Civil and Sustainable
Urban Engineering

Research Article
Volume 2(1), 2020, 33-43
https://doi.org/10.53623/csue.v2i1.85

Interactions Among the Main Characteristics of Open Building Systems

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SUBMITTED: 17 April 2022; REVISED: 10 May 2022; ACCEPTED: 12 May 2022

ABSTRACT: Constant need-for-change in the construction market and social trends has resulted in the demand for more adaptable building systems. The ability to practise and accommodate change has consequently become a new necessity for buildings. Adaptability, therefore, is to be considered in both the pre-construction stage and the entire life cycle of the construction. The further civilization develops, the more we need to take advantage of the Open Building Systems (OBS) concept, introduced to the construction industry almost 70 years ago. However, conventional methods are still common due to the lack of knowledge in OBS, resistance to change, monopoly of conventional building materials manufacturing, insufficient legislation, and lack of end-user's awareness. The ability to practise and accommodate changes has consequently become a new necessity for building construction. This research aims to address the interactions among the influential factors of OBS. The initial move was to identify and verify the significant open building influential factors in a conceptual model based on previous relevant literature. Then the second step was to find the interactions between the variables through the Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique. The results indicate that one of the most significant and main factors is the "Level of Independence", and the main cause factor identified was "Standardization (St)", which had a major role in the success of construction OBS performance.

KEYWORDS: Open Building Systems; adaptable building; modular building; design for change; DEMATEL

1. Introduction

Lack of knowledge in implementing Open Building Systems is a significant challenge that necessitates additional research. This research is aimed at investigating the interactions and relations between significant factors of Open Building Systems (OBS) to enhance its implementation for construction decision-makers and designers to assure the satisfaction of end-users in the pre-construction stage. In other words, this research aims to answer this question: what are the interactions and relationships of the main factors influencing OBS application in the construction industry?

2. Research Methods

To find the interaction among factors to address the objective of this research, the DEMATEL was employed as a methodological tool. DEMATEL is an influential tool that enables gathering group data to develop an operational model. This method also helps to visualize the fundamental interactions between complicated primary factors and sub-factors via a cause-effect diagram and a dependency matrix. Those matrices and diagrams characterize an appropriate relation among the factors of the study so that a quantitative rate showing the degree of influence can be achieved. Moreover, this method enabled the researcher to distribute further the fundamental components and affected components in Decision-Making models such as the AHP and the ANP analysis approaches [1]. This model helps decision-makers to investigate and figure out research issues by separating various measurement components into different groups according to the cause and effect concept to recognize fundamental interactions. Some significant benefits of applying the DEMATEL technique are reviewed as follows [2]:

- It states the fundamental relationships, dependencies, and interactions among variables.
- It helps the independence assumption of statistical approaches by avoiding the implication errors initiated by components with fundamental interactions and complications caused by sample data.
- It streamlines the dependency among components in complex situations with a justifying cause or effective association, using an Impact Relation Map (IRM).
- It also helps to show the interactions among the components by collecting data from a group of experts. This method has been used for answering reliance and reaction difficulties in numerous studies, especially those applying the Multi-criteria Decision Making (MCDM) approach in management fields [3].

The eight (8) main factors of the initial model were found in earlier literature and are listed as follows: Open Characters with Influence (8) OBS variables influencing sustainability development (SD). investigated in this research to identify the internal relationship among them by employing the Decision-making Trial and Evaluation Laboratory (DEMATEL) method.

In this research, the DEMATEL technique is employed to calculate the expert ideas and recognise the interactions among the primary factors of the Open Building concept. Therefore, these factors are referred to as "cause factors", "central roles" and "effect factors." The differences among these three (3) criteria are illustrated in Figure 1 [4].

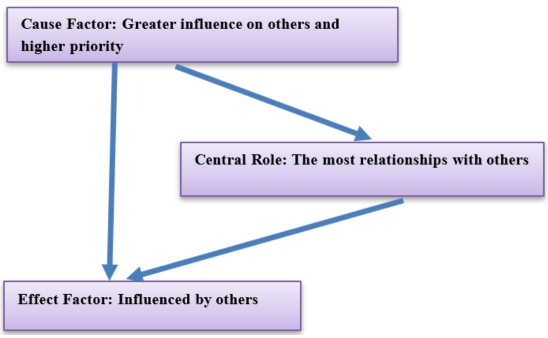

Figure 1. The differentiation amongst “cause factors”, “central-roles” and “effect factors” by Mirdad [4].

According to Wu and Lee [5], Yang et al. [6], and Shieh et al. [7], the main progress line of the DEMATEL technique is summarized in Figure 2.

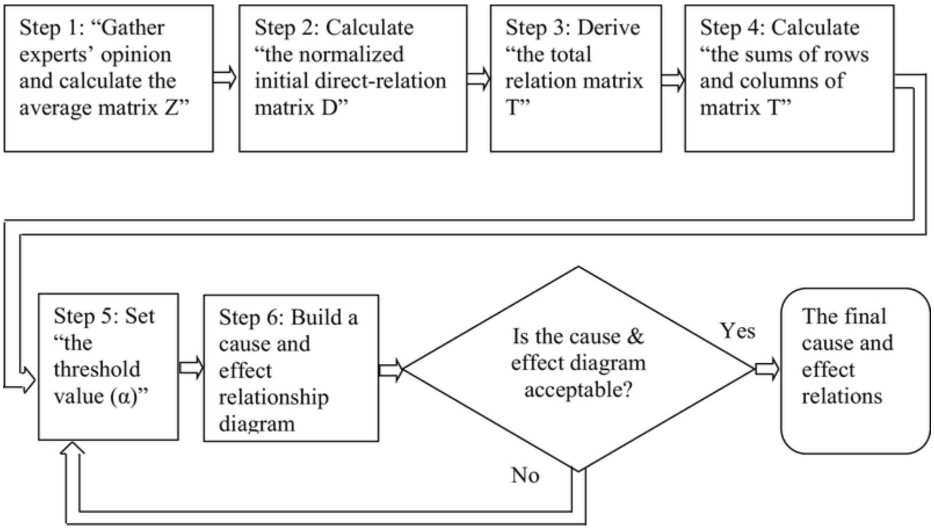

Figure 2. The DEMATEL Procedure [7].

Step 1, Creating a direct relation matrix: According to the questionnaire, the panel was requested to score the degree of direct effect between each pair of elements based on their experience. The assessment was designed with 5 levels of scales from 0 to 4, which represents the following rates; 0 (No Influence), 1 (Low Influence), 2 (Medium Influence), 3 (Great Influence), and 4 (Very Great Influence). The primary direct-relation matrix was attained by converting experts' opinion evaluations into values. The evaluations from each expert offer a primary direct matrix refers to the expression as below in Eq. (1).

$$T = \left[t_{ij}\right]_{n\times n}, i,j = 1,2,\dots \quad X^{(k)} = \left[a_{ij}^{(k)}\right]_{n\times n} = \begin{bmatrix} E_1 & E_2 & \dots & E_n \\ 0 & a_{12}^{(k)} & \dots & a_{1n}^{(k)} \\ a_{21}^{(k)} & 0 & \dots & a_{2n}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}^{(k)} & a_{n2}^{(k)} & \dots & 0 \end{bmatrix} \tag{1}$$

* In this formula (n) represents the number of elements, and i, j =1, 2, ... n

Later, the primary experts' direct matrix helps to develop the direct-relation matrix as given in Eq. (2):

$$H = \frac{1}{P}\sum_{k=1}^{P}\left[a_{aj}^{(k)}\right]_{n\times n} = \left[h_{ij}\right]_{n\times n} \tag{2}$$

Step 2, Calculating a normalized initial direct relation matrix: For dependencies of each factor (refers to H in Eq. (3)) and the normalized direct-relation matrix (refers to N in Eq. (4)) the following expressions are applied:

$$N = \lambda * H \tag{3}$$

$$\lambda = \frac{1}{max_{1\le i\le n}\sum_{j=1}^{n} h_{ij}}, i,j = 1,2,\dots,n \tag{4}$$

Step 3, Total-relation matrix: Following previous steps, the total relation matrix (*T*), can be achieved using Eq. (5) as follows:

$$T = N(1 - N)^{-1} \quad (5)$$

Step 4, Setting a threshold value: To segregate minor effects explained in the total relation matrix (*T*) and to attain a suitable cause-effect diagram it is necessary to set a threshold value. This value is shown with (*Z*) in Eq. (6). If the factors with (*T*) value are more than the (*Z*) value, it can be indicated in the cause-effect diagram.

$$T^Z = \left[t_{ij}\right]_{n\times n}, i, j = 1,2, \ldots, n, t_{ij} \geq z \quad (6)$$

Step 5, Illustrating the cause-effect diagram: The following Eq. (7) and Eq. (8) are used to calculate the sum of rows and columns to indicate vector *R* and vector *C*.

$$R = [r_i]_{n\times 1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1}, \quad (7)$$

$$C = [c_i]_{1n} = \left[\sum_{i=1}^{n} t_{ij}\right]_{n1}, \quad (8)$$

Impact Relation Map (IRM) as the cause-effect diagram was later obtained by drawing the dataset of the (D+C) and (D-C). In other words, the horizontal axis (D+C) called" Dependency", showing how important each element is, whereas the vertical axis (D-C), called "Influence" divides elements into two (2) different groups respectively known as cause and effect. This separates the elements based on their influences on other elements.

Step 6, Acquiring the dependency matrix: As the final step, the sum of each column must be equal to 1.0 based on the normalization technique to be accepted, and accordingly, the dependency matrix can be acquired [8-11].

3. Results and Discussion

3.1. Initial model

The eight (8) main factors, as mentioned earlier, shaped the clusters of the model where the network depends on the main criterion. Therefore, for every single criterion, the network of influence is different, and the super-matrix of limiting influence needs to be calculated for each main control criterion in the model. Later, each super-matrix needs to be weighted based on the priority of its control criterion, and subsequently, the output is synthesised from the calculation of all the control criteria [12]. Figure 3 shows the Conceptual Analytical Model (CAM), which can potentially be used in ANP analysis.

Building influence factors in the construction industry can be determined with the support of the Super Decisions software. The first row of Level 1 (green background) of the CAM shows the ultimate goal to be achieved, which is the evaluation of the Open Building implementation. Then this goal was separated into the eight (8) main factors (clusters) in Level 2 (red background) and connected to their associated sub-factors in Level 3 (null background). The interactions amongst the clusters were investigated in a loop shown in Level 2.

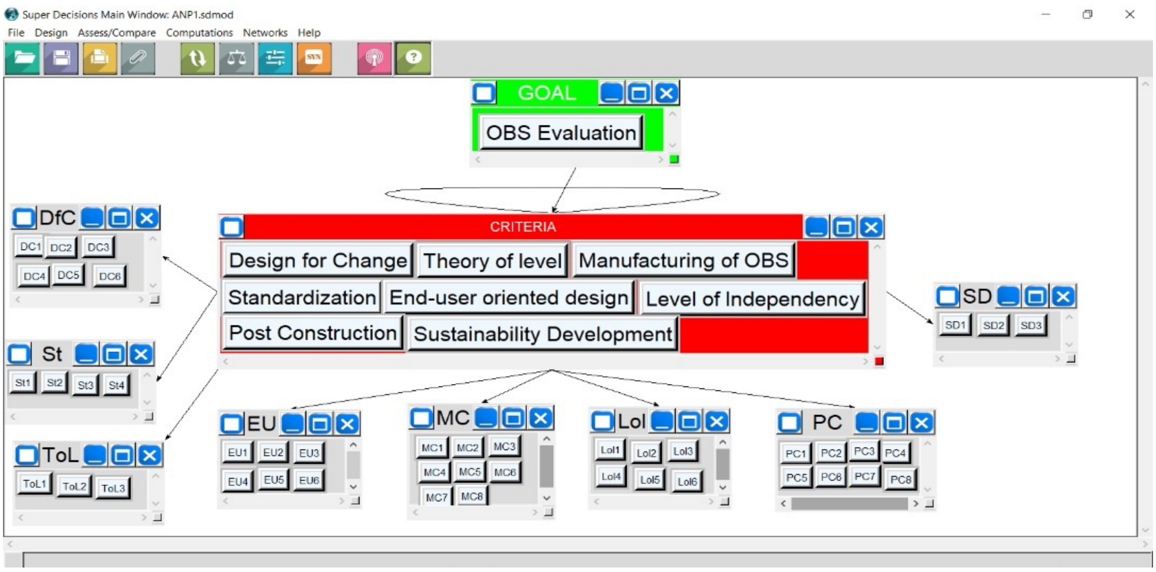

Figure 3. ANP decision model for the Open Building Systems evaluation in Super Decision Software.

3.2. Interaction among factors by DEMATEL

After recognising the Open Building's main factors, the DEMATEL questionnaire, which includes the pairwise comparison matrix, was developed. The survey was carried out in 2 phases. Phase 1 covered the demographic information such as organisational characteristics, sectors, and others. Meanwhile, Phase 2 covered the DEMATEL questions as the concern of this research. The number of questions that the questionnaire contains is, where *N* is the number of the main factors, which is 8 for this study. Therefore, the matrix included was 8cells and considered for the pairwise comparisons. The question for the pairwise comparison followed the following structure: "What is the impact of 'X principle' on each of the following?" A higher score for each factor shows more influence than the other factor. In this survey, experts indicated the direct influence by selecting 1 of these indicators: (0 equals to no influence), (1 equals to low influence), (2 equals to moderate influence), (3 equals to significant influence), and (4 equals very high influence) [13].

Table 1. Cronbach's alpha reliability test for DEMATEL questionnaire.

Open Building Factors	Cronbach's Alpha Rate
Design for Change (DFC)	0.807
Standardization (ST)	0.817
Level of decision-making 'Theory of level' (TOL)	0.812
End-user oriented design (EU)	0.859
Manufacturing of OBS components (MC)	0.819
Level of Independency of Building Systems/subsystems (LOI)	0.927
Enhanced Post Construction Maintenance (PC)	0.887
OBS factors influencing sustainability development (SD)	0.789

Prior to the launch of the main DEMATEL questionnaire, a preliminary questionnaire was distributed as a pilot survey to assess the validity of the questionnaire and to ensure its performance [14]. This pilot study was done among the 8 experts, which included 5 professionals in OBS-related fields and 3 academic professionals in the construction management field. Therefore, experts provide their ideas on the structure of the questionnaire, the semantic transparency of definitions, and the questions. Then, the questionnaires were revised and designed based on this feedback, where their views were incorporated into the preparation of the questionnaire. Table 1 presents the correlation rate of the answers using SPSS software. The rate was higher than 0.7 for the DEMATEL techniques, indicating the reliability of the results. This reliability test was employed in a similar manner by previous research [15-17].

The questionnaire was distributed among academic professionals in the construction management field and professionals of the construction industry of Malaysia in the OBS fields. The questionnaire enclosed a cover letter to explain the terms and statements used in the survey as well as the purpose of the study to collect more uniform and accurate results. A total number of 30 sets of questionnaires were distributed as a brief explanation to what was required from the experts. As illustrated in Table 2, 27 sets of questionnaires were answered and returned, showing a participation respondent rate of almost 90%. From those 27 sets, 6 sets were rejected due to being illegible with having unclear multiple and blank answers. Therefore, only 21 sets were verified as valid returns from the respondents, giving a rate of almost 70% engagement. The relatively medium sample size of distribution in the survey is considered acceptable due to the general insufficient number of experts in the field of the Open Building concept. Therefore, the quality of the respondents was considered more important than the quantity.

Table 2. Questionnaires distributions and return rates for the DEMATEL Survey

Description	Quantity	Percentage (%)
Number of Sets Distributed	30	100
Returned Sets and Approved	21	70
Returned Sets and Disapproved	6	23
Unreturned Sets	3	7

3.2.1. DEMATEL survey

The initial direct relation matrix or average matrix was generated as the first step of the survey progress. From the collected data, the direct relation matrix was developed and analyzed with the help of Microsoft Excel. The results are presented in Table 3.

Table 3. DEMATEL questionnaire initial direct matrix

	DFC	ST	TOL	EU	MC	LOI	PC	SD	SUM
DFC	1.00	4.20	3.10	3.20	4.55	3.89	2.98	1.98	24.90
ST	2.99	1.00	2.10	0.00	1.99	1.10	2.10	0.00	11.28
TOL	1.98	1.05	1.00	1.00	2.00	0.96	0.05	2.08	10.12
EU	0.98	0.00	2.05	1.00	2.00	2.97	1.97	0.99	11.96
MC	2.89	1.00	1.10	2.88	1.00	2.00	1.00	1.98	13.85
LOI	2.98	2.05	2.10	2.07	2.95	1.00	1.99	1.00	16.14
PC	1.88	2.10	0.00	1.00	1.96	3.05	1.00	2.00	12.99
SD	1.10	0.00	0.99	1.97	1.00	2.00	4.05	1.00	12.11
Sum	15.800	11.400	12.440	13.120	17.450	16.970	15.140	11.030	0.0402

Notes: DFC = Design for Change, ST = Standardization, TOL = Theory of Levels, EU = End User, MC = Modular Coordination, LOI = Level of Independency, PC = Post Construction, SD = Sustainability Development

In the second step, the normalized initial direct relation matrix also known as matrix *N* was estimated and analyzed with the related expression explained in Section 2.. Table 4 shows the normalized initial direct relation matrix for dependencies of each Open Building main cluster.

Table 4. Normalized initial direct relation Matrix for dependencies of each factor.

	DFC	ST	TOL	EU	MC	LOI	PC	SD	RAW	NORMAL
DFC	1.00	0.17	0.12	0.13	0.18	0.16	0.12	0.08	0.96	0.226863
ST	0.12	1.00	0.08	0.00	0.08	0.04	0.08	0.00	0.41	0.097579
TOL	0.08	0.04	1.00	0.04	0.08	0.04	0.00	0.08	0.37	0.086569
EU	0.04	0.00	0.08	1.00	0.08	0.12	0.08	0.04	0.44	0.104034
MC	0.12	0.04	0.04	0.12	1.00	0.08	0.04	0.08	0.52	0.121974
LOI	0.12	0.08	0.08	0.08	0.12	1.00	0.08	0.04	0.61	0.143711
PC	0.08	0.08	0.00	0.04	0.08	0.12	1.00	0.08	0.48	0.113811
SD	0.04	0.00	0.04	0.08	0.04	0.08	0.16	1.00	0.45	0.105458
				TOTAL					4.23	1

Notes: DFC = Design for Change, ST = Standardization, TOL = Theory of Levels, EU = End User, MC = Modular Coordination, LOI = Level of Independency, PC = Post Construction, SD = Sustainability Development

In the third step of the survey, as part of a DEMATEL task the total-relation matrix was developed and analyzed with the help of Microsoft Excel. Table 5 shows the total relation matrix for each cluster accordingly.

Table 5. Total relation matrix.

	DFC	ST	TOL	EU	MC	LOI	PC	SD
DFC	2.978	-4.949	2.505	2.991	-1.262	-1.729	-4.919	0.051
ST	37.439	75.341	60.936	-56.815	12.952	-80.291	-44.991	-3.476
TOL	-0.573	2.282	7.432	-9.178	-4.946	-5.233	4.894	7.404
EU	-47.736	-87.616	-62.515	76.755	-17.964	90.760	46.685	3.832
MC	-36.700	-70.607	-54.813	57.175	-4.808	69.928	34.833	3.308
LOI	-16.758	-34.114	-16.749	25.366	-5.920	36.531	9.048	1.399
PC	39.888	77.685	49.716	-62.548	14.401	-77.705	-35.638	-11.343
SD	43.280	90.570	44.179	-76.248	10.309	-83.688	-31.863	-3.690

Notes: DFC = Design for Change, ST = Standardization, TOL = Theory of Levels, EU = End User, MC = Modular Coordination, LOI = Level of Independency, PC = Post Construction, SD = Sustainability Development

The fourth step of the survey analysis was done by isolating the minor effects shown in the total relation matrix, to achieve a proper cause-effect diagram. Therefore, the average matrix *T* had to be assessed to calculate the threshold value of the relations. The threshold rate in this study was considered as 0.12 and the relations with the higher rates are given in Table 6.

Table 6. Total relation matrix after isolating the minor effects.

	DFC	ST	TOL	EU	MC	LOI	PC	SD
DFC	0.00	0.17	0.12	0.13	0.18	0.16	0.12	0.08
ST	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOL	0.13	0.00	0.00	0.00	0.12	0.00	0.00	0.00
EU	0.00	0.00	0.00	0.00	0.12	0.12	0.00	0.00
MC	0.12	0.00	0.00	0.12	0.00	0.12	0.00	0.00
LOI	0.12	0.00	0.12	0.00	0.12	0.00	0.00	0.00
PC	0.00	0.12	0.00	0.00	0.00	0.12	0.00	0.12
SD	0.00	0.00	0.00	0.12	0.00	0.00	0.16	0.00

Notes: DfC = Design for Change, St = Standardization, ToL = Theory of Levels, EU = End User, MC = Modular Coordination, LoI = Level of Independency, PC = Post Construction, SD = Sustainability Development

The fifth step in the analysis was to develop the cause-effect diagram based on the outcomes from Table 7. The vectors C and D were analysed from the sum in the columns and in the rows of the matrix *T*, respectively. Subsequently, (D+C) and (D-C) were achieved. The summation of (D+C) indicates the influence of a factor in sending and receiving. In contrast, the subtraction of (D-C) indicates the net impact of a factor on the system.

Table 7. Results of the summation (D+C) and subtraction (D-C) (Influence).

	DfC	St	ToL	EU	MC	LoI	PC	SD	D
DfC	1.978	-4.949	2.505	2.991	-1.262	-1.729	-4.919	0.051	-5.3356
St	37.439	74.341	60.936	-56.815	12.952	-80.291	-44.991	-3.476	0.0944
ToL	-0.573	2.282	6.432	-9.178	-4.946	-5.233	4.894	7.404	1.0816
EU	-47.736	-87.616	-62.515	75.755	-17.964	90.760	46.685	3.832	1.2003
MC	-36.700	-70.607	-54.813	57.175	-5.808	69.928	34.833	3.308	-2.6843
LoI	-16.758	-34.114	-16.749	25.366	-5.920	35.531	9.048	1.399	-2.1958
PC	39.888	77.685	49.716	-62.548	14.401	-77.705	-36.638	-11.34	-6.5433
SD	43.280	90.570	44.179	-76.248	10.309	-83.688	-31.863	-4.690	-8.1496
C	20.8179	47.5921	29.6914	-43.50	1.761	-52.4275	-22.9504	-3.515	

Notes: DfC = Design for Change, St = Standardization, ToL = Theory of Levels, EU = End User, MC = Modular Coordination, LoI = Level of Independency, PC = Post Construction, SD = Sustainability Development, D = Dependency (Effect rate on other factors), C = Cause (Effect rate from other factors)

The sixth or final step, calculates the total amount of each column, which is equal to 1.0 by the normalisation technique, and therefore the dependency matrix can be developed as explained in the sequence of tables and figures. Figure 4 depicts the cause-effect diagram for the Open Building main factors' dependency.

3.2.2. Results and discussion for the DEMATEL survey

Table 7 shows the results of the summation of (D+C) and subtraction of (D-C) to determine the Open Building main cause factors (highest D-C) and main effect factors (lowest D-C). In other words, the summation of (D+C) determined the influence strength of both "dispatch and receiving". In addition, the highest summation of (D+C) represents the central factor, or in other words, the factor that has the most relationship with the other factors. From the results, the Level of Independence (LoI) was identified as the central factor and considered as one of the most important factors. Considering the significance of factors, as presented in Table 8, the importance is identified in a descending sequence as LOI > ST > EU > TOL > PC > DFC > SD > MC.

Table 8. Dependency matrix for OBS factors.

	Effect Rate on Other factors D	Effect Rate from Other factors C	Total Effect Rate (D+C)	Net Effect on System (D-C)
DFC	-5.33559	20.8179	15.4823	-26.1534
ST	0.094393	47.5921	47.6864	-47.4977
TOL	1.081634	29.6914	30.7730	-28.6098
EU	1.200273	-43.5014	-42.3011	44.7017
MC	-2.68429	1.7612	-0.9231	-4.4455
LOI	-2.19578	-52.4275	-54.6233	50.2317
PC	-6.5433	-22.9504	-29.4937	16.4071
SD	-8.14963	-3.5155	-11.6651	-4.6341

As shown in Figure 4, the cause-effect relationship diagram was acquired by mapping the (D+C) and (D-C). As illustrated, the factors are visually divided into two (2) groups, either the (D-C) is positive or negative. Therefore, the cause group with a positive (D-C) includes DfC, St, and ToL, and the other factors of EU, MC, PC, SD, and LoI are in the effect group since the (D-C) is negative. Referring to Table 8 and Figure 4, each OBS factor's impact can be analysed and discussed on the whole system. Hence, the critical OBS performance factors can be detected.

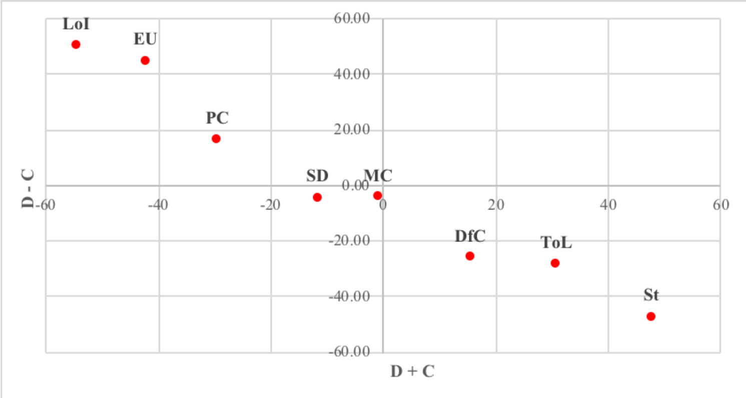

Figure 4. The cause-effect diagram for dependency of OBS factors.

3.2.3. Cause factors analysis

Since these cause-factors have a net impact on the whole system, their performance can greatly influence the overall goal. Therefore, this research not only identifies and evaluates the relationship between OBS factors but also tries to explicitly analyse each factor in the cause group to select those that are more likely to be significant. Among all the factors in the cause group, "Level of Independency (LOI)" had the highest subtraction of (D-C). This means that it had more impact on the whole system than it received from the other factors. Furthermore, Table 7 indicates that the degree of influential impact (D) of LOI is 50.23, which ranks first among all the causal factors. This indicates that the LoI had a remarkable impact on the other factors, and improvement of this factor could result in improvement of the whole system. To summarize, LoI is a critical factor that deserves much more attention among all the factors in this study to enhance the Open Building concept. The factor having the second highest subtraction of (D-C) is "Standardization (ST)". Other factors are ranked in a decreasing trend as follows: EU > TOL > DFC > PC > SD > MC.

3.2.4. Effect factors analysis

Generally, factors in the effect group tend to be easily impacted by others, which makes effect factors unsuitable to be considered as critical factors. Nevertheless, it is still necessary to discuss the effects of factors to determine the features of each factor. Therefore, 1 out of the 11 is recognised as a critical factor after further analysis of effective factors. Among all 8 factors, "Level of Independency (LOI)" has the highest summation of (D+C) at -54.62. This shows that it is a central factor and one of the most significant factors. However, in Figure 4, the subtraction of the (D-C) score of LoI is 50.23, a value greater than zero, announcing LoI as a net effect factor. To further illustrate this phenomenon, its degree of influenced impact, C is -52.42, which is also the highest rate among the other factors. This suggests that although LOI is a net receiver, it plays a vital role in fulfilling the OBS concept. Similar calculations in Figure 4 can show the level of importance of the other factors.

3.2.5. Dispatch and receive arrows

The total numbers of dispatch and receive arrows for each OBS factor are demonstrated in Table 9. The "Theory of Levels (TOL)" was dispatched to 4 factors and received from 5 factors (9 relationships as total), which indicated its significance to reach the goal. Meanwhile, the

"Design for Change (DFC)" with a total relationship of 6 (3+3) was ranked the least. Other factors scored an average of 7 or 8 in total.

Table 9. The dispatch and receive arrows for OBS Factors

OBS Factors		Factors Dispatching to	Total	Receiving from	Total
Design for Change	(DFC)	PC, LOI M, EU	3	ST, PC, SD	3
Standardization	(ST)	DC, ST, DFC, MC	4	ST, DFC, PC, SD	4
Theory of Levels	(TOL)	ST, DFC, PC, SD	4	DFC, ST, DFC, PC, SD	5
End-user oriented design	(EU)	EU, LOI,PC,SD	4	DFC, EU, Mn, LoI	4
Manufacturing of OBS Components	(MC)	EU, LoI,PC,SD	4	ST, PC, SD	3
Level of independency	(LOI)	EU, LOI,PC,SD	4	EU, MC, LOI	3
Post Construction maintenance	(PC)	PC, ST, DFC, MC	4	DFC, EU, MC, LOI	4
Sustainability Development	(SD)	PC, ST, DFC, MC	4	DFC, EU, MC, LOI	4

4. Conclusions

The objective of the study dealt with determining the interaction between open building factors. In order to investigate the interaction between the factors and measure the experts' points of view, the DEMATEL method was used in this study. Initially, the DEMATEL questionnaire was designed for the OBS factors, which were identified from earlier studies. The results indicate that one of the most significant and main factors found was the "Level of Independence (LOI)." It is also noteworthy to mention that the main cause factor identified was "Standardization (ST)," which had a major role in construction OBS performance's success. This study developed a DEMATEL model to evaluate the application of the open building concept in construction projects. Subsequently, the weights of the identified factors were assessed through procedures and calculations according to DEMATEL techniques. Other investigators are encouraged to utilise other MCDM tools to determine the weights of variables and compare their findings with this study.

Conflict of interest

The authors declare no conflict of interest.

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