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Near optimum selection of module configuration for efficient modular construction

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ABSTRACT

Modular construction gained considerable momentum over the last decade due to its positive impact on project cost, schedule, quality, and safety. Current literature in this field focused on cranes selection and scheduling methods, without due consideration for optimum module configuration. This paper introduces a novel modular suitability indicator which utilizes five indices; 1) connections index (CI) to evaluate module connections using the matrix clustering technique, 2) transportation dimensions index (TDI) to evaluate module dimensions' effects on transportation, 3) transportation shipping distance index (TSDI) to evaluate the distance between manufacturing facility and the construction site, 4) crane cost penalty index (CCPI) to evaluate the crane cost relevant to the module placing rate, and 5) concrete volume index (CVI) to evaluate the project's foundation concrete quantities. Calculating the modular suitability index (MSI) provides a unified indicator to accomplish a near optimum selection of module configuration for efficient delivery in residential construction.

1. Introduction

Offsite construction systems vary depending on the size of prefabricated components which affect the need for onsite construction. These systems include many categories such as modular, panelized, prefabricated, and processed materials construction. Blending two or more of these categories results in a “hybrid” offsite construction system. Each category has its own unique configuration based on its own constraints such as transportation, manufacturing, and onsite lifting and positioning limitations. Choosing between the use of any offsite construction system depends on project characteristics and its targeted cost, schedule, and the scope of off-site manufacturing that can be used.

Modular construction provides a viable alternative to traditional (stick building) construction in view of enabling technologies developed earlier such as that used in the shipbuilding and automotive industries. The percentage of off- site manufacturing for modular construction ranges between 60 and 70%, comparing to 30 to 50% for hybrid construction and 15 to 25% for panelized construction [1].

This accounts for 50 to 60% of construction time reduction for modular construction compared to 30 to 40% for hybrid construction and 20 to 30% for panelized construction [1].

The advantages of modular construction were identified several decades ago [2] and more recently by O'Connor et al., [3]; investigating a set of critical success factors and enablers for optimum industrial modularization. Studying the critical success factors for modularization provided an overall idea highlighting needed changes in current engineering, procurement and construction (EPC) project delivery system to support optimal use of modularization. These studies, however, did not provide a systematic process to quantify the degree of modularity in construction projects. This quantification will enable the modular construction system to compete with the hybrid construction system. Since more manufacturers are beginning to use hybrid construction to eliminate some of the dimensional limitations that modular manufacturers currently face [4].

This paper provides a novel methodology for near optimum selection of module configuration. The methodology addresses the lack of knowledge by architects about the limitations of the manufacturing process of modules, which was identified in an earlier study [5]. In fact, architects should design modules as production designers to standardize the process of module manufacturing [6].

The developed methodology is accomplished by considering a set of practical constraints and factors that affect module configuration such as onsite connections limitation, transportation and weights limitations,

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crane cost limitation, and the required concrete quantities for project foundation.

2. Literature review

Modularization is a concept of mass customization for products that have been successfully adapted by various industries [7]. Product configuration focuses on structuring and standardizing products models to fulfill customer needs [8]. In the construction industry, the needs of customers have been identified based on building geometrical shapes; arranged in a manner that maximizes the Quality Function Deployment (QFD) in the design phase [9,10].

The QFD analysis requires the input of customer requirements. This is often evaluated in market surveys where different market segments are investigated using statistical methods and questionnaires [11]. However, standardized products considerably impact the design of buildings; especially when the design needs to be adapted to satisfy the customer requirements. Thus, such adaptation causes waste and quality problems in the production system [12]. The demand for customization compels the manufacturing industry to develop new methods for adaptation of their mass production to satisfy the individual needs of customers [7,8].

A method called MFD (Modular Function Deployment) was developed by Erixon [7] to investigate different strategies in product modularization. MFD utilizes the QFD for a product using a market survey and systematic analysis to find customer needs for any specific market.

Jensen et al. [13] developed another method to standardize the production and configuration processes by conducting functional requirement analysis to identify design parameters for modular construction of buildings. This method constrains the modularization of project using four views; 1) Customer view that controls the modular design according to customer requirements, 2) Engineering view which constrains the modular design according to deflection, strength, wind loads, fire, acoustics and national regulations, 3) Production view that identifies product dimensions and transportation constraints according to factory regulations and capacity, and 4) Site view for assembly constraints on site according to site plans.

Smith [6] presented a comprehensive description for modular configuration constraints and mass customization including transportation, assembly, craning, and tolerances limitation. Modular builders contributed to this study by identifying the optimum configuration of modules based on their experience. Another method was introduced by Jensen et al. [14] which integrates the rules and constraints of a modular building or product platform in a family of architectural CAD application such as; Revit structures. Lawson et al. [15] studied particular features and key design aspects for steel, concrete and timber modules in the UK, and provided several case studies for the dimensions of hybrid, panelized and modular construction. However, there was no systematic procedure for optimizing modular building designs.

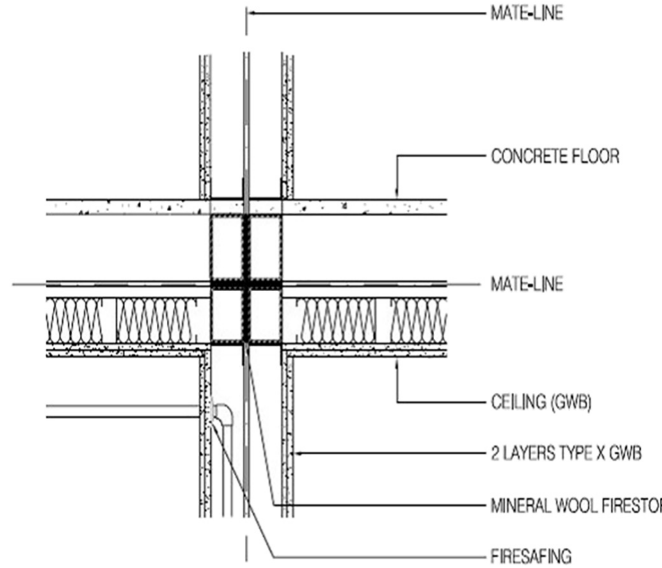

Fig. 2. Internal connection plan view [16].

3. Methodology

The developed methodology utilizes five indices, which accounts for connections of modules onsite (CI), transportation of fabricated modules to construction jobsite (TDI and TSDI), crane operating condition and related cost (CCPI) and project concrete foundation (CVI). These five indices are integrated into one indicator (MSI) measuring the relative suitability of competing modular designs. These indices are described below.

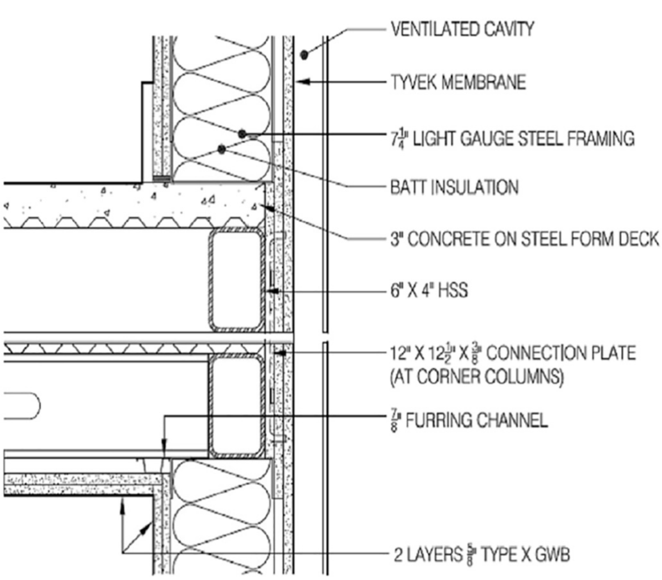

Fig. 1. External connection side view [16].

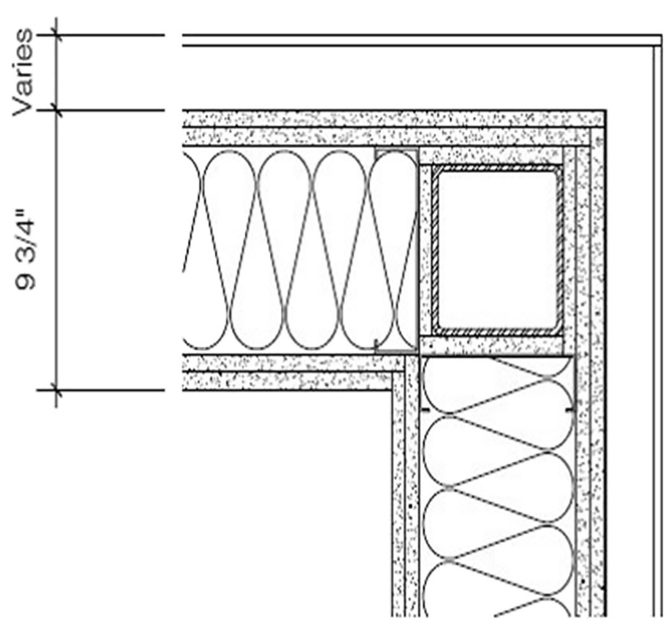

Fig. 3. Corner connection details [16].

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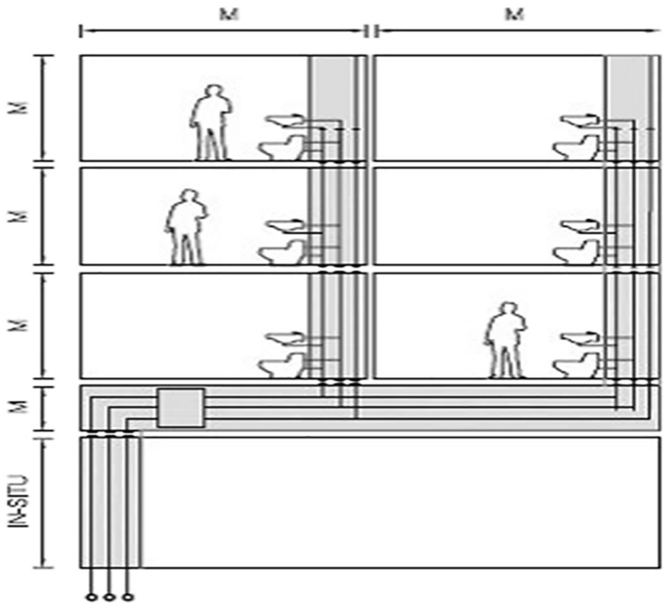


Fig. 4. Mechanical, electrical, and plumbing (MEP) connection between vertically aligned modules [16].

3.1. Connections index (CI)

Investigating module's main connection types is necessary to reach a full understanding of the modular construction process as well as for assigning the needed resources and costs for each connection existing in the modular design. It is also essential in identifying and comparing the suitability of modular design and configuration of modules. Connection types depends on module's material whether it is wooden, steel, or precast modules. Connection types are also different from a manufacturer to another based on each manufacturer's practices. The connections studied in this paper were designed for steel modules of Kullman buildings Corporation. The main connection types considered are external, internal, corner, vertical circulation, Mechanical, electrical, and plumbing connections as shown in Figs. 1 to 5.

Reducing the number of modules in any modular design is cost efficient as long as the transportation limitations are satisfied. This is because increasing modules connections increases construction and maintenance costs and requires more lifts by the crane as well as more trucks for transportation.

Most of modular construction contractors do not identify module connections cost separately and the pinning costs of these connections are usually included within the cost of installing the nearest structural element. Though analyzing module connections' costs is very beneficial to understand how each connection adds penalty costs due its installation, material, and maintenance costs.

Two different modular designs with identical plan area were used to analyze module connections as illustrated in Fig. 6. Each design consists of three stories however, design A comprises 18 modules as indicated in Table 1, which require 16 truckloads and would take two days for the crane onsite to set them into their positions. Design B, on the other hand, comprises only 9 modules, which require only 8 truckloads and would take only one day for the crane onsite to set them into their final positions. The red lines in Fig. 6 refer to module interfaces and the red circles refer to module connection positions.

3.1.1. Analyzing module connections using the matrix clustering technique

Cost efficient configuration of modules depends on connections cost, number of transportation trucks, and the onsite crane cost. The optimum module configuration should target fewer connections and module interfaces. The proposed connections index is assessing the modular suitability through evaluating and comparing the connections in each modular design.

Matrix clustering technique was used in a previous study [17] to identify the modularity advantages for modular nuclear power plants. The same technique is used in this paper to analyze the interdependencies between residential modules after configuring and quantifying the connection types between them. The importance of the developed matrices for project stakeholders is to assign priority to some module interfaces regarding resources and budget allocation. The modules are clustered as per the following steps:

1- Arbitrary cost penalties were assigned hypothetically to demonstrate the use of the developed methodology. Penalties assigned to each connection type are included in Table 2 to quantify modules interfaces' connections.

2- Multiplying all the identified connections by their assumed arbitrary cost penalty for all the modules interfaces to reach the unclustered cost penalty matrix as presented in Table 3.

3- Reordering the rows and columns of the unclustered matrix to cluster the array of connections' cost penalties having large values. This task is accomplished by multiplying an element a(ij) of the matrix by the sum of elements surrounding it to the left, right, top and bottom [18] as illustrated in Fig. 7.

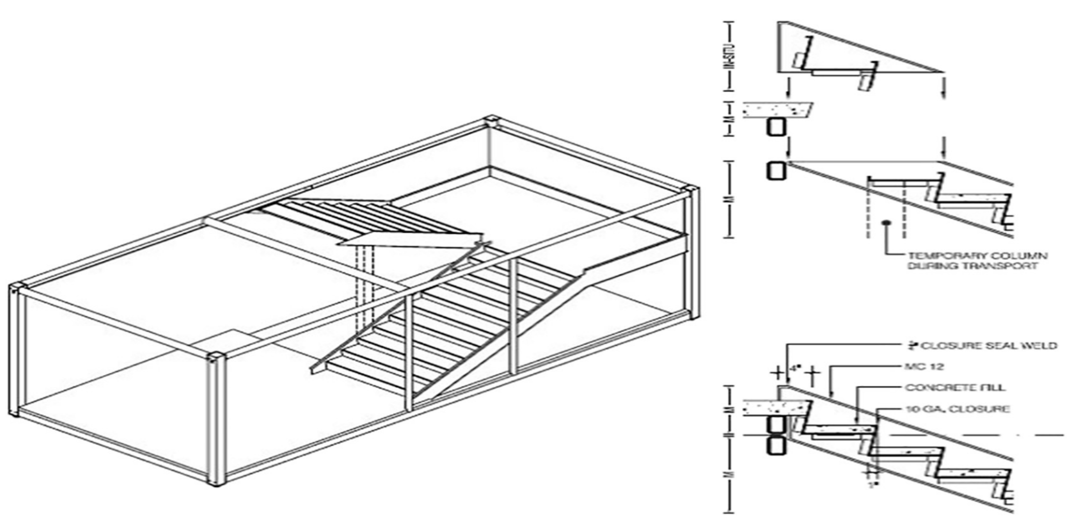


Fig. 5. Vertical circulation connection details [16].

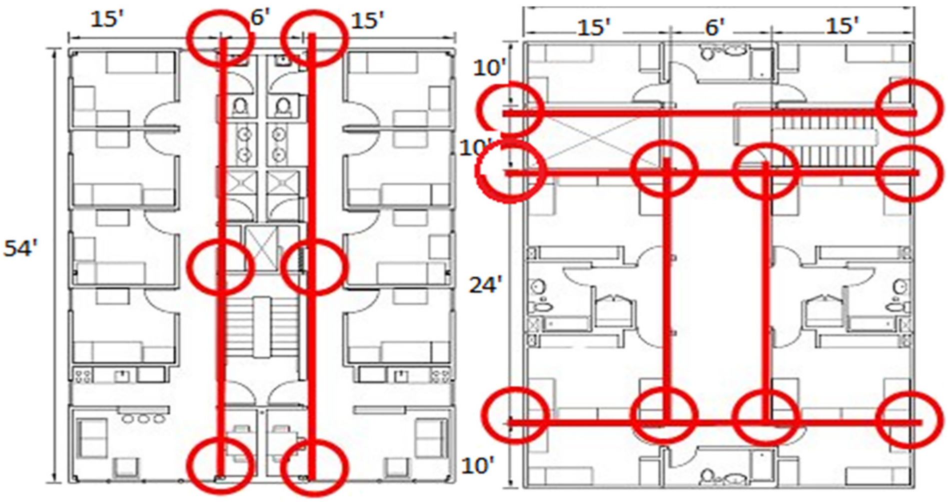


Fig. 6. Design A to the right, and design B to the left [4].

Then, summing over rows (or columns) of the multiplications to acquire the bond energy algorithm (BEA) value. Afterwards the rows and columns are reordered within the matrix until this reordering gives the largest value of the BEA. Taking into consideration that the optimal matrix clustering is obtained by reaching the maximum measure of effectiveness (ME), where the ME is identified as follows:

a- Assuming that the relationships matrix's dimension M by N with non-negative elements a(ij).
b- Identifying the quantity A (ij) as indicated in Eq. (1) as follows:

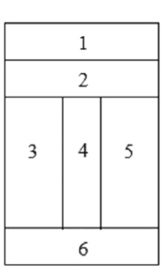
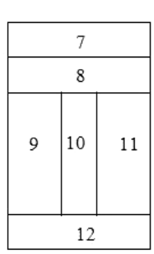
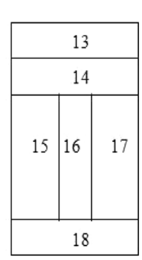
$$A_{ij} = 0.5 \times \left[a_{i+1,j} + a_{i-1,j} + a_{i,j+1} + a_{i,j-1} \right]. \quad (1)$$

c- Identifying the measure of effectiveness (ME) as indicated in Eq. (2) as follows:

$$ME = \sum \text{All } i,j \ \left[a_{ij} \times A_{ij} \right] \quad (2)$$

4- Representing the final clustered matrix as presented in Table 4.

Table 1
Numbering of modules for design A.

Numbering of modules for design A.		
First Floor	Second Floor	Third Floor
		

3.1.2. Analyzing the results of clustering

Clustering modules' connections cost penalties is beneficial in prioritizing the resource assignment to certain connections and interfaces depending upon its priority as illustrated in Table 4. This technique's capability will be more beneficial in analyzing more complex modular construction projects that needs robust budget and resources allocation based on the priority of each grouped interfaces. This priority can be noticed when comparing the clusters of modules number 2, 7,8,13 and 14 to the clusters of modules 16 and 18. Since the first clustering group has higher connections cost penalty values than the second clustering group, and its clustering group area is bigger. Hence it requires more attention towards its cost and construction.

Comparing the nature of clusters complexities between modular projects is also an advantage of using this technique. Finding less complicated clusters would be the optimum solution for any modular project that lead to less complex modular design and construction. Since more complex clusters means that many resources and trades shall be needed to work on the same module interfaces, and coordinating such complex resources and trades takes more effort and time.

3.1.3. Calculation of the connections index (CI)

This paper presents the connections index (CI) which account for connections quantity and modules' connections cost implications to compare between different modular construction designs and identify suitability of design and configuration of project modules. Connections cost penalty is simply the summation of the calculated hypothetical cost penalties. Hence it is the summation of half the hypothetical cost penalties indicated in the symmetrical clustered matrix. The connection index is calculated by indexing/ dividing connections cost penalties for any design over the least possible connections cost penalties for alternative modular design that have the same plan area in any city.

$$CI = \frac{\sum \text{connections cost penalties}}{\text{least possible connections cost penalties for other design}} \quad (3)$$

3.2. Transportation dimensions index (TDI)

Modular transportation and trucking plans include many studies for transportation methods, transportation routes, and transportation handling equipment. Though "the first design parameter established for a modularized plant is the maximum size and weight of a module that is practical and economical to transport from its construction yard to the plant site." [19].

Table 2
Connections codes and its arbitrary cost penalty.

Connection	Code	Arbitrary cost penalty
External connection	1	20
Internal connection	2	15
MEP connection	3	10
Vertical circulation connection	4	20
Corner connection	5	10

Minimizing the number of modules (boxes) that should be manufactured for any modular construction project is a clear economical solution for modular designs. Since the most cost efficient module is the

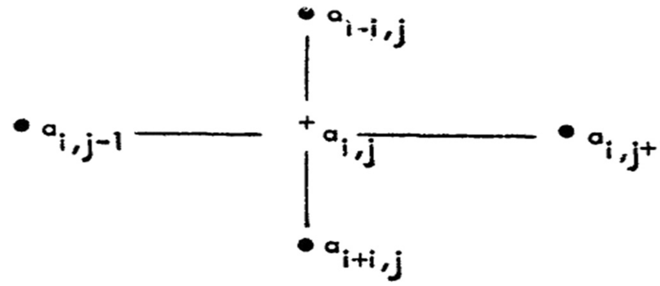


Fig. 7. Representation or bond energy ME [17]..

Table 3
Quantifying module interfaces' connections for unclustered matrix of design A. Number of connections ∗ (connection code).

Module #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	2(1) + 2(4)	0	0	0	0	2(1) + 2(4) + 2(5) + 1(3)	0	0	0	0	0	0	0	0	0	0	0
2	2(1) + 2(4)	1	1(1)	0	1(1)	0		4(1) + 2(4)	0	0	0	0	0	0	0	0	0	0
3	0	1(1)	1	3(3)	0	1(1) + 1(2)	0	0	2(1) + 2(2) + 1(3)	0	0	0	0	0	0	0	0	0
4	0	0	3(3)	1	2(2)	2(2)	0	0	0	4(2)	0	0	0	0	0	0	0	0
5	0	1(1)	0	3(3)	1	1(1) + 1(2)	0	0	0	0	2(1) + 2(2) + 1(3)	0	0	0	0	0	0	0
6	0	0	1(1) + 1(2)	2(2)	1(1) + 1(2)	1	0	0	0	0	0	2(1) + 2(4) + 2(5) + 1(3)	0	0	0	0	0	0
7	2(1) + 2(4) + 2(5) + 1(3)	0	0	0	0	0	1	2(1) + 2(4)	0	0	0	0	2(1) + 2(4) + 2(5) + 1(3)	0	0	0	0	0
8		4(1) + 2(4)	0	0	0	0	2(1) + 2(4)	1	1(1) + 1(2)	0	1(1) + 1(2)	0		4(1) + 2(4)	0	0	0	0
9	0	0	2(1) + 2(2) + 1(3)	0	0	0	0	1(1) + 1(2)	1	2(2)	0	1(1) + 1(2)	0	0	2(1) + 2(2) + 1(3)	0	0	0
10	0	0	0	4(2)	0	0	0	0	2(2)	1	2(2)	2(2)	0	0	0	4(2)	0	0
11	0	0	0	0	2(1) + 2(2) + 1(3)	0	0	1(1) + 1(2)	0	2(2)	1	1(1) + 1(2)	0	0	0	0	2(1) + 2(2) + 1(3)	0
12	0	0	0	0	0	2(1) + 2(4) + 2(5) + 1(3)	0	0	1(1) + 1(2)	2(2)	1(1) + 1(2)	1	0	0	0	0	0	2(1) + 2(4) + 2(5) + 1(3)
13	0	0	0	0	0	0	2(1) + 2(4) + 2(5) + 1(3)	0	0	0	0	0	1	2(1) + 2(4)	0	0	0	0
14	0	0	0	0	0	0		4(1) + 2(4)	0	0	0	0	2(1) + 2(4)	1	1(1)	0	1(1) + 1(4)	0
15	0	0	0	0	0	0	0	0	2(1) + 3(2) + 3(3)+	0	0	0	0	1(1)	1	2(2)	0	1(1) + 1(2)
16	0	0	0	0	0	0	0	0	0	6(2)	0	0	0	0	3(3)	1	1(2) + 1(4)	2(2)
17	0	0	0	0	0	0	0	0	0	0	2(1) + 3(2) + 3(3)+	0	0	1(1)	0	3(3)	1	1(1) + 1(2)
18	0	0	0	0	0	0	0	0	0	0	0	2(1) + 2(4) + 2(5) + 1(3)	0	0	1(1) + 1(2)	2(2)	1(1) + 1(2)	1

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Table 4
The clustered cost penalty matrix for design A.

The clustered cost penalty matrix for Design A.																		
Module #	13	8	14	7	2	1	9	15	3	10	12	6	18	16	11	4	5	17
13	1	0	80	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	1	120	80	120	0	35	0	0	0	0	0	0	0	35	0	0	0
14	80	120	1	0	0	0	0	20	0	0	0	0	0	0	0	0	0	40
7	110	80	0	1	0	110	0	0	0	0	0	0	0	0	0	0	0	0
2	0	120	0	0	1	80	0	0	20	0	0	0	0	0	0	0	20	0
1	0	0	0	110	80	1	0	0	0	0	0	0	0	0	0	0	0	0
9	0	35	0	0	0	0	1	80	80	30	35	0	0	0	0	0	0	0
15	0	0	20	0	0	0	80	1	0	0	0	0	35	30	0	0	0	0
3	0	0	0	0	20	0	80	0	1	0	0	35	0	0	0	30	0	0
10	0	0	0	0	0	0	30	0	0	1	30	0	0	60	30	60	0	0
12	0	0	0	0	0	0	35	0	0	30	1	110	110	0	35	0	0	0
6	0	0	0	0	0	0	0	0	35	0	110	1	0	0	0	30	35	0
18	0	0	0	0	0	0	0	35	0	0	110	0	1	30	0	0	0	35
16	0	0	0	0	0	0	0	45	0	60	0	0	30	1	0	0	0	35
11	0	35	0	0	0	0	0	0	0	30	35	0	0	0	1	0	80	80
4	0	0	0	0	0	0	0	0	30	60	0	30	0	0	0	1	30	0
5	0	0	0	0	20	0	0	0	0	0	0	35	0	0	80	30	1	0
17	0	0	40	0	0	0	0	0	0	0	0	0	35	35	80	0	0	1

largest module that could be transported with the most amounts of interior finishes. Hence designing fewer larger modules would be better than smaller modules because there is less cost when getting more square footage per truckload [4].

Transportation routes control as well the practical module dimensions, since some routes require different ways of transportation from the manufacturing facility to the construction site. Such intermodal transportation requires a great deal of planning and coordination since size constraints is different from a shipping method to another and from a state to another.

Trucks, trailers, railways, and boats are used for transporting manufactured modules. The advantage of railways lies in its capabilities to transport heavier truckloads, and it should be considered as an alternative if its location is close to the manufacturing facility or construction site. It can transport an 11 ft wide module without permits, and modules with 11 to 14 ft width with a permit. If modules' width exceeds 14 ft, a special train is used [6]. Railways height constraint is 17 ft from the top of rail and railcars can accommodate modules up to 88 ft of length [6]. However, railways' major disadvantage is its higher overall costs comparing to regular trucks. Moreover, transporting offsite construction by boat is more affordable but transit time on the ocean may affect the project overall schedule.

International intermodal transportation for offsite construction may use the three aforementioned ways of transportation in one route,

State	Width	Height	Length	State	Width	Height	Length
Alabama	12' (16')	* (16')	76' (150')	Montana	12'-6" (18')	* (17')	* (120')
Alaska	10' (22')	*	100' (*)	Nebraska	12' (*)	14'-6" (*)	85' (*)
Arizona	11' (14')	* (16')	* (120')	Nevada	8'-6" (17')	* (16')	105' (*)
Arkansas	12' (20')	15' (17')	90' (*)	New Hampshire	12' (16')	13'-6" (16')	80' (100')
Califonia	12' (16')	* (17')	85' (135')	New Jersey	14' (18')	14' (16')	100' (120')
Colorado	11' (17')	13' (16')	85' (130')	New Mexico	* (20')	* (18')	* (190')
Connecticut	12' (16')	14' (*)	80' (120')	New York	12' (14')	14' (*)	80' (*)
Delaware	12' (15')	15' (17'-6")	85' (120')	North Carolina	12' (15')	14'-5" (*)	100' (*)
District of Columbia	12' (*)	13'-6" (*)	80' (*)	North Dakota	14'-6" (18')	* (18')	75' (120')
Flordia	12' (18')	14'-6" (18')	95' (*)	Ohio	14' (*)	14'-10" (*)	90' (*)
Georgia	12' (16')	15'-6" (*)	75' (*)	Oklahoma	12' (16')	* (17')	80' (*)
Idaho	12' (16')	14'-6" (16')	100' (120')	Oregon	9' (16')	*	95' (*)
Illinois	* (18')	* (18')	* (175')	Pennsylvania	13' (16')	14'-6" (*)	90' (160')
Indiana	12'-4" (16')	14'-6" (17')	90' (180')	Rhode Island	12' (*)	14' (*)	80' (*)
Iowa	8' (16'-6")	14'-4" (20')	85' (120')	South Carolina	12' (*)	13'-6" (16')	(125')
Kansas	* (16'-6")	* (17')	* (126')	South Dakota	10' (*)	14'-6" (*)	*
Kentucky	10'-6" (16')	14' (*)	75' (125')	Tennessee	10' (16')	15' (*)	75' (120')
Louisana	10' (18')	* (16-'5")	75' (125')	Texas	14' (20')	17' (18'-11")	110' (125')
Maine	8'-6" (18')	8'-6" (*)	80' (125')	Utah	10' (17')	16' (17'-6")	105' (120')
Maryland	13' (16')	14'-6" (16')	85' (120')	Vermont	15' (*)	14' (*)	100' (*)
Massachuetts	12' (14')	13'-9" (15')	80' (130')	Virginia	10' (*)	15' (*)	75' (150')
Michigan	12' (16')	14'-6" (15')	90' (150')	Washington	12' (16')	14' (16')	*
Minnesota	12'-6" (16')	*	95' (*)	West Virgina	10'-6" (16')	15' (*)	75' (*)
Mississippi	12' (16'-6")	* (17')	53' (*)	Wisconsin	14' (16')	*	80' (110')
Missouri	12'-4" (16')	15'-6" (17'-6")	90' (150')	Wyoming	* (18')	* (17')	* (110')

Fig. 8. Module dimensions regulations for truck transportation according to the state [16]. * ( ) indicates maximum possible dimension requires permits or escorts.

especially for rural areas. In that case the minimum practical dimensions for the three ways of transportation are used to reduce any transportation conflicts. For local transportation, trucks are commonly used for transportation. Accordingly, trucks and their related limitations will be considered in the developed methodology. There are three standard types of trailers used to transport manufactured modules such as those described in a previous study [6] and are briefly described below.

1- Standard flatbed trailer: This is a two-axle trailer used when weight and height are not an issue. The trailer bed is 8 ft.-6 in. wide and 48 ft long, though the maximum module height is limited to 8 ft.-6 in because the bed is so high off the ground. Using this trailer, the module maximum weight is 48,000 lbs.
2- Single-drop deck/trailer: This trailer can be two or three axles which has a single-drop deck. In a triaxle single-drop deck trailer, the module length can reach 50 ft., width of 13 ft., and height of 12 ft. Using this trailer the module maximum weight ranges from 44,000 to 45,000 lbs.
3- Double-drop deck/trailer: This trailer is known in the market as the "lowboy," and its main advantages that it is able to transport higher loads without permitting as well as providing extra feet of height for modules due its lower bed. The module length can reach 40 ft., width of 13 ft., and height of 15 ft.-6 in.

These limitations are different from a state to another, and should be checked before planning any transportation routes between different states. For a practical optimization of the modules dimensions, trailers dimensions limitations should be integrated with the commercial trucking regulations such as those stipulated by two agencies in the USA. The first is at the federal level (Federal Size Regulations for Commercial Motor Vehicles); U.S. Department of Transportation, Federal Highway Administration (FHWA) and the second is at the state level. In Canada every state has its own stipulated regulations according to the published regulations of its department of transportation (DOT), and to "the heavy truck weight and dimension limits for interprovincial operations memorandum of understanding" published by the council of ministers responsible for transportation and highway safety in Canada [20].

In the USA and Canada every state has three categories for shipping dimensions; the first is named the legal dimensions which do not require any permits, the second is the Oversized permitted shipments that require routine trucking permits for usual oversized shipments. These permits' fees are marginal comparing to the overall shipping cost. The third is the super load shipments for the unusual module's dimensions or weights and it requires special permits.

The legal dimensions in Utah for example is 14 ft for height, 8 ft.-6 in for width, and 48 ft for length of semitrailer [6], knowing that these legal dimensions are different from a state to another and it is subjected for changes from time to time. The oversized permitted dimensions in Utah are 14 ft for height, 14 ft.-6 in for width, and 105 ft for length [6]. Hence modular manufacturers tend to pay for the marginal permits to get the extra 6 ft of width in particular because the room width architecturally cannot depend on the allowable legal width of 8 ft.-6. A list of truck transportation regulations was developed by Kullman Buildings Corporation as shown in Fig. 8 which identifies the dimensional requirements and indicates possible special permits or escorts for over-dimensioned loads.

Considering the cost of renting the three standard types of trailers depicted in Fig. 9, the least trailer's rental cost would be the standard flatbed trailer, then renting the single-drop deck would cost higher; and then renting the double-drop deck is higher than the previous two trailers. Moreover, the standard flatbed trailer might enable a better length for module transportation though its limitations regarding module width and height makes the single-drop deck a better alternative. Although the double-drop deck would allow the modules to have a heavier weight and an extra one feet of module height, it has the same width limitation as the single-drop deck and its allowable module length is less than the single-drop deck trailer by 10 feet, as shown in the Fig. 10, as well as it has higher cost among all trailers. Hence the single-drop deck is the most commonly used alternative between the three types of trailers for

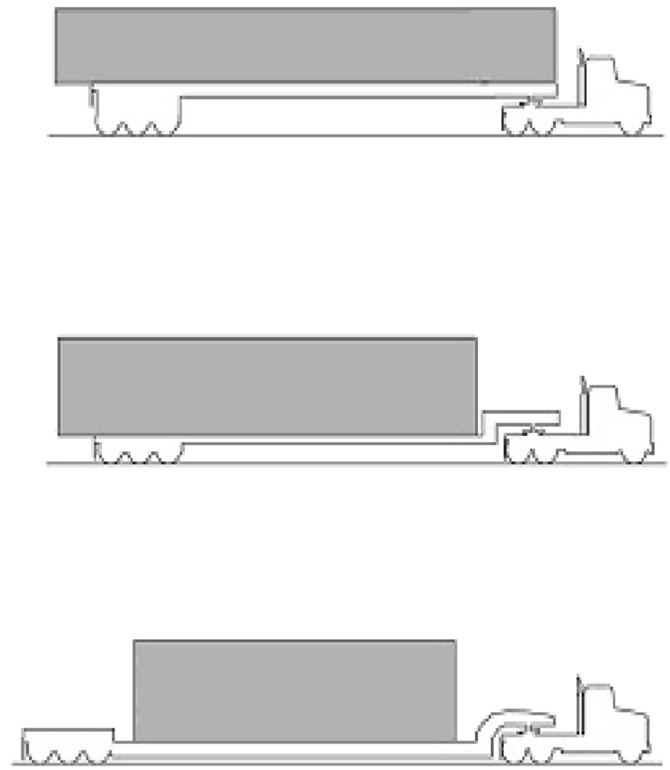
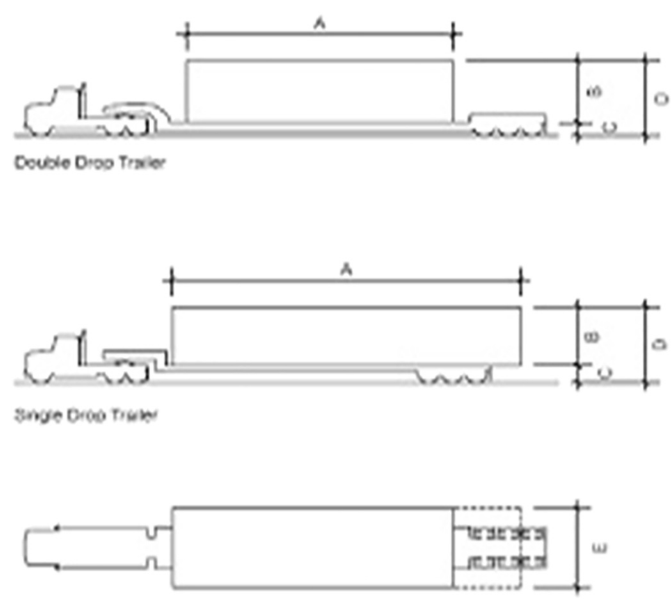


Fig. 9. The three standard types of trailers used to transport modules: Top: standard flatbed trailer, Middle: single-drop deck; and Bottom: double-drop deck [6].



	Double Drop	Single Drop
A	40'-0"	50'-0"
B	13'-0"	12'-0"
C	2'-0"	3'-2"
D	15'-0"	15'-2"
E	13'-0"	13'0"

Fig. 10. Generalized trailers and modules limiting dimensions [16].

Table 5
The optimum residential modules' dimensions.

Dimensions	Common maximum	Oversized maximum
Module width	13 ft	16 ft
Module length	52 ft	60 ft
Module height	12 ft	

modules transportation, unless the module has over weight components, in that case the double-drop deck would be the best alternative.

Based on the aforementioned facts, the optimum residential modules' dimensions is in line with the modular builders contribution to "the guide to modular design and construction" [6] as presented in Table 5. This paper presents a transportation dimension index (TDI) to represent the dimensional optimality of a module in conjunction with its cost per square foot per truckload and the number of modules in the project as presented in Eq. (4). Eq. (5) represents a simplified form of Eq. (4) and it can be used to calculate the TDI as the sum of all ratios of modules divided by the total number of modules in the design being considered. The ratio of each module is calculated as the ratio of the square footage of a truck over the square footage of that module.

$$\mathrm{TDI} = \frac{1}{\text{number of modules}} \times \sum \frac{\text{proposed module design square footage cost per truck load}}{\text{Truck square footage cost per truck load}} \tag{4}$$

$$\mathrm{TDI} = \frac{1}{\text{number of modules}} \times \sum \frac{\text{Truck square footage}}{\text{Module square footage}} \tag{5}$$

3.3. Transportation shipping distance index (TSDI)

The locations of the manufacturing plants relevant to construction sites are complementing the selection process of the optimum route of module transportation. Since the locations of the manufacturing plants affects the transportation method, module weight and dimensions. Hence, planning the optimum transportation route has a great effect on selecting the optimum module configuration that has the best manufacturing plant location which has the least expensive

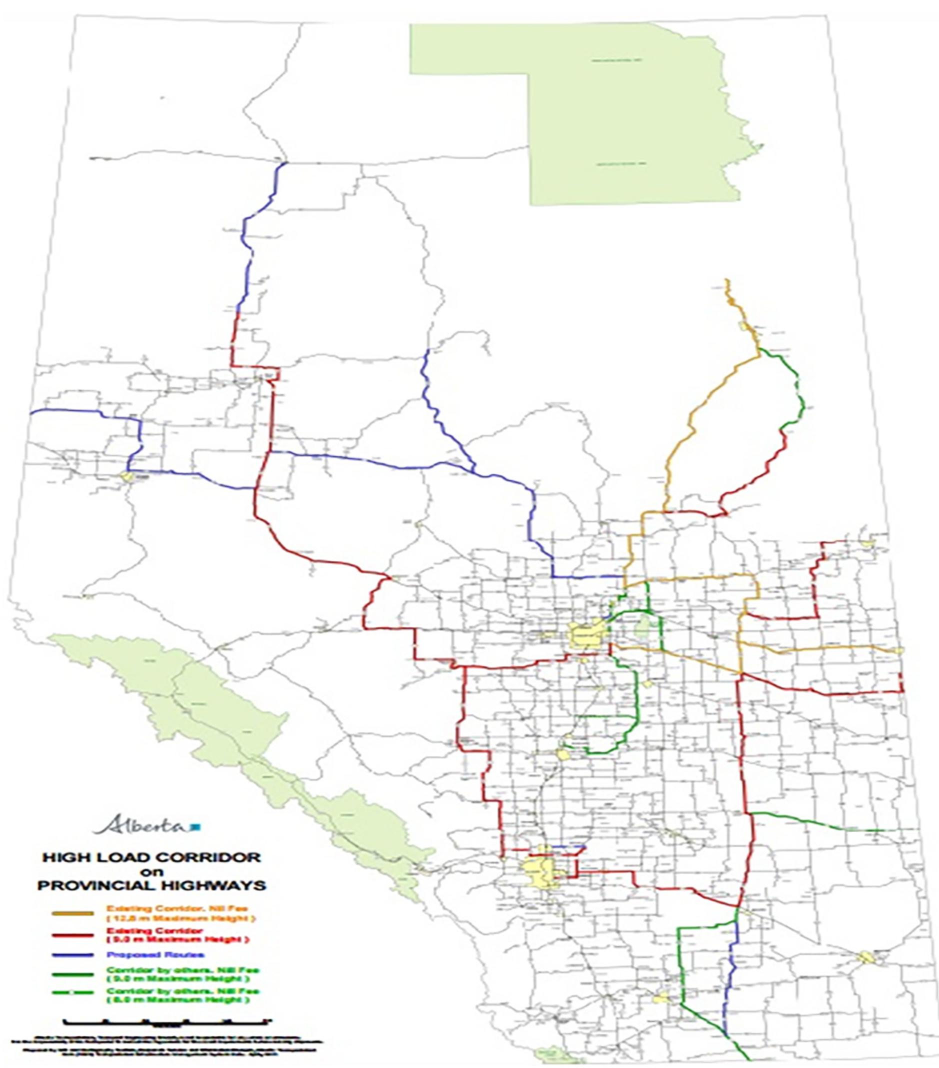


Fig. 11. High-load corridor on provincial highways in Alberta province, Canada [21].

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transportation cost to the construction site. Construction sites which are located far from industrialized cities usually have less chance of utilizing offsite construction capabilities. A transportation route study should be conducted to select qualifying manufacturing plants for any project. This study should identify potential obstacles, such as bridges, tunnels, and overhead utilities that might require extra preparation.

In fact, modular construction industry can change the transportation industry due to requests from modular manufacturers to change the allowable weight and dimension limits on the highways. In 1985 the Canadian government began to construct the high-load corridor in Alberta province which had the overhead utility lines raised to accommodate loads up to 9.0 m to support the increasing transportation demands of the modular construction manufacturers for the oil sands industry in Alberta. The high-load corridor has been expanded every year by the government while permit fees are collected from the industry to recover its costs as shown in Fig. 11.

Several studies indicate that the industry generally recognizes 125 miles as the maximum practical distance for modules to travel from manufacturing plant to construction site [6]. Moreover, shipping modules becomes cost prohibitive when they travel more than 150 to 200 miles from the manufacturing plant to the construction site. In the case of offsite modules having a width of 12 ft. or greater, transportation cost increases exponentially [6].

Furthermore, these studies indicate an average cost for transporting residential modules that has a width of 8.5 to 12 ft. to be \$3.27/S.F. while the average cost for modules with a width greater than 12 ft. was \$5.00/S.F., however these average costs reflect the average of module transportation without including the cost associated with the distance between the manufacturing facility to the construction site. Hence this cost estimate can be used to choose between different manufacturing facilities for supplying modules to the construction site based on their distance from the construction site.

This paper presents a transportation shipping distance index (TSDI) which represents the effect of shipping distance from the offsite manufacturing/assembly facility to the construction job site on the module transportation cost.

The TSDI assumes the practical transportation distance of 125 miles to be the optimum transportation distance and assigns it an optimum transportation value of 1. Any transportation distance up to 200 miles should have a transportation value which is linearly proportional to this optimum transportation value.

$$\mathrm{TSDI} = \frac{1}{\text{number of modules}} \times \sum \frac{\text{Transportation value} \times \text{overall truck cost}}{\text{module square footage} \times \text{average transportation cost}} \quad (6)$$

3.4. Crane cost penalty index (CCPI)

In the last two decades, modular construction industry has rapidly gained momentum with the help of advanced computer aided modelling and the new capacities of heavy lift cranes. This allowed constructing larger modules as needed.

The crane cost may range between 3500 and 4500 \$ per day without counting road permits or closures. Hence cranes require careful planning so the crane will never be idle [22]. Crane type planning must be made in conjunction with the design of any offsite construction system. The main types of cranes are mobile cranes and fixed tower cranes. Mobile cranes are usually used in modular construction since fixed tower cranes are more expensive to lift few modules. Though fixed tower cranes can be used if multiple levels of module placement exist. Choosing the right crane requires a comprehensive study for many variables as indicated in a number of previous studies [23,24] such as the required

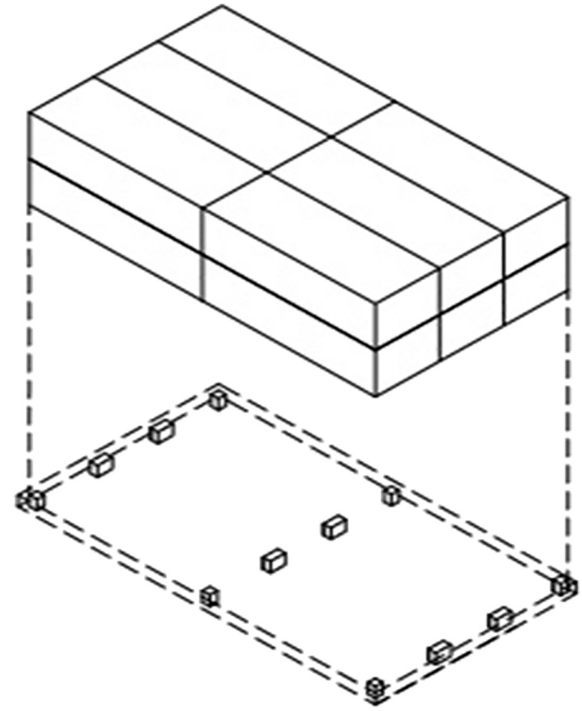


Fig. 12. Isolated footings for modules' foundation [20].

lifting capacity, working radius, lifting height, clearances, and optimal crane path.

Boom size also has an effect on choosing the best crane based on the load capacity it can provide. A standard truck-mounted hydraulic crane with a smaller 25- to 70-ft. boom can handle 22 tons. A 100-ft. boom crane can handle 33 tons [6]. The selection of crane type is based on its weight and reach. However, a rule of thumb in choosing the right crane for a modular construction project is to choose a small and

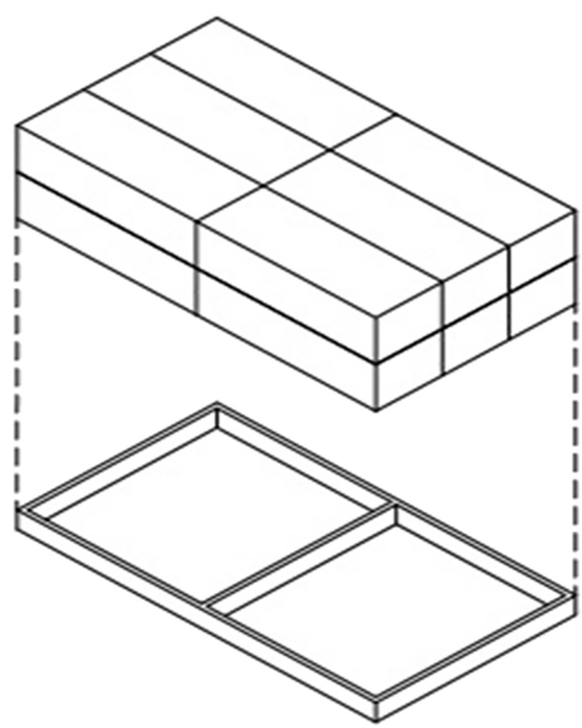


Fig. 13. Perimeter basement foundation [20].

Table 6
Connections codes and its arbitrary cost penalty.

Connection	Code	(Design A)			(Design B)		
		Arbitrary cost penalty	Number of connections	Total cost penalty	Arbitrary cost penalty	Number of connections	Total cost penalty
External connection	1	20	42	840	30	24	720
Internal connection	2	15	39	585	20	0	0
MEP connection	3	10	11	110	10	12	120
Vertical circulation connection	4	20	20	400	30	24	720
Corner connection	5	10	8	80	20	8	160
Total cost penalty				2015			1720

accessible crane to lift multiple modules rather than choosing a large crane to lift one or two lifts.

Generally modular construction of buildings would require a crane with a capacity of 40 to 75 tons, depending on design [16]. Choosing the right crane requires the definition of the average weight of modules per square feet as well as the largest module onsite which will control the crane capacity.

The regular traditional modules weight ranges from 10 to 25 tons depending on their floor size [22]. Knowing that the modules' placing rate per day (i.e. speed of construction) is different from project to another, this rate can be 7 modules per day [22], or 8 modules a day as considered by a Seattle-based modular fabrication facility. In other cases estimates of 10–12 modules per day were considered [25]. This placing rate depends on the module dimensions, site constraints, crane capacity, and weather conditions.

The crane cost penalty (CCP) accounts for the crane cost per module, taking into consideration the cost of renting the crane per hour including mobilization and demobilization costs, the hourly module placing rate, and the number of modules in the project as per Eq. (7). The crane cost penalty index (CCPI) is calculated as the ratio of CCP for any design over the least CCP for the same modular design plan area in any city as per Eq. (8).

$$\mathrm{CCP} = \frac{\text{Crane renting cost per hour} \times \text{number of project modules}}{\text{hourly module placing rate}} \tag{7}$$

$$\mathrm{CCPI} = \frac{\text{CCP for any design}}{\text{least CCP for the same plan area}} \tag{8}$$

3.5. Concrete volume index (CVI)

Wooden framed modules in housing construction commonly transfer the load to the foundation uniformly and can result in strip footings. On the other hand, steel framed modules, such as those produced by Kullman Buildings Corporation generate a point load rather than a

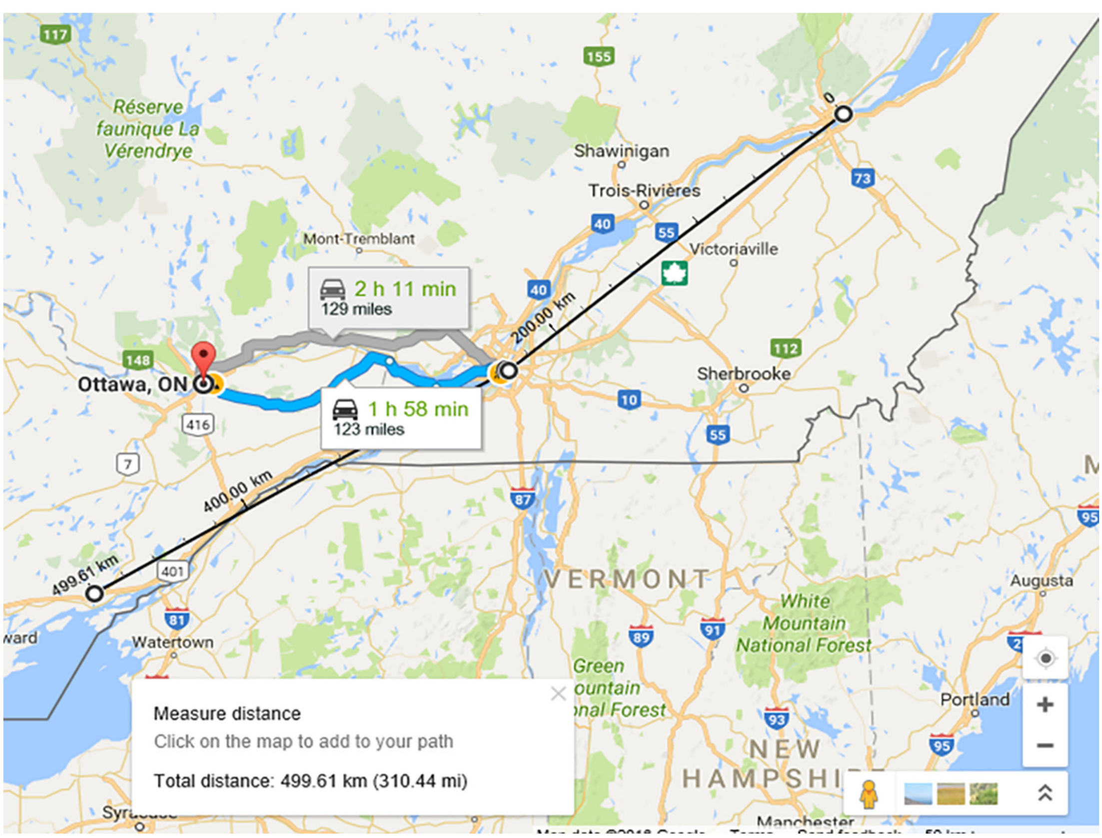


Fig. 14. Identifying distances between Montreal, Ottawa, Quebec City, and Kingstone.

Table 7
Crane cost penalty index (CCPI) calculations.

City	Design	Crane rental ($/hr)	Number of modules	Daily placing rate	Daily working hours	Hourly placing rate	CCP ($)	CCPI
Ottawa	Design A	437.5	18	10	8	1.25	6300	1.13
	Design B	750	9	6	8	0.75	9000	1.62
Quebec City	Design A	462.5	18	12	8	1.5	5550	1
	Design B	812.5	9	8	8	1	7312.5	1.31
Kingstone	Design A	487.5	18	11	8	1.375	6381.8	1.14
	Design B	875	9	7	8	0.875	9000	1.62

distributed load. Hence perimeter and isolated footings foundation systems are the best solution [6].

Considering steel framed modules, such as those produced by Kullman Buildings Corporation, the more module connections exist in any modular design the more isolated footings shall be required as shown in Figs. 12 and 13. Smith [6] stated that foundations for modular construction can either be piers, linear footings, or continuous footings.

This paper presents the concrete volume index (CVI) which evaluates the suitability of a modular design based on the required concrete volume. This index accounts for the quantities of concrete for the foundation, and is referred to in this paper as concrete volume. The foundation concrete volume cost (CVC) is calculated for any design. The index CVI accounts for the volume of concrete used in the project's foundations and relate it directly to the cost of the project. CVI is calculated as the ratio of the volume of concrete foundation over the least foundation concrete cost of each alternative modular building that has same plan area in any city as per Eq. (10).

$$\text{CVC} = \text{total concrete volume} \times \text{concrete cost per unit volume} \tag{9}$$

$$\text{CVI} = \frac{\text{CVC for specific design}}{\text{least CVC for other modular design}} \tag{10}$$

3.6. Modular suitability index (MSI)

The modular suitability index (MSI) integrates the above mentioned five indices into one unified index to be used as an indicator of the modular suitability based on reducing the economic implications of different project costs. Modular construction cost needs considerable attention to the process of suitability evaluation of different modular design configurations. The integrated MSI is calculated using the weighted sum expressed by:

$$\begin{aligned}\text{MSI} = &(\text{W1} \times \text{CI}) + (\text{W2} \times \text{TDI}) + (\text{W3} \times \text{TSDI}) + (\text{W4} \times \text{CCPI}) \\ &+ (\text{W5} \times \text{CVI})\end{aligned} \tag{11}$$

In which W1 to W5 are relative weights, which account for the preference of the project stakeholders. This preference could be based on real data extracted from actual modular projects to make sure that each index's relative weight does not affect the overall modular suitability index more than it should.

The integration of the proposed five indices indicates by numbers how modular designs are properly optimized to reach the optimum modular overall design based on the optimum module configuration. Hence, if the modular design is properly modularized it will not generate any extra penalty costs.

4. Case study

This hypothetical case study is presented to illustrate the use of proposed indices and to validate the proposed methodology by comparing indices values for the manufacturing two projects in three different cities (e.g. Ottawa, Quebec City, and Kingston) by three different manufacturers. Each manufacturer develops one project as design A and one project as design B as shown in Fig. 6, while this project is constructed in Montreal after comparing the three manufacturers cost penalty indices and comparing design A to design B as follows:

4.1. Connections index (CI)

All connections are identified for designs A and B, and then the number of each connection type is multiplied by the assigned cost penalties as shown in Table 6. However, the cost penalty of design A is different from design B due to the difference of loading on each connection type which affect the capacity and sizes of that connection.

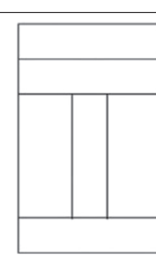
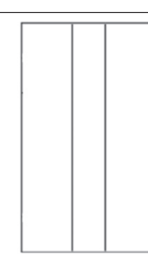
Connection penalty costs are calculated as shown in Table 6 to be 2015 for design A and 1720 for design B. Then, Eq. (3) is used to calculate the connection indices for design A and design B as 1.17, and 1, respectively. This indicates that the cost of connections in design A is higher than that of design B because it has a larger number of modules and accordingly larger number of connections.

4.2. Transportation dimensions index (TDI)

This index is calculated using Eq. (5) after identifying the required number of trucks for designs A and B. Thirteen (13) single-drop deck trailers were needed for design A to transport 18 modules; three trucks for modules 3,5,9,11,15 and 17 with a rate of 2 modules per truck, one truck for modules 4, 10 and 16 with a rate of 3 modules per truck, and nine trucks for modules 1,2,6,7,8,12,13,14, and 18 with a rate of 1 module per truck. Eight trucks are required to transport the modules of design B; each module is transported by one single-drop deck truck except the middle module in the first and second floors which shares one truck.

Transportation dimension index is then calculated to be 1.25 for design A, and 0.9 for design B, which indicates that module arrangements for transportation is more economical for design B because the area of trailers is used efficiently.

Table 8
Strip foundation plan lines for design A and B.

Strip foundation plan lines for design A and B.	
(Design A)	(Design B)
	

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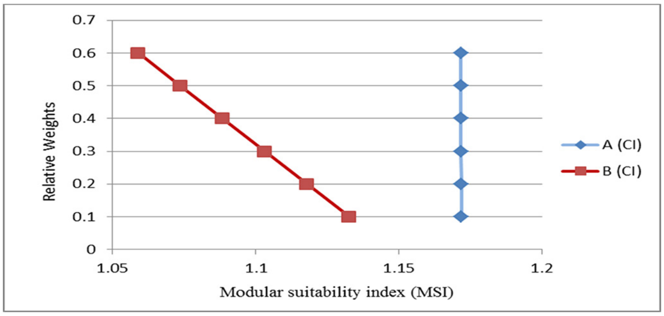

Fig. 15. Sensitivity analysis for connection index (CI) effect on modular suitability index while manufacturing design A and B in Ottawa.

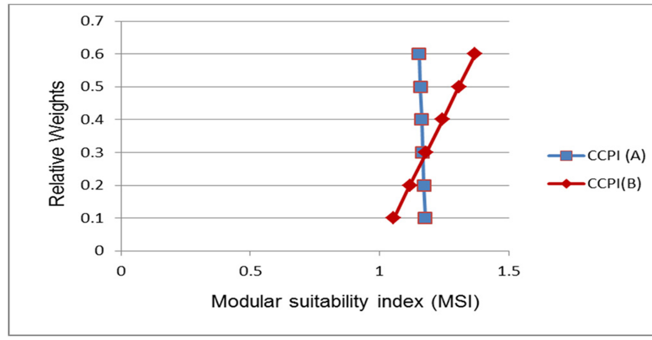

Fig. 17. Sensitivity analysis for crane cost penalty index (CCPI) effect on modular suitability index while manufacturing design A and B in Ottawa.

4.3. Transportation shipping distance index (TSDI)

The distances between the construction site in Montreal and the three manufacturers in Ottawa, Quebec City and Kingstone were identified from Google maps as shown in Fig. 14. The distances between Montreal and Ottawa, Quebec City and Kingstone are 123, 157 and 179 miles, respectively. These distances are used in Eq. (6) to identify the transportation value comparing to the practical transportation distance of 125 miles.

The transportation values are calculated as 0.98, 1.256, and 1.432 for the distance between Montreal and Ottawa, Quebec City and Kingstone respectively. The single-drop deck truck cost was assumed to be $1500 for transporting modules with a width of 12 ft or less, and $3000 for transporting modules with a width more than 12 ft to account for the required permits and escorts on the road. The average cost for transporting modules that has a width less than 12 ft. was taken $3.27/S.F. while the average cost for modules with a width more than 12 ft. is $5.00/S.F. [6]. Transportation shipping distance index was calculated for manufacturing design A and B to be 1.13 and 1.06 for Ottawa, 1.45 and 1.36 for Quebec City, 1.59 and 1.55for Kingstone respectively. This result indicates that design B is more cost efficient than A regarding transportation distance variable because the number of modules is lower in design B than A. It should be noted that design B has higher cost of trucks than design A due to the needs for permits and escorts even though design B remains more efficient than design A.

4.4. Crane cost penalty index (CCPI)

Crane cost penalty is calculated using Eq. (7) and the assumed variables are included in Table 7. The crane daily working hours are assumed to be 8 h while the hourly placing rate is calculated as the ratio of assumed daily placing rate over daily working hours. Crane cost penalty indices (CCPI) are calculated using Eq. (8) by dividing all crane cost penalties to the lower cost penalty which is the cost penalty for design A in Kingstone. Design A proved to be more cost efficient than B regarding crane cost penalties. This can be attributed to the lower assumed daily placing rate for design A comparing to design B due to the heavy weight of design B modules since design B has 9 modules only comparing to design A that has 18 modules.

4.5. Concrete volume index (CVI)

Concrete cost penalty is calculated using Eq. (9) while considering that the foundation constitutes of strip footings around building perimeter and under modules' connections as shown in Table 8. Strip footing foundation is assumed to have 1 ft of width and 3 ft of height; hence concrete foundation volumes of design A and B are 1008 and 864 cubic feet respectively. By multiplying these volumes to the cost of cubic feet of concrete which is 14 $, then concrete cost penalties are 14,112 and 12,096 $ for design A and B. Dividing cost penalty of design A over design B generates the concrete volume index to be 1.16 and 1 for design A and B using Eq. (10). This means that the foundation of design A costs more than that of design B due to the difference in the total number of modules which require more foundations as presented in Table 8 and accordingly higher volume of concrete.

4.6. Modular suitability index (MSI)

Modular suitability index (MSI) is calculated using Eq. (11) assuming different values for the relative weights W1 to W5. A sensitivity analysis is performed to investigate the effect of each index on the overall MSI. Relative weights values start by 0.1 for each weight then it increases with 0.1 increments till it reaches 0.6. For each trial the specific weight is fixed to a specific value while the rest of weights for

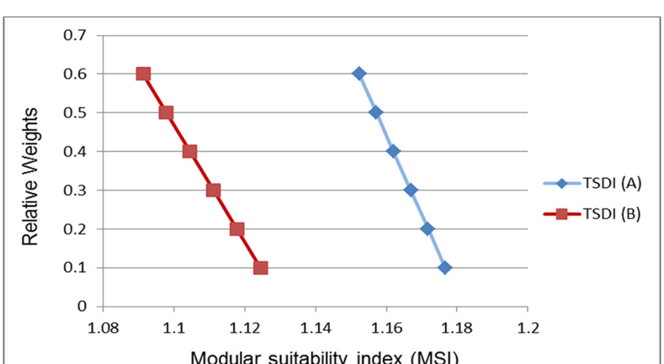

Fig. 16. Sensitivity analysis for transportation shipping distance index (TSDI) effect on modular suitability index while manufacturing design A and B in Ottawa.

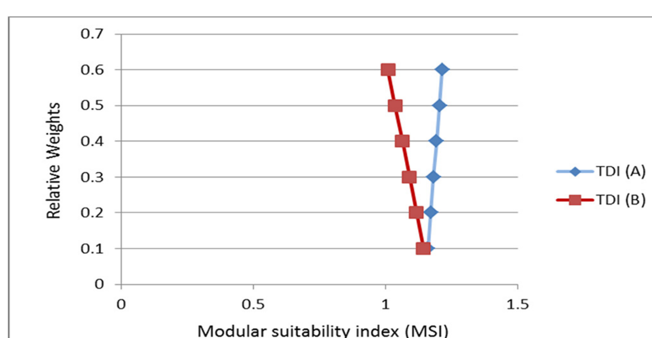

Fig. 18. Sensitivity analysis for transportation dimensions index (TDI) effect on modular suitability index while manufacturing design A and B in Ottawa.

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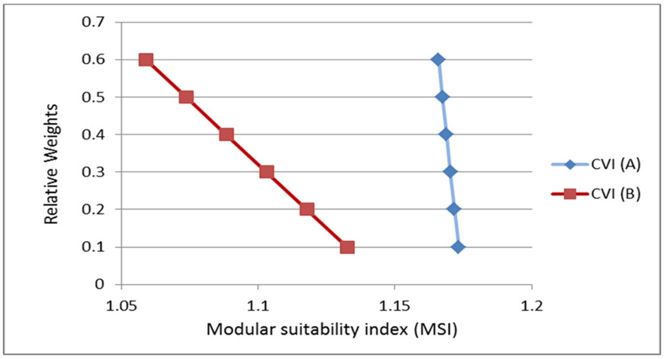

Fig. 19. Sensitivity analysis for concrete volume index (CVI) effect on modular suitability index while manufacturing design A and B in Ottawa.

other indices are kept equal. For example, if relative weight W1 equals 0.3 then relative weights W2 to W5 are equal to 0.175.

Figs. 15–19 explain the effect of different indices on MSI, and indicate that design B has lower MSI generally for most cases, though design A may be better if CCPI relative weight is higher than 0.3 or TDI is lower than 0.1. Fig. 20 compares between different cities and designs and indicates that the design B is selected to be manufactured in Kingston because it has the lowest MSI according to connection index (CI).

5. Discussion

Offsite construction systems are competing currently to gain more share in the market place. This creates competition against traditional stick-built construction and invites construction managers to assess and evaluate these two competing alternatives with respect to project schedule, cost, quality, and project's unique constraints such as transportation, manufacturing, and craning limitations. This evaluation requires structured tools to assist in the selection process. Critical to the selection is optimization of module configurations as demonstrated in the case study.

This paper introduced a systematic methodology to support the search for near optimum module configurations. This optimization enables modular construction to compete against other alternative offsite construction systems, especially the hybrid system. This developed methodology will also benefit the industry in standardizing module configuration selection process.

Transportation limitations represent major factors that control module dimensions. Therefore, constructing new infrastructure and highways that can sustain modular construction overload and oversize is essential for the growth of this industry. Transportation agencies should take the lead in analyzing futuristic needs of the offsite construction industry to construct needed infrastructure. The offsite construction industry also should have a clear role in financing such projects and providing their needs for the regulators to be considered in updating regulations for transportation limitations.

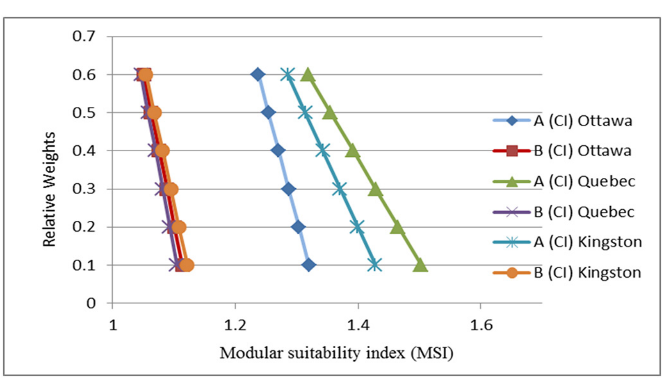

Fig. 20. Sensitivity analysis for connection index (CI) effect on modular suitability index while manufacturing design A and B in for all cities.

6. Conclusion and future work

This paper presented a newly developed methodology to support the process of identification and selection of near optimum module configurations that account for project conditions. It assists developers and project stakeholders in delivering projects not only with accelerated schedules but also with cost reduction. The developed modular suitability index (MSI) provides a quantitative indicator for the suitability of module design configurations in building construction. It integrates the effect of five newly developed indices; connections index (CI), transportation dimensions index (TDI), transportation shipping distance index (TSDI), crane cost penalty index (CCPI), and concrete volume index (CVI). The optimum practical module dimensions were identified based on transportation and weight constraints. It was concluded that reducing the number of module connections shall be cost efficient as long as transportation and weight limitation are satisfied. MSI can be reduced by developing new cost efficient connections between modules that requires lower field installation and maintenance costs. Acquiring experienced personnel for trucking and cranes' selection, location, lifting and positioning enables modular construction companies to deliver construction projects efficiently.

Suggested future work may consider expanding the developed methodology to account for customer satisfaction. The methodology can also be expanded to include a commissioning index to its MSI, particularly for industrial projects. The analytic network process (ANP) can also be used to calculate the relative weight assigned to each of the 5 indices in the developed method.

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