in Egypt.

RESULTS AND DESCUTION

Characteristics of the sample

100 completed and correct questionnaires were received, one month after the questionnaire was sent and a reminder message was sent to professionals to complete the questionnaire and resend it. After reviewing the received questionnaires, it was found that there were 10 questionnaires that were not completed as required, as there were many answers not available. The questionnaires were distributed as follows: 5 questionnaires from owner engineers, 35 from contractor engineers and 50 from consultant engineers. The overall response rate was 41.86%, and the sub- response rates ranged between 33% and 50%, as shown in Table 3.

Table (3) response rate

respondents	Sent- out	valid	Percentage (%)	Response rate (%)
owners	15	5	5.56 %	33.33 %
engineers	100	50	55.56 %	50 %
contractors	100	35	38.88 %	35 %
Total	215	90	100 %	41.86 %

The respondents were from different organizations in a number of Governorates (EGYPT), including architectural firms, engineering firms, consulting firms, general contractors, construction managers, and AECs (Architecture, Engineering, and Construction), precast concrete manufacturers. The diversity of the samples is a guarantee of obtaining holistic criteria. In the present study, architectural designers and structural engineers are referred to as engineer; general manager, construction manager, project manager, and superintendent were categorized as contractor due to their similar job characteristics.

All of the survey participants were experienced construction experts. About 12% of them had more than 20 years of experience in the construction industry, 27% had experience between 15 and 20 years, and 19% between 10 and 15 years. The respondents' experience in the construction industry is shown in Fig. 4.

The participant history of industrial buildings projects that the respondents have been involved in was also impressive. As shown in Fig. 5, about 12% respondents were involved in more than 60 industrial buildings projects, and the average number of industrial buildings was 22.

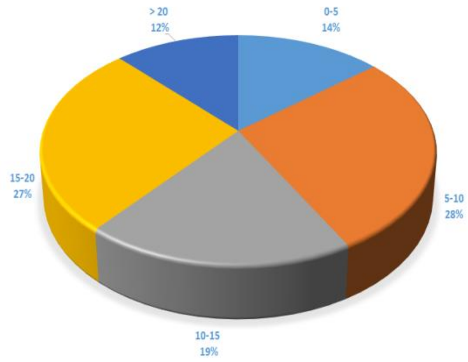

Figure (5) Survey participants' experiences in construction industry

As the experience of the respondents in the industrial buildings projects and in the construction industry is quite respectable, opinions and views on relevance of SPC obtained through the survey can be regarded as important and reliable.

- Reliability check

As stated in the methodology section, a reliability analysis was conducted to examine the internal consistency of the questionnaire survey. The data collected through the completed forms was fed into the SPSS software as input and four rounds of reliability analyses were performed. The analyses included one analysis that considered all SPCs as a whole set of sustainability criteria (overall TBL SPCs), and three independent analyses that separately considered the SPCs associated with the sustainability categories (i.e., environmental, economic, and social).

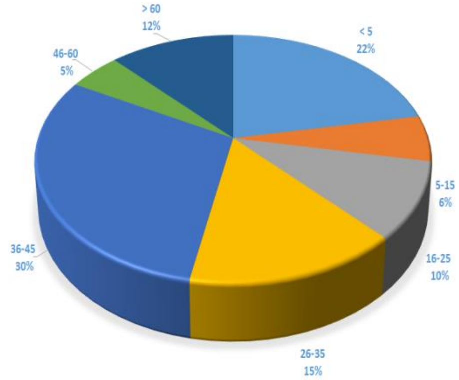

Figure (6) Survey participants' experiences in industrial buildings projects

As discussed previously, a minimum reliability coefficient of 0.70 ensures that adequate internal consistency of a test exists. The resulted Cronbach's alpha values are shown in Table 4, which are much higher than the 0.70 value recommended by Nunnally (1978) [25]. The reliability coefficient values for the

TBL SPC set, environmental SPC set, economic SPC set, and social SPC set indicate strong internal consistency of the questionnaire.

Table (4) Reliability coefficients for different SPC categories.

Sustainability category	SPC count	Cronbach's alpha
Economic	14	0.834
Social	7	0.836
Environmental	9	0.941
Total	30	0.939

- Ranking analysis

Similar to the reliability check, four rounds of ranking analyses were conducted.

Based on the output of the SPSS software (i.e., valid percentage values) and equation 1, severity index (SI) values were obtained. These SI values were used to identify the rank of all the SPCs under the overall SPCs as well as within their associated sustainability categories. According to the severity index value of a SPC, its importance level was assigned using the severity scale defined above ranging from "extremely high" to "extremely low".

- Economic criteria

Results of the ranking analysis for economic category are presented in Table 5. Based on the values of the severity indices, among 14 SPCs in the economic category, 3 SPCs, 3 SPCs, 5 SPCs, and 3 SPCs placed in the "very high", "high", "medium", and "extremely low" levels, respectively. "Very high" and "high" level criteria consist of "construction time", "initial construction costs", "loading capacity", "maintenance cost", "flexibility (adaptability)", and "material costs".

The first top ranked ("very high") economic SPC, as already anticipated, was identified as "construction time" with the SI value of 92.25%. This SPC was ranked first under the overall TBL SPCs, which indicates the importance of this indicator among all the SPCs as well.

The next major economic concern of the respondents was "initial construction costs" (SI = 90.28%). This SPC was found to be at second rank under the overall TBL SPCs. As shown in Table 5, the costs associated with the material production and construction phases of a building life cycle, such as design, coordination, material, and labor, grabbed the attention of the respondents more than the costs associated with the other life cycle phases. The possible reason could be the costs associated with the initial phases of a building life cycle can be perceived as short- term costs; therefore, they are more perceptible (tangible). Interestingly, the costs related to the end of life phase are long- term costs and rated as the least important SPC under the economic category (with SI value of 74.23), even though it is still a "medium" importance level indicator. Accordingly, it can be observed from Table 6 that "operational costs" and "maintenance costs", which are both mid- term costs, were assigned close SI values and located somewhere between "initial construction costs" and "disposal costs".

Table (5) Ranking of the economic sustainability performance criteria.

Economic category	SI (%)	Rank in category	Over all rank	Level of importance
E1: construction time	92.25	1	1	VH
E2: initial construction costs	90.28	2	2	VH
E9: loading capacity	85.31	3	3	VH
E3: maintenance costs	84.20	4	4	H
E8: flexibility (adaptability)	77.05	5	5	H
E11: material costs	76.52	6	6	H
E12: labor costs	74.23	7	7	M
E10: lead- times	72.98	8	8	M
E7: Investment and related risks	71.58	9	9	M
E13: constructability (buildability)	70.24	10	10	M
E6: Durability	70.21	11	11	M
E5: defects and damages	40.02	12	27	EL
E14: integration of supply chains (logistics)	38.32	13	28	EL
E4: disposal costs	35.21	14	29	EL

- Social criteria

In addition to the economic sustainability criteria, the outcomes resulting from the social criteria ranking analysis are reviewed. As Table 6 illustrates, among 7 social SPCs, only one SPC was rated as "extremely low" and two SPCs were rated as "very low", while one SPC, and 4 SPCs placed in the "medium", and "low" importance levels, respectively.

Table (6) Ranking of the social sustainability performance criteria.

Social category	SI (%)	Rank in category	Over all rank	Level of importance
S4: workers' health and safety	66.05	1	15	M
S1: health of occupants (indoor air quality)	63.01	2	17	L
S3: aesthetic options	59.84	3	20	L
S5: labor availability	58.05	4	21	L
S7: traffic congestion	47.02	5	25	VL
S2: influence on job market	46.26	6	26	VL
S6: community disturbance	30.01	7	30	EL

- Environmental criteria

All of the environmental SPCs were assigned as "medium" to "low" importance, except 3 SPCs. As shown in Table 7, there is no "extremely high" and "very high" level SPCs; however, 3 SPCs were ranked "medium" level criteria with SI values ranging from 67.65% to 68.02%. These medium addressed criteria included "energy consumption in design and construction", and "energy efficiency in building use (thermal mass)". The most significant indicator among the top ranked environmental SPCs is "energy consumption in design and construction" (with a SI value of 68.02%). which is also considered as highly ranked indicator in the overall TBL SPIs (6th among all 33 SPIs).

Table (7) Ranking of the environmental sustainability performance criteria.

Environmental category	SI (%)	Rank in category	Over all rank	Level of importance
V6: energy consumption in design and construction	68.02	1	12	M
V5: material consumption	67.98	2	13	M
V3: energy efficiency in building use (thermal mass)	67.65	3	14	M
V1: site disruption	64.78	4	16	L
V8: pollution generation	62.04	5	18	L
V9: water consumption	60.02	6	19	L
V4: reusable/recyclable elements	50.07	7	22	VL
V7: waste	48.89	8	23	VL
V2: recyclable/renewable contents	47.58	9	24	VL

Conclusions

Off- site construction methods have increasingly been used as alternative for conventional (on-site) construction methods during the last few years. One of the main methods of off- site construction is modular construction, which offers various advantages that can effectively contribute to sustainable construction. In order to assess and compare the life cycle sustainability performance of modular construction with conventional construction all triple bottom line (TBL) sustainability dimensions, i.e., economic, environmental, and social, should be addressed.

The sustainability evaluation criteria (SEC) comprise the TBL sustainability categories i.e., environmental, economic, and social, in which each category includes numerous sustainability criteria associated with different life cycle phases of a building. Therefore, the most applicable (important) TBL sustainability performance criteria (SPC) should be identified, by which the life cycle sustainability of these two construction methods can be distinguished. Following a comprehensive literature review, 9 environmental SPCs, 14 economic SPCs, and 7 Social SPCs were developed. Using these TBL SPCs, a questionnaire survey captured the construction industry practitioners' perceptions of the most applicable sustainability criteria for comparing the sustainability of modular and conventional construction method in industrial buildings in Egypt. The survey sample population was mainly construction experts in Egypt who had experience in construction processes and had diverse professional backgrounds in industrial buildings. Ranking analysis using the severity index (SI) was the primary technique used for data analysis. Based on each SPC's SI value, it was assigned an importance level according to a severity scale ranging from "extremely high" to "extremely low". Results of analyses showed that among 30 TBL SPCs, 6 SPCs were rated as either "very high" or "high" importance criteria (there were no "extremely high" importance SPCs) which comprises of 20% of total SPCs. In addition, 9 SPCs were assigned as "medium" importance level, and 14 SPIs were among either "low" to "extremely low" importance level criteria. No study has been conducted so far on sustainability criteria identification for the selection of modular and conventional construction methods for industrial buildings in Egypt.

According to the construction industry practitioners, the economic criteria still play the most significant role in distinguishing the sustainability of two construction methods. Furthermore, the impact of the research participants' professional experience on the rank order of SPCs was examined. In both the economic and the social categories, there were impressive consistencies of SPC rankings assigned by respondents with less than 20 years and over 20 years of professional experience. However, in the case of the environmental SPCs, there were some inconsistencies of the rankings by these two groups of respondents. The results of this research can assist the construction industry experts to gain in- depth understanding of the most significant TBL sustainability criteria to distinguish between the sustainability of modular and conventional construction methods. By identification of applicable sustainability evaluation criteria (SEC), all sustainability dimensions can be balanced over the life cycle of building projects and different stakeholders' concerns can be addressed, which can lead to sustainable construction.

With the use of the most applicable TBL SPCs in this paper, future research may investigate the ways to measure and use them in a framework to comparatively asses the sustainability of modular and conventional industrial buildings.

The next step of this research is to identify the appropriate sub- SPCs under each selected SPC. Then, by investigating the most and least desirable sustainability performance levels (i.e., benchmark values) for each sub- SPC, the performance level of a given building project (modular/conventional) can be measured. By aggregating the performance levels of all sub- SPCs associated with a SPI, and their relative importance weights, the performance level of the building with respect to that SPC is obtained. Once the performance levels of all SPCs within a sustainability category (e.g., environmental category) are measured, the sustainability index for that category can be derived. As mentioned above, Multi Criteria Decision Making (MCDM) analyses can be used in the process of deriving the sustainability performance indices. The outcome of the above steps can be incorporated in a decision- support tool by which the sustainability performance of different case study buildings constructed by modular and/or conventional method(s) are compared with each other and also with the desirable sustainability performance levels.

Appendix (1) **Descriptions of the SPC**

SPC	Description
Economic criteria	
E1: construction time	*Duration of* *on- site installation/construction of the building, whether modular or traditional.* *site establishment and set- up for entire project (as influenced by the specific element).* *commissioning and testing stage for the modules, and the entire facility.*
E2: initial construction costs	*Costs of all initial activities such as setting up site, etc.*
E3: maintenance costs	*Costs of repair and maintenance of the building during the operation phase.*
E4: disposal costs	Costs of dismantling and waste treatment (recycling, disposal, etc.)
E5: defects and damages	*Failures to achieve the specifications, or damage to the product before final Completion.* *Level of damage during installation or before hand- over, that can be repaired locally (as opposed to requiring a new pod, or substantial replacement).* *How easily can the product be damaged, particularly after manufacture.*
E6: Durability	Specifying durable and low- maintenance building materials and assemblies in order to have a building with a long usable life leading to economic benefits.
E7: Investment and related risks	The speed of return on loans or other investments and the associated risks.
E8: flexibility (adaptability)	Compatibility of the product and adaptability to accommodate substantial changes in the future at a lower cost (e.g., using fastening systems that allow for easy disassembly)
E9: loading capacity	Ability to reach high carrying capacity
E10: lead- times	*Duration of* *all pre- construction phases include planning, design and procurement of the project relevant to the element.* *off- site module manufacture.*
E11: material costs	costs of material and transportation of it.
E12: labor costs	costs of labor and housing.
E13: constructability (buildability)	the ease and efficiency with which structures can be built
E14: integration of supply chains (logistics)	a close alignment and coordination within a supply chain, often with the use of shared management information systems.... Supply chain refers to all inputs required to produce a product and fulfil a purchase.
Social criteria	

SPC	Description
S1: health of occupants (indoor air quality)	Health, comfort and well- being of the end users in the occupancy phase of the building life cycle (e.g., indoor air pollutants).
S2: influence on job market	Impact on job opportunities, whether by providing new job opportunities or reducing labor
S3: aesthetic options	Containing design features intended for human delight, spirit and place appropriate to its function, internal and external beauty, and visual appearance.
S4: workers' health and safety	Risks of any health and safety issues in the workplace (e.g., injury, damage, chronic health risks, etc.)
S5: labor availability	Availability of skilled labor in the region surrounding the project
S6: community disturbance	Impacts of the construction activities on occupants and surrounding local communities (e.g., construction noise and dust, traffic congestion, etc.).
S7: traffic congestion	Impact on the traffic surrounding the project during the construction phase.
Environmental category	
V1: site disruption	Promoting natural biodiversity (e.g., providing adequate open space), planning for storm water management, avoiding blocking fresh air or sunlight or natural waterways for adjacent developments, and so forth.
V2: recyclable/renewable contents	Content such as concrete, steel,...etc. is renewable and recyclable at the end of the project life cycle (demolition phase)
V3: energy efficiency in building use (thermal mass)	level of energy efficiency for the building and its systems.
V4: reusable/recyclable elements	Elements such as beams, columns,...etc. are renewable and recyclable at the end of the project life cycle (demolition phase)
V5: material consumption	The amount of any product or natural resource used during the design and construction phase of the building.
V6: energy consumption in design and construction	Level of consumption during the construction phases of the project, and during operation (indicator of the energy- saving measures incorporated into the design)
V7: waste	Degree of waste management in design, and during construction. E.g. waste minimization, segregation, recycling, re- use etc.
V8: pollution generation	Noise and light pollution on the community both during construction and throughout the life of the project. Air, water and land pollution, both during construction and throughout the whole life.
V9: water consumption	Level of consumption during the construction phases of the project, and during operation (indicator of the water- saving measures incorporated into the design)

REFRANCES

[1] Kwatra, S., Kumar, A., & Sharma, P. (2020). A critical review of studies related to construction and computation of Sustainable Development Indices. Ecological Indicators, 112, 106061.

[2] WCED, S. W. S. (1987). World commission on environment and development. Our common future, 17(1), 1- 91.

[3] Sev, A. (2009). How can the construction industry contribute to sustainable development? A conceptual framework. Sustainable Development, 17(3), 161- 173.

[4] Smirnova, E., & Larionov, A. (2020). Justification of environmental safety criteria in the context of sustainable development of the construction sector. In E3S Web of Conferences (Vol. 157, p. 06011). EDP Sciences..

[5] Dean, B., Dulac, J., Petrichenko, K., & Graham, P. (2016). Towards zero- emission efficient and resilient buildings.: Global status report.

[6] https://gocontractor.com/blog/how- does- construction- impact- the- environment. retrieved 24- 8- 2020

[7] Pan, W., & Sidwell, R. (2011). Demystifying the cost barriers to offsite construction in the UK. Construction Management and Economics, 29(11), 1081- 1099.

[8] Cameron, P. J., & Di Carlo, N. G. (2007). Piecing together modular: understanding the benefits and limitations of modular construction methods for multifamily development (Doctoral dissertation, Massachusetts Institute of Technology).

[9] Lu, N., & Liska, R. W. (2008). Designers' and general contractors' perceptions of offsite construction techniques in the United State construction industry. International journal of construction education and research, 4(3), 177- 188.

[10] Lu, N. (2007). Investigation of Designers' and General Contractors' Perceptions of Offsite Construction Techniques in the United States Construction Industry.

[11] Goodier, C., & Gibb, A. (2007). Future opportunities for offsite in the UK. Construction Management and Economics, 25(6), 585- 595.

[12] Gibb, A. G. F., & Pendlebury, M. C. (2006). Build offsite glossary of terms. Construction Industry Research & Information Association (CIRIA), London.

[13] Bakar, A. H. A., & Cheen, K. S. (2013). A framework for assessing the sustainable urban development. Procedia- Social and Behavioral Sciences, 85, 484- 492.

[14] Heravi, G., Fathi, M., & Faeghi, S. (2017). Multi- criteria group decision- making method for optimal selection of sustainable industrial building options focused on petrochemical projects. Journal of Cleaner Production, 142, 2999- 3013.

[15] San- José, J. T., Losada, R., Cuadrado, J., & Garrucho, I. (2007). Approach to the quantification of the sustainable value in industrial buildings. Building and Environment, 42(11), 3916- 3923.

[16] San- José, J. T., Garrucho, I., Losada, R., & Cuadrado, J. (2007). A proposal for environmental indicators towards industrial building sustainable assessment. The International Journal of Sustainable Development & World Ecology, 14(2), 160- 173.

[17] Shen, L. Y., Ochoa, J. J., Shah, M. N., & Zhang, X. (2011). The application of urban sustainability indicators—A comparison between various practices. Habitat international, 35(1), 17- 29.

[18] Jeong, J., Hong, T., Ji, C., Kim, J., Lee, M., Jeong, K., & Lee, S. (2017). An integrated evaluation of productivity, cost and CO2 emission between prefabricated and conventional columns. Journal of cleaner production, 142, 2393- 2406.

[19] Op't Veld, P. (2015). MORE- CONNECT: Development and advanced prefabrication of innovative, multifunctional building envelope elements for modular retrofitting and smart connections. Energy Procedia, 78, 1057- 1062.

[20] Heravi, G., Fathi, M., & Faeghi, S. (2015). Evaluation of sustainability indicators of industrial buildings focused on petrochemical projects. Journal of Cleaner Production, 109, 92- 107.

[21] O'Neill, D., & Organ, S. (2016). A literature review of the evolution of British prefabricated low-rise housing. Structural Survey.

[22] Baghchesaraei, O. R., Lavasani, H. H., & Baghchesaraei, A. (2016). Behavior of prefabricated structures in developed and developing countries. Bulletin de la Société des Sciences de Liège, 85, 1229- 1234.

[23] Kamali, M., & Hewage, K. (2017). Development of performance criteria for sustainability evaluation of modular versus conventional construction methods. Journal of cleaner production, 142, 3592- 3606.

[24] Kyjaková, L., & Bašková, R. (2016). Advantages and disadvantages of modern methods of construction used for modular schools in Slovakia. Czasopismo Techniczne, 2016(Budownictwo Zeszyt 1- B (6) 2016), 35- 41.

[25] Nunnally, J. C. (1978). Psychometric theory (2nd edit.). New York.

[26] Bhattacharyya, G. K., Johnson, R. A., & Mehrotra, K. G. (1977). On the completeness of minimal sufficient statistics with censored observations. The Annals of Statistics, 547- 553.