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ORIGINAL CONTRIBUTION

Evaluation of Key Performance Indicators of Integrated Project Delivery and BIM Model for Infrastructure Transportation Project in Ahmedabad, India through Decision-Making Approach

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Abstract Building Information Modeling (BIM) and Integrated Project Delivery (IPD) are widely adopted by the Architecture Engineering and Construction industry because of its distinguished benefits to the complex infrastructure projects throughout the project life cycle. This paper aims at evaluating Key Performance Indicators (KPI) of Integrated Project Delivery and Building Information Modeling for an infrastructure project like a metro-rail construction project in Ahmedabad, a city in western India, through decision-making tools like Factor Comparison Method (FCM) and fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL). After an extensive literature review and experts' opinions, a list of 24 Key Performance Indicators were generated. FCM and fuzzy DEMATEL were applied for prioritizing and evaluating the identified KPIs and disclosing their interrelationships based on influential weight. The findings revealed that 16 most critical key performance indicators are vital for BIM and IPD adoption in highly complex infrastructure projects with visualizing their interrelationship by causal diagram showing cause-and-effects groups. The results showed the four most influential and critical KPIs as accessibility and accuracy of information by BIM, facilitating access to real-time data, interoperability and compatibility of data, minimizing claims and disputes which should be given more consideration for enhanced performance and successful completion of the complex infrastructure projects in the future.

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Introduction

Building Information Modeling (BIM) is an evolving tool that is utilized for creating and handling digital visual representative information of the projects along with its entire project life cycle. A huge investment budget amount of 1 trillion USD has been set by the Indian government for the development of infrastructure of the country, even with such huge investments in developing infrastructure, the time and cost overruns are fueled by frequent design changes and poor planning strategies [1]. There has been a significant loss of profits in the projects due to increasing rework as stated by Manzione et al. [2]. The authors have also proposed a prototype method that focuses to define Key Performance Indicators (KPI) to evaluate the efficiency of the process. A study by Luth et al. [3] shows the benefits of High Definition Building Information Modeling (HiDef BIM) optimizing project time and cost, it also directly generates detailed shop drawings from the model required in the execution and construction phase of the project. Tatsiana and Saad [4] has identified KPI which enables to control of the design process of the project based on its main design sub-processes. Joy [5] developed KPI to support transparency and sustainability in the project with the respective project stakeholders. Tansania and Saad [4] recognized KPIs offering control on the process in the planning and designing phase of the project. Asmar et al.

[6] evaluated Integrated Project Delivery (IPD) performance for its adoption among other delivery systems. Azhar et al. [7] investigated factors affecting the IPD implementation on infrastructure projects. Chang et al. [8] studied the impact of BIM implementation on IPD acceptability for public projects.

IPD and BIM are developments of present day project management. IPD is a process for reducing the complexity of mega-infrastructure projects by increasing the coordination, collaboration and minimizing litigations and disputes. BIM is a very effective tool to implement IPD. Since the inception of BIM and IPD, both are used as a tool and process, respectively, to enhance coordination, project performance, productivity and profits [9, 10]. Misevaluation of KPI factors may turn into a wrong consideration of the factors affecting the project profits and timeline [11]. Hence, the accurate assessment of BIM and IPD KPIs is essential for the success of a project because it minimizes the costs, time and risks associated with the infrastructure project [12]. It has also been observed that the KPIs of IPD and BIM have a non-statistical behavior and thereby the most effective way of evaluating them is through fuzzy set approach.

The primary objective of this study is to identify the KPIs related to IPD and BIM performance for large-scale complex construction projects. Furthermore, the identified KPIs have been evaluated, analyzed and prioritized with the application of the FCM and Fuzzy DEMATEL approach to obtain Most Critical Key Performance Indicators (MCKPIs) of BIM and IPD to improve the project performance and successful completion rate of the complex infrastructure projects.

Literature Review

Joy [5] identified the KPIs for improvement in the performance of project management for infrastructure projects. Fernández-Sánchez and Rodríguez-López [13] developed a methodology to identify construction management-based KPIs for infrastructure projects. There are also many critical hindrances to Building Information Modeling (BIM) implementation which needs to be reduced Liao et al.[14]. Ilozor and Belly [15] stated that further research is required for a better understanding of the relationship between BIM and IPD implementation and its performance measures of the project. IPD and BIM adoption has shown productivity benefits in large-scale construction projects Kraatz et al.[16]. Abdirad and Pishdad-Bozorgi [17] developed an assessment framework of metrics for collaboration of IPD. Ma et al. [18] determined that project leadership and software functionality are the two most important factors for BIM implementation. Various decision-making tools have been studied and applied by several researchers. Sarkar and Dutta [19] applied the Expected Value Method (EVM) decision-making tool for risk analysis of metro-rail projects. Sarkar and Singh [20] applied another decision-making tool like the Fuzzy Analytical Hierarchy Process (FAHP) for the development of risk index for metro-rail projects. Furthermore, Sarkar and Singh [21] applied another decision-making tool like Fuzzy Failure Mode and Effect Analysis (FFMEA) for risk analysis of the metro-rail projects. A comparative study of the available decision-making tools like Fuzzy Expected Value Method (FEVM), FAHP and FFMEA has been carried out by Singh et al. [22]. Ranganath et al. [23] worked with the decision-making methods for developing a fuzzy TOPSIS method for analyzing and evaluating the risk of the different phases of the solar power plant projects in India. The methodology developed by the authors can compare the severity of the identified risks of the activities of each phase of the project through Fuzzy Positive Ideal Solution (FPIS), Fuzzy Negative Ideal Solution (FNIS) and Closeness Coefficient (CC). Qarnain et al. [24] explored the application of Interpretive Structural Modeling (ISM) for analyzing the energy conservation factors in Indian scenario. Furthermore, Arukala et al. [25] evaluated the sustainable performance parameters for built environment through Analytical Hierarchy Process (AHP). Their proposed framework would enable the policy makers to develop sustainable mitigation strategies.

Many researchers have applied the fuzzy DEMATEL approach on risk evaluation [26], assessment of critical risk factors for BIM projects while mentioning that all risk factors might not be covered due to the complex nature of construction industry and it is not generalized as the study is restricted to one country. Decision making for developing supplier selection criteria was carried out by Chang et al. [27] and also suggested to apply the same approach to explore the green supply chain as the future scope of the study. Determination of technological risk influences was carried out by Durán et al. [28], and vulnerability assessment and resilience were carried out by Hiete et al. [29]. Rating and evaluation of green building system were done by Liu et al. [30] who also pointed out that the limitation of the study is being restricted to Taiwan only as the data set used was collected from the small region of Taiwan. Khan et al. [31] carried out condition assessment for bridge projects through visual fuzzy-based inspection approach. In their study, they reviewed the existing literature and their techniques available in this area and tried to list out the advantages and disadvantages of each method.

The analysis of potential occupational risks on site of construction projects was carried out by Seker and Zavadskas [32]. Risk assessment of road projects carried out by Patel et al. [33] and sustainable building material selection by Bapat et al. [34] were done using Fuzzy Factor Comparison Method (F-FCM) approach. Their study tried to recommend alternative materials which would be green and sustainable in nature for the flooring, roofing, internal wall finish and external cladding for an infrastructure facility like metro-rail station box of Ahmedabad, India. Qin et al., [35] worked on the Critical Success Factors (CSFs) for BIM adoption. The limitation of their study was that it was restricted to a small region which cannot be further generalized. Paradigm shift has been observed in the AEC industry to move from conventional 2D paper-based data exchange and contract toward new digital technology like BIM and IPD (Patel and Patel [36]). However, the decision-making process for the BIM and IPD adoption is time consuming, complex and abstruse process due to the multiple various factors involved in it [37]. Therefore, it becomes a puzzle for infant BIM user organizations and project stakeholders due to the association of many KPIs as it requires significant efforts, a great experience and special knowledge to identify, analyze and prioritize them. However, there have been no research attempts made to study and identify the KPIs and their interrelationship (cause and effect) for BIM and IPD adoption together.

Reviewing the available literature, it has been observed that adequate work has been carried out on decision making but no proper literature was found for any work in the area of application of Multi-Criteria Decision-Making (MCDM) tools like FCM and fuzzy DEMATEL particularly for infrastructure projects. Furthermore, the application of decision-making tools for the evaluation of performance indicators of IPD and BIM is in a nascent stage. Thereby the present research aims at developing a knowledge-based MCDM framework by the application of FCM and fuzzy DEMATEL for evaluation of the Key Performance Indicators (KPI) for the IPD and BIM model for an infrastructure project like the construction of metro-rail in Ahmedabad, India. The justification of using FCM is that it is a tool which quite precisely helps in prioritizing the different factors with the help of scores and rankings through paired comparison method. The justification of using fuzzy DEMATEL is that it helps in establishing the relationships of the different identified factors through the cause-and-effect diagram. The causes and effects can be identified through distance-based relationships and equations. The relationship between the factors would help the project authorities to understand the system complexity and they should develop corrective and preventive mitigation measures accordingly.

Methodology

Figure 1 depicts the outline of the methodology of the research study carried out. Most relevant Key Performance Indicators have been identified along the entire project life cycle through substantial literature study and opinions of expert professionals working with similar fields. The identified KPIs which may also be considered as the causal factors creating effects in the project were further evaluated through a Multi-Criteria Decision-Making (MCDM) tool like fuzzy DEMATEL. The outline of the research methodology is presented in Fig. 1.

The list of the identified KPIs based on the IPD process and BIM tool is presented in Table 1.

Questionnaire survey is an effective way to acquire all project stakeholders' inputs. The responses obtained from the respondents need to be analyzed efficiently [33]. For the present study, totally 90 experts were approached for their response, personally as well as virtually to obtain importance level against each of the KPIs of IPD and BIM adoption in reference to a five-point Likert scale. It has been observed that 74 out of 90 experts responded to this study, depicting an 82% response rate. Table 2 represents the experts' details of the respondents of the questionnaire survey. Respondents were selected from the top and mid-level officials from government, BIM consultancies, design consultancies, contractors and project management consultancies.

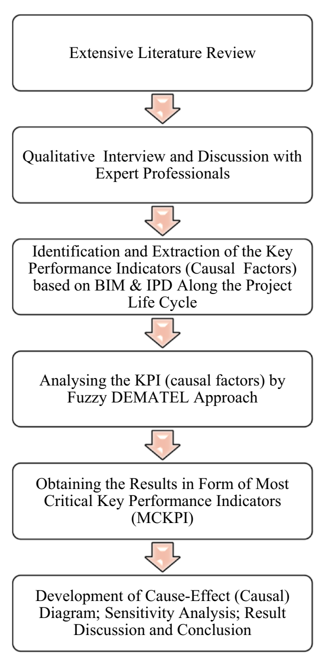

Fig. 1 Outline of the research methodology

Table 1 List of key performance indicators (KPI) (causal factors) for BIM and IPD adoption

Sr. no.	Description of KPI	Reference	Code
Conceptualization and initiation phase			
1	Initial cost of BIM adoption	Manzione et al. [2]	A
2	Awareness and benefits of IPD and BIM for infrastructure project	Manzione et al. [2]	B
3	Project stakeholder's early involvement in IPD and BIM adopted projects	Ma, G. et al. [18]	C
4	Imparting BIM training to the employees	Ma, G. et al. [18]	D
5	Mandatory implementation of BIM and IPD by government authorities	Ma, G. et al. [18]	E
6	Enhancing collaborative decisions by adoption of IPD and BIM	Chang et al. [27]	F
Planning and designing phase			
7	Accessibility and accuracy of information by BIM	Manzione et al. [2]	G
8	Effect on overall life cycle cost of project by use of IPD and BIM	Manzione et al. [2]	H
9	Improved design flexibility by utilizing IPD and BIM	Manzione et al. [2]	I
10	Better time and cost management by use of IPD and BIM	Manzione et al. [2]	J
11	Coordinated multi-disciplinary model for communication by adoption of IPD and BIM	Bapat and Sarkar [1]	K
12	Improvement in productivity through use of IPD and BIM	Sarkar et al. [38]	L
Execution and construction phase			
13	Resource optimization by collaboration of IPD and BIM	Sarkar et al. [38]	M
14	Better safety management by implementation of IPD and BIM	Sarkar et al. [38]	N
15	Efficient change management by adoption of IPD and BIM	Bapat and Sarkar [38, 42]	O
16	Progress monitoring efficiency for infrastructure project through IPD and BIM	Sarkar al [38]	P
17	Minimized amount of rework by integrating IPD and BIM	Sarkar et al. [38]	Q
18	Speed of construction and delivery after IPD and BIM adoption	Sarkar et al. [38]	R
Finishing and maintenance phase			
19	Quick and proactive decision making	Sarkar et al. [38]	S
20	Facilitating access to real-time data by IPD and BIM	Sarkar et al. [38]	T
21	Potential maintenance cost savings by using BIM as FM tool	Sarkar et al. [38]	U
22	Interoperability and compatibility of data by IPD and BIM	Sarkar et al. [38]	V
23	Minimizing claims and disputes through implementation of IPD and BIM	Sarkar et al. [38]	W
24	Client's satisfaction by implementing BIM and IPD	Sarkar et al. [38]	X

Table 2 Details of the experts responded for the questionnaire survey

Description	Category	Numbers
Type of company	Government organization	10
	BIM and design consultancy	34
	Contractors	12
	Project management consultancy	18
Designation/position level	Top-level	44
	Mid-level	28
Experience (years)	< 5 years	18
	5—10 years	32
	> 10 years	22

The sample size for the questionnaire survey was calculated using the below mentioned equation [20, 39, 40]

$$n = \frac{n'}{\left(1 + \frac{n'}{N}\right)}$$

$$n' = \frac{p*q}{v^2}$$

where n = sample size; n' = first estimate of sample size; N = the size of the population; p = the proportion of the characteristic being measured in the population, $q = 1 - p$; and v = the standard error of the sampling population. The values of p and q were taken as 0.5 to get the maximum sample size. The standard error was kept at 4% (maximum allowable value of the standard error is 10%). The total target respondents were 90. Thus, the size of the population is N = 100. By substituting these values in the equations.

$$n' = \frac{0.5*0.5}{0.04^2} = 156$$

Table 3 Factor comparison method (FCM) matrix for shortlisting the KPIs of IPD and BIM

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Score	Rank
A	B4	C4	A1	E4	F4	G4	H4	I4	J4	K4	L4	M4	N2	O4	P4	A2	R4	A1	T4	U1	V4	W4	X4	4	22
B		B4	B4	B3	B4	G3	H1	B1	B4	B4	B3	B4	B4	B4	B2	Q2	B3	B4	T4	B4	V4	W3	B4	59	7
C			C4	E3	F3	G4	H4	I4	C2	C3	L3	M2	C4	C0	P4	Q4	R4	C4	T4	C4	V4	W4	X1	25	15
D				E4	F4	G4	H4	I4	J4	K4	L4	M4	N2	O4	P4	Q4	R4	D2	T4	U2	D1	W4	X4	3	23
E					E2	G4	H3	I2	E4	E4	E2	E2	E4	E4	P1	Q3	E1	E4	T4	E4	V4	W4	E3	45	11
F						G4	H4	I3	F3	F4	L1	F1	F4	F3	P3	Q4	R2	Q4	T4	F4	V4	W4	F2	32	14
G							G2	G4	G4	G4	G4	G4	G4	G4	G3	G4	G4	G4	T2	G4	V2	G2	G4	78	2
H								H1	H4	H4	H4	H4	H4	H4	H3	Q3	H4	H4	T2	H4	V3	W2	H4	63	6
I									I4	I4	I3	I4	I4	I4	I1	Q3	I3	I4	T3	I4	V4	W3	I4	56	8
J										J1	L4	M3	J3	O1	P4	Q4	R4	J4	T4	J2	V4	W4	X2	18	18
K											L4	M3	K3	O2	P4	Q3	R4	K4	T4	K1	V4	W4	X3	17	19
L												L2	L4	L3	P3	Q4	R1	L4	T4	L4	V4	W4	L3	40	12
M													M4	M3	P4	Q3	R2	M4	T4	M4	V4	W4	M1	36	13
N														O3	P4	Q4	R4	N3	T4	U1	N2	W4	X4	6	21
O															P4	Q4	R4	O4	T4	O2	V4	W4	X2	20	17
P																Q2	P2	P4	T4	P4	V4	W3	P4	53	9
Q																	Q4	Q3	T3	Q4	V2	Q4	Q4	66	5
R																		R4	T4	R4	V4	W4	R4	51	10
S																			T4	U3	S2	W4	X4	2	24
T																			T	T4	V1	T2	T4	80	1
U																					V4	W4	X3	7	20
V																						V2	V4	70	4
W																							W4	74	3
X																								22	16

$$n = \frac{156}{\left(1 + \frac{156}{90}\right)} = 57.07 \text{ say } 58 \text{ nos}$$

Out of a target size of 90 respondents, 74 responses were received. The response rate was 82%, which is considered acceptable [20, 40]. The details of the experts who responded to the questionnaire survey are presented in Table 2.

Analysis and Results

Application of Factor Comparison Method (FCM) for Evaluation of KPI

The factor comparison method (FCM), a Multi-Criteria Decision-Making (MCDM) method, can be applied as a funnel process to prioritize the most important KPIs of IPD and BIM adoption for further analysis with fuzzy DEMATEL technique. The FCM matrix was developed using five-point scale ranging from 0 to 4. Score "0" represents "no importance," score "1" represents "low importance," score "2" represents "medium importance," score "3" represents "high importance," and score "4" represents "extreme importance," respectively. Each factor was compared with other factors with pairwise comparison to calculate their relative weights. From a list of 24 KPIs, 16 KPIs have been shortlisted based on the FCM score ranking as shown in Table 3.

According to Table 3, in the process of paired comparison, factor (*A*) which is "Initial cost of BIM adoption" has been compared with the factor (*B*) which is "Awareness and benefits of IPD and BIM for infrastructure project." It has been observed that factor (*B*) need to be given "extreme importance" over factor (*A*) through the judgmental decision and thereby the corresponding cell has obtained a score of B4 as the score for "extreme importance" is "4." Similarly when factor (*A*) is compared with factor (*C*) which is "Project stakeholder's early involvement in IPD and BIM adopted projects" it has been observed that factor (*C*) is of "extreme importance" over factor (A) thus the corresponding cell has obtained a score of C4. Similar computation is carried out for all the cells and finally the score of each factor is added row-wise. For factor (*A*), the total score is $A1 + A2 + A1$ (all in row 1) which gives a score of $1 + 2 + 1 = 4$. For score 4, factor (*A*) has obtained a rank of 22. Similar computations have been carried out for all the factors and thereby it has been observed that factor (*T*) which is "Facilitating access to real-time data by IPD and BIM" has obtained a maximum score of 80, thus obtaining rank 1. Similarly the factors which has obtained rank 2 to 16 are considered for further analysis by fuzzy DEMATEL.

Application of Fuzzy DEMATEL for Evaluation of KPI

Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) is also a Multi-Criteria Decision-Making (MCDM) method that can be used for evaluation of the criticality or significance level of the KPIs (causal factors) of IPD and BIM tool. The DEMATEL method is most commonly applied to determine and obtain a cause-and-effect diagram of the factors which have interdependencies with each other. This method is better than other conventional decision-making methods due to its ability to rank the criteria according to the type and relationships and interdependencies between the criteria considered for study [32]. In the present study, the DEMATEL method has been combined with fuzzy triangular membership functions to reduce the vagueness and increase the prediction accuracy of the decision-making method. In the process of decision making, fuzzy logic deals with the vagueness of ideas and language of humans [41]. DEMATEL is an extended-method used for analyzing and developing a structural model to analyze the influential relation among complex criteria. Nevertheless, decision-making process is tough in fuzzy settings to segment complex criteria. Out of multiple available methods for selection factors analysis like Grey theory, Analytical Hierarchy Process (AHP) and Analytical Network Process (ANP), Quality Function Deployment (QFD) and data mining, Grey-based decision making, etc., which requires large amount of confidential and complex data, Fuzzy DEMATEL method has exhibited a unique advantage with the capability of showing the relationship between the factors influencing the other factors in key performance indicators [27].

Steps for Fuzzy DEMATEL Analysis

Step 1

To find the model of the relations between the n KPIs, initially, an $n \times n$ matrix is generated. The influence of the factors/parameters in each row applied on the factors/parameters in each column of the matrix can be further represented by a fuzzy number.

$$z = \begin{bmatrix} 0 & \cdots & \tilde{z}_{n1} \\ \vdots & \ddots & \vdots \\ \tilde{z}_{1n} & \cdots & 0 \end{bmatrix} \quad (1)$$

Step 2

Setting up of direct relation matrix. This matrix is developed based on the fuzzy linguistic variables.

Step 3

Convert triangular fuzzy numbers into the preliminary direct relation matrix.

Step 4

The next step is normalization of fuzzy direct relation matrix. The normalized fuzzy direct relation matrix can be obtained using the following formula:

$$\tilde{x}_{ij} = \frac{\tilde{z}_{ij}}{r} = \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{u_{ij}}{r}\right) \quad (2)$$

where

$$r = \max_{i,j}\left\{\max_i \sum_{j=1}^{n} u_{ij}, \max_j \sum_{i=1}^{n} u_{ij}\right\} \quad i,j \in \{1,2,3,\ldots,n\}$$

Step 5

In this step, the fuzzy total relation matrix has been calculated by the following formula:

$$\tilde{T} = \lim_{k \to +\infty}\left(\tilde{x}^1 \oplus \tilde{x}^2 \oplus \cdots \oplus \tilde{x}^k\right) \quad (3)$$

Each element of the fuzzy total relation matrix is expressed as $\tilde{t}_{ij} = \left(l''_{ij}, m''_{ij}, u''_{ij}\right)$, it can be calculated as follows:

$$\left[l''_{ij}\right] = x_l \times (I - x_l)^{-1} \quad (4)$$

$$\left[m''_{ij}\right] = x_m \times (I - x_m)^{-1} \quad (5)$$

$$[u''_{ij}] = x_u \times (I - x_u)^{-1} \quad (6)$$

After developing the normalized matrix, the inverse is first calculated, and then it is subtracted from the matrix I, and finally the normalized matrix is multiplied by the resulting matrix.

Step 6

Setting up crisp total relation matrix.

The Converting Fuzzy Data into Crisp Scopes (CFCS) method proposed by (Opricovic and Tzeng [43]) has been used to obtain a crisp value of total relation matrix. The equations of CFCS method are as follows:

$$m^n_{ij} = \frac{\left(m^t_{ij} - \min l^t_{ij}\right)}{\Delta^{\max}_{\min}} \quad (7)$$

$$l^n_{ij} = \frac{\left(l^t_{ij} - \min l^t_{ij}\right)}{\Delta^{\max}_{\min}} \quad (8)$$

$$u^n_{ij} = \frac{\left(u^t_{ij} - \min l^t_{ij}\right)}{\Delta^{\max}_{\min}} \quad (9)$$

So that,

$$\Delta^{\max}_{\min} = \max u^t_{ij} - \min l^t_{ij} \quad (10)$$

The upper and lower bounds of normalized values can be computed from the following equations:

$$l^s_{ij} = m^n_{ij} \Big/ \left(1 + m^n_{ij} - l^n_{ij}\right) \quad (11)$$

$$u^s_{ij} = u^n_{ij} \Big/ \left(1 + u^n_{ij} - l^n_{ij}\right) \quad (12)$$

The output of the CFCS algorithm is crisp values. Total normalized crisp values can be calculated from the following equation:

$$x_{ij} = \frac{\left[l^s_{ij}\left(1 - l^s_{ij}\right) + u^s_{ij} \times u^s_{ij}\right]}{\left[1 - l^s_{ij} + u^s_{ij}\right]} \quad (13)$$

Step 7

Sum computation of rows and columns.

In this step, the sum of each row and each column of T (in step 4) has been computed. The sum of rows (R_i) and columns (C_j) can be calculated as follows:

$$R_i = \sum_{j=1}^{n} T_{ij} \quad (14)$$

$$C_j = \sum_{i=1}^{n} T_{ij} \quad (15)$$

Then, the values of $\underline{R}_i + C_j$ and $R_i - C_j$ can be calculated by R_i and C_j, where $R_i + C_j$ represent the degree of importance of factor j in the entire system and $R_i - C_j$ represent net effects that factor i contributes to the system.

Implementation of Fuzzy DEMETAL Approach

Step 1

Determine the KPIs (causal factors) using extensive literature review and personal experience of authors. 24 KPIs (causal factors) were identified and 16 KPIs (causal factors) were shortlisted based on the ranking obtained by FCM.

Step 2

The shortlisted/prioritized KPIs based on FCM ranking are listed separately with respect to their phase and code for further analysis by fuzzy DEMATEL. Table 4 represents

Table 4 List of shortlisted KPIs considered for analysis by fuzzy DEMATEL

Sr.No	Phase	KPI (causal factors)	Symbols
1	Conceptualization and initiation phase	Awareness and benefits of IPD and BIM for infrastructure project	KPI 1
2		Mandatory implementation of BIM and IPD by government authorities	KPI 2
3		Project stakeholder's early involvement in IPD and BIM adopted projects	KPI 3
4		Enhancing collaborative decisions by adoption of IPD and BIM	KPI 4
5	Planning and designing phase	Accessibility and accuracy of information by BIM	KPI 5
6		Improved Design flexibility by utilizing IPD and BIM	KPI 6
7		Effect on overall life cycle cost of project by use of IPD and BIM	KPI 7
8		Improvement in productivity through use of IPD and BIM	KPI 8
9	Execution and construction phase	Resource optimization by collaboration of IPD and BIM	KPI 9
10		Progress monitoring efficiency for infrastructure project through IPD and BIM	KPI 10
11		Minimized amount of rework by integrating IPD and BIM	KPI 11
12		Speed of construction and delivery after IPD and BIM adoption	KPI 12
13	Finishing and maintenance phase	Facilitating access to real-time data by IPD and BIM	KPI 13
14		Interoperability and compatibility of data by IPD and BIM	KPI 14
15		Minimizing claims and disputes through implementation of IPD and BIM	KPI 15
16		Client's satisfaction by implementing BIM and IPD	KPI 16

Table 5 Fuzzy-based linguistic scale values

Linguistic terms	Score	Triangle fuzzy numbers
No influence (NI)	1	0.0, 0.0, 0.25
Low influence (LI)	2	0.0, 0.25, 0.5
Moderate influence (MI)	3	0.25, 0.5, 0.75
High influence (HI)	4	0.5, 0.75, 1
Extreme influence (EI)	5	0.75, 1, 1

the short-listed KPIs for analysis through fuzzy DEMATEL.

Step 3

Five-point scale was utilized [27] to obtain ideal solutions, which included the following level-scale factor influence relationships like "No influence," "Low influence," "Moderate influence," "High influence," and "Extreme influence." The details of the triangular fuzzy-based linguistic scale values are presented in Table 5.

Step 4

Using linguistic variables pairwise comparison was made based on the intensity of the influence of KPI on each other. The initial direct relation matrix was obtained using the fuzzy scale as given in Table 6.

The linguistic values of the shortlisted KPIs are converted to their respective fuzzy values as presented in Table 7.

Step 5

Making use of the initial direct relation matrix, the normalized fuzzy direct relation matrix "R" was developed. The normalized fuzzy direct relation matrix is calculated using Eq. 7 and the same is presented in Table 8.

Step 6:

After having obtained the normalized direct relation fuzzy matrix, the total relation fuzzy matrix was derived using equation 8.The total relation fuzzy matrix is presented in Table 9.

Step 7

The Converting Fuzzy Data into Crisp Scores (CFCS) method is used to generate the crisp values of the total relation matrix according to the steps mentioned for the Fuzzy DEMATEL approach consisting of calculation of upper and lower bound of normalized values and CFCS algorithm to obtain crisp values of total relation matrix. The crisp total relation matrix is presented in Table 10.

The threshold value must be obtained to calculate the internal relations matrix. Accordingly, partial relations are neglected and the Network Relationship Map (NRM) is plotted. Only relations whose values in matrix *T* are greater than the threshold value are depicted in the NRM. To compute the threshold values for relations, it is sufficient to calculate the average values of the matrix *T*. After the threshold intensity is determined, all values in matrix

Table 6 Direct relation matrix

	KPI 1	KPI 2	KPI 3	KPI 4	KPI 5	KPI 6	KPI 7	KPI 8	KPI 9	KPI 10	KPI 11	KPI 12	KPI 13	KPI 14	KPI 15	KPI 16
KPI 1	–	2 (LI)	2 (LI)	4 (HI)	3 (MI)	3 (MI)	3 (MI)	4 (HI)	3 (MI)	4 (HI)	4 (HI)	3 (MI)	1 (NI)	3 (MI)	2 (LI)	2 (LI)
KPI 2	2 (LI)	–	5 (EI)	3 (MI)	3 (MI)	3 (MI)	3 (MI)	4 (HI)	4 (HI)	3 (MI)	5 (EI)	4 (HI)	2 (LI)	3 (MI)	3 (MI)	3 (MI)
KPI 3	4 (HI)	3 (MI)	–	5 (EI)	3 (MI)	3 (MI)	4 (HI)	3 (MI)	5 (EI)	4 (HI)	4 (HI)	5 (EI)	1 (NI)	2 (LI)	5 (EI)	4 (HI)
KPI 4	3 (MI)	3 (MI)	4 (HI)	–	4 (HI)	4 (HI)	4 (HI)	5 (EI)	4 (HI)	4 (HI)	5 (EI)	5 (EI)	2 (LI)	1 (NI)	4 (HI)	5 (EI)
KPI 5	3 (MI)	4 (HI)	4 (HI)	3 (MI)	–	5 (EI)	4 (HI)	3 (MI)	3 (MI)	5 (EI)	5 (EI)	3 (MI)	4 (HI)	4 (HI)	2 (LI)	4 (HI)
KPI 6	2 (LI)	2 (LI)	3 (MI)	4 (HI)	4 (HI)	–	4 (HI)	3 (MI)	1 (NI)	3 (MI)	4 (HI)	4 (HI)	2 (LI)	3 (MI)	2 (LI)	3 (MI)
KPI 7	2 (LI)	3 (MI)	3 (MI)	4 (HI)	3 (MI)	3 (MI)	–	4 (HI)	4 (HI)	3 (MI)	4 (HI)	3 (MI)	3 (MI)	1 (NI)	3 (MI)	5 (EI)
KPI 8	3 (MI)	4 (HI)	4 (HI)	5 (EI)	4 (HI)	3 (MI)	5 (EI)	–	5 (EI)	4 (HI)	5 (EI)	5 (EI)	2 (LI)	2 (LI)	3 (MI)	4 (HI)
KPI 9	4 (HI)	4 (HI)	4 (HI)	4 (HI)	3 (MI)	3 (MI)	5 (EI)	4 (HI)	–	3 (MI)	4 (HI)	4 (HI)	2 (LI)	1 (NI)	2 (LI)	4 (HI)
KPI 10	2 (LI)	3 (MI)	3 (MI)	3 (MI)	2 (LI)	2 (LI)	4 (HI)	4 (HI)	4 (HI)	–	4 (HI)	5 (EI)	5 (EI)	4 (HI)	4 (HI)	4 (HI)
KPI 11	4 (HI)	4 (HI)	4 (HI)	4 (HI)	5 (EI)	3 (MI)	5 (EI)	5 (EI)	4 (HI)	3 (MI)	–	5 (EI)	4 (HI)	3 (MI)	4 (HI)	4 (HI)
KPI 12	4 (HI)	4 (HI)	4 (HI)	4 (HI)	3 (MI)	3 (MI)	5 (EI)	5 (EI)	5 (EI)	4 (HI)	4 (HI)	–	3 (MI)	2 (LI)	3 (MI)	4 (HI)
KPI 13	3 (MI)	3 (MI)	3 (MI)	5 (EI)	4 (HI)	4 (HI)	4 (HI)	3 (MI)	3 (MI)	5 (EI)	5 (EI)	4 (HI)	–	4 (HI)	4 (HI)	3 (MI)
KPI 14	4 (HI)	3 (MI)	3 (MI)	4 (HI)	5 (EI)	5 (EI)	3 (MI)	4 (HI)	3 (MI)	5 (EI)	5 (EI)	3 (MI)	4 (HI)	–	2 (LI)	3 (MI)
KPI 15	4 (HI)	4 (HI)	5 (EI)	3 (MI)	4 (HI)	2 (LI)	3 (MI)	3 (MI)	3 (MI)	3 (MI)	4 (HI)	4 (HI)	2 (LI)	2 (LI)	–	4 (HI)
KPI 16	4 (HI)	4 (HI)	4 (HI)	3 (MI)	3 (MI)	2 (LI)	3 (MI)	3 (MI)	3 (MI)	4 (HI)	4 (HI)	4 (HI)	2 (LI)	3 (MI)	4 (HI)	–

T which are smaller than the threshold value are set to zero, that is, the causal relation mentioned above is not considered. In this study, the threshold value is equal to 0.142. All the values in matrix *T* which are smaller than 0.142 are set to zero, that is, the causal relation mentioned above is not considered.

Step 8:

Centre of Area (COA) defuzzification technique was used to defuzzify $R_i + C_j$ and R_i—C_j and Best Non-fuzzy Performance (BNP) values were obtained. In the COA method, the defuzzified factor of the KPIs (causal factors) is represented by the geometric center of area limited by the curve that represents its membership functions. Crisp values of R_i, C_j, $R_i + C_j$ and $R_i - C_j$ were computed which are presented in Table 11.

Generation of Causal Diagram for Evaluated KPIs

Figure 2 represents the model of significant relations termed as causal diagram. This model can be represented as a diagram in which the values of $(R_i + C_j)$ are placed on the *x*-axis and the values of $(R_i - C_j)$ on the y-axis. The position and interaction of each factor with a point in the coordinates $[(R_i + C_j), (R_i - C_j)]$ are determined by the coordinate system. The KPIs with the higher value of $(R_i - C_j)$ are classified under the cause group factors and the KPIs with lower value of $(R_i - C_j)$ are classified under the effects group factors.

Table 7 Conversion of linguistic values to fuzzy values

	KPI 1	KPI 2	KPI 3	KPI 4	KPI 5	KPI 6	KPI 7	KPI 8	KPI 9	KPI 10	KPI 11	KPI 12	KPI 13	KPI 14	KPI 15	KPI 16
KPI 1	(0.000, 0.000, 0.000)	(0.000, 0.250, 0.500)	(0.000, 0.250, 0.500)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.000, 0.000, 0.250)	(0.250, 0.500, 0.750)	(0.000, 0.250, 0.500)	(0.000, 0.250, 0.500)
KPI 2	(0.000, 0.250, 0.500)	(0.000, 0.000, 0.000)	(0.750, 1.000, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)
KPI 3	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.000, 0.000, 0.000)	(0.750, 1.000, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.750, 1.000, 1.000)	(0.000, 0.000, 0.250)	(0.000, 0.250, 0.500)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)
KPI 4	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.000, 0.000, 0.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)	(0.000, 0.250, 0.500)	(0.000, 0.000, 0.250)	(0.500, 0.750, 1.000)	(0.750, 1.000, 1.000)
KPI 5	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.000, 0.000, 0.000)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.250, 0.500)	(0.500, 0.750, 1.000)
KPI 6	(0.000, 0.250, 0.500)	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.000, 0.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.000, 0.000, 0.250)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)
KPI 7	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.000, 0.000, 0.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.000, 0.000, 0.250)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)
KPI 8	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.000, 0.000, 0.000)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)	(0.000, 0.250, 0.500)	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)
KPI 9	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.000, 0.000)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.250, 0.500)	(0.000, 0.000, 0.250)	(0.000, 0.250, 0.500)	(0.500, 0.7f50, 1.000)
KPI 10	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.000, 0.250, 0.500)	(0.000, 0.250, 0.500)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.000, 0.000)	(0.500, 0.750, 1.000)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)
KPI 11	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.750, 1.000, 1.000)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.000, 0.000, 0.000)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)
KPI 12	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.000, 0.000)	(0.250, 0.500, 0.750)	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)
KPI 13	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.000, 0.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)

Table 7 continued

	KPI1	KPI2	KPI3	KPI4	KPI5	KPI6	KPI7	KPI8	KPI9	KPI10	KPI11	KPI12	KPI13	KPI14	KPI15	KPI16
KPI 14	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.000, 0.000, 0.000)	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)
KPI 15	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.750, 1.000, 1.000)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.250, 0.500)	(0.000, 0.250, 0.500)	(0.000, 0.000, 0.000)	(0.500, 0.750, 1.000)
KPI 16	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.000, 0.250, 0.500)	(0.250, 0.500, 0.750)	(0.500, 0.750, 1.000)	(0.000, 0.000, 0.000)

According to the cause-effect diagram, "Interoperability and compatibility of data by IPD and BIM," "Facilitating access to real-time data by IPD and BIM," "Accessibility and accuracy of information by BIM" and "Minimizing claims and disputes through implementation of IPD and BIM" are identified as cause group factors, and "Awareness and benefits of IPD and BIM for infrastructure project," "Mandatory implementation of BIM and IPD by government authorities," "Project stakeholder's early involvement in IPD and BIM adopted projects," "Enhancing collaborative decisions by adoption of IPD and BIM," "Improved Design flexibility by utilizing IPD and BIM design flexibility," "Effect on overall life cycle cost of project by use of IPD and BIM," "Improvement in productivity through use of IPD and BIM", Resource optimization by collaboration of IPD and BIM," "Progress monitoring efficiency for infrastructure project through IPD and BIM," " Minimized amount of rework by integrating IPD and BIM," "Speed of construction and delivery after IPD and BIM adoption" and "Client's satisfaction by implementing IPD and BIM" are identified as effects group factors. As the cause group factors have an influence on the effects group factors, their degree of importance is more and should be given more consideration. Hence, any change or modification in the cause group factors can have a significant impact on the effects group factors as well. The most critical KPI revealed is interoperability and compatibility of data (KPI14) with the highest value of $(R_i - C_j)$ 0.89 and $(R_i + C_j)$ 3.911, which shows its prominent influence and moderate impact, respectively. Similarly, facilitating access to real-time data (KPI13) has received the second rank with the value of $(R_i - C_j)$ 0.88 and $(R_i + C_j)$ 4.048. Subsequently, the third position is obtained by the accessibility and accuracy of information by BIM (KPI5), having the value of $(R_i - C_j)$ 0.143 and $(R_i + C_j)$ 4.674. Furthermore, minimizing claims and disputes (KPI12) is found as the fourth important factor of BIM software selection, receiving the value $(R_i - C_j)$ 0.138 and $(R_i + C_j)$ 4.177, portraying sound influence and impact, respectively.

Conclusion

This research study presents a novel approach for analyzing the KPIs of IPD and BIM adoption for infrastructure project by using FCM and Fuzzy DEMATEL method. Since this concept is generic, the method and results obtained are applicable globally with minor modification in the input parameters based of the geography of the location. Total 24 KPIs were categorized into major four project life cycle phases (1) initiation, (2) design, (3) execution and (4) maintenance through extensive literature review

Table 8. Normalized fuzzy direct relation matrix

	KPI 1	KPI 2	KPI 3	KPI 4	KPI 5	KPI 6	KPI 7	KPI 8	KPI 9	KPI 10	KPI 11	KPI 12	KPI 13	KPI 14	KPI 15	KPI 16
KPI 1	(0.000, 0.000, 0.000)	(0.000, 0.017, 0.033)	(0.000, 0.017, 0.033)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.000, 0.000, 0.017)	(0.017, 0.033, 0.050)	(0.000, 0.017, 0.033)	(0.000, 0.017, 0.033)
KPI 2	(0.000, 0.017, 0.033)	(0.000, 0.000, 0.000)	(0.050, 0.067, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)
KPI 3	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.000, 0.000, 0.000)	(0.050, 0.067, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.050, 0.067, 0.067)	(0.000, 0.000, 0.017)	(0.000, 0.017, 0.033)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)
KPI 4	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.000, 0.000, 0.000)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.050, 0.067, 0.067)	(0.050, 0.067, 0.067)	(0.000, 0.017, 0.033)	(0.000, 0.000, 0.017)	(0.033, 0.050, 0.067)	(0.050, 0.067, 0.067)
KPI 5	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.000, 0.000, 0.000)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)	(0.050, 0.067, 0.067)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.017, 0.033)	(0.033, 0.050, 0.067)
KPI 6	(0.000, 0.017, 0.033)	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.000, 0.000)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.000, 0.000, 0.017)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)
KPI 7	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.000, 0.000, 0.000)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.000, 0.000, 0.017)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)
KPI 8	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)	(0.000, 0.000, 0.000)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.050, 0.067, 0.067)	(0.050, 0.067, 0.067)	(0.000, 0.017, 0.033)	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)
KPI 9	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.000, 0.000)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.017, 0.033)	(0.000, 0.000, 0.017)	(0.000, 0.017, 0.033)	(0.033, 0.050, 0.067)
KPI 10	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.000, 0.017, 0.033)	(0.000, 0.017, 0.033)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.000, 0.000)	(0.033, 0.050, 0.067)	(0.050, 0.067, 0.067)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)
KPI 11	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.050, 0.067, 0.067)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.000, 0.000, 0.000)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)
KPI12	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)	(0.050, 0.067, 0.067)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.000, 0.000)	(0.017, 0.033, 0.050)	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)
KPI13	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)	(0.050, 0.067, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.000, 0.000)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)

Table 8. continued

	KPI1	KPI2	KPI3	KPI4	KPI5	KPI6	KPI7	KPI8	KPI9	KPI10	KPI11	KPI12	KPI13	KPI14	KPI15	KPI16
KPI14	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.050, 0.067, 0.067)	(0.050, 0.067, 0.067)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.050, 0.067, 0.067)	(0.050, 0.067, 0.067)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.000, 0.000, 0.000)	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)
KPI15	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.050, 0.067, 0.067)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.017, 0.033)	(0.000, 0.017, 0.033)	(0.000, 0.000, 0.000)	(0.033, 0.050, 0.067)
KPI16	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.033, 0.050, 0.067)	(0.000, 0.017, 0.033)	(0.017, 0.033, 0.050)	(0.033, 0.050, 0.067)	(0.000, 0.000, 0.000)

and authors personal experience. The factor comparison method was utilized as a funnel process to prioritize the top-ranked 16 KPIs for further computation with Fuzzy DEMATEL method. The proposed approach proves to be more effective and efficient as compared to the conventional approaches because of the ability of revealing the interrelationships between the KPIs and the intensity of their effects on each other with respect to the ranking. According to the results, it can be suggested to emphasize focus for more consideration on the cause group factors due to their influences on the effect group factors. The decision-making authorities should emphasize more consideration to “Interoperability and compatibility of data by IPD and BIM (KPI 14),” “Facilitating access to real-time data by IPD and BIM (KPI 13),” “Accessibility and accuracy of information by BIM (KPI 5)” and “Minimizing claims and disputes through implementation of IPD and BIM (KPI 15).”. These KPIs have a huge influence on the other KPIs from the effect group, like awareness and benefits of IPD and BIM for infrastructure project (KPI 1),” “Mandatory implementation of BIM and IPD by government authorities (KPI 2),” “Project stakeholder’s early involvement in IPD and BIM adopted projects (KPI 3),” “Enhancing collaborative decisions by adoption of IPD and BIM (KPI 4)”, “Improved Design flexibility by utilizing IPD and BIM design flexibility (KPI 6),” “Effect on overall life cycle cost of project by use of IPD and BIM (KPI 7),” “Improvement in productivity through use of IPD and BIM (KPI 8),” “Resource optimization by collaboration of IPD and BIM (KPI 9),” “Progress monitoring efficiency for infrastructure project through IPD and BIM (KPI 10),” “Minimized amount of rework by integrating IPD and BIM (KPI 11),” “Speed of construction and delivery after IPD and BIM adoption (KPI 12)” and “Client’s satisfaction by implementing IPD and BIM (KPI 16)”. This research study provides a checklist of KPIs that requires special attention for IPD and BIM adoption. The result offers a logical base to deepen the understanding to select efficient and effective way of IPD and BIM adoption for complex infrastructure project.

This proposed methodology is believed to be superior than the available conventional techniques because the proposed methodology tries to expose the interrelation among the KPIs (causal factors) and their effects on the project performance. This methodology has the capability of dealing with group decision making in fuzzy environment. According to the analysis and findings, it has been observed that several corrective and preventive mitigation measures can be adopted to reduce the adverse impact of the KPIs (causal factors) affecting the project. It has been recommended to focus on the cause group criteria than the effect group criteria. Furthermore, the project authorities should focus on the Most Critical Key Performance

Table 9 Total relation fuzzy matrix

	KPI 1	KPI 2	KPI 3	KPI 4	KPI 5	KPI 6	KPI 7	KPI 8
KPI 1	(0.007,0.046,0.235)	(0.009,0.066,0.279)	(0.011,0.072,0.293)	(0.044,0.107,0.330)	(0.027,0.085,0.295)	(0.024,0.077,0.272)	(0.030,0.095,0.317)	(0.046,0.108,0.328)
KPI 2	(0.013,0.075,0.295)	(0.014,0.063,0.275)	(0.065,0.134,0.353)	(0.034,0.107,0.345)	(0.030,0.097,0.323)	(0.026,0.088,0.296)	(0.036,0.111,0.347)	(0.050,0.122,0.356)
KPI 3	(0.047,0.113,0.338)	(0.033,0.102,0.336)	(0.020,0.079,0.305)	(0.068,0.144,0.375)	(0.033,0.103,0.336)	(0.028,0.093,0.308)	(0.056,0.134,0.377)	(0.039,0.116,0.357)
KPI 4	(0.032,0.100,0.333)	(0.035,0.106,0.348)	(0.054,0.131,0.380)	(0.023,0.086,0.324)	(0.050,0.123,0.363)	(0.045,0.112,0.334)	(0.058,0.140,0.389)	(0.071,0.150,0.383)
KPI 5	(0.029,0.097,0.333)	(0.047,0.118,0.362)	(0.051,0.127,0.379)	(0.038,0.117,0.373)	(0.018,0.075,0.301)	(0.062,0.128,0.335)	(0.055,0.136,0.389)	(0.038,0.117,0.369)
KPI 6	(0.009,0.064,0.274)	(0.010,0.068,0.286)	(0.028,0.090,0.315)	(0.045,0.109,0.337)	(0.043,0.103,0.317)	(0.009,0.048,0.230)	(0.047,0.113,0.339)	(0.030,0.094,0.319)
KPI 7	(0.011,0.071,0.289)	(0.029,0.091,0.317)	(0.032,0.099,0.333)	(0.048,0.117,0.354)	(0.029,0.093,0.317)	(0.025,0.083,0.291)	(0.018,0.073,0.293)	(0.048,0.117,0.350)
KPI 8	(0.032,0.102,0.334)	(0.051,0.123,0.363)	(0.055,0.133,0.380)	(0.071,0.151,0.388)	(0.050,0.125,0.363)	(0.030,0.099,0.320)	(0.074,0.157,0.390)	(0.025,0.090,0.322)
KPI 9	(0.044,0.105,0.333)	(0.046,0.110,0.346)	(0.049,0.118,0.362)	(0.051,0.122,0.370)	(0.030,0.096,0.331)	(0.027,0.087,0.304)	(0.068,0.141,0.372)	(0.051,0.123,0.366)
KPI 10	(0.014,0.080,0.311)	(0.032,0.100,0.340)	(0.035,0.108,0.356)	(0.037,0.113,0.363)	(0.017,0.088,0.325)	(0.012,0.077,0.297)	(0.054,0.132,0.379)	(0.052,0.128,0.374)
KPI 11	(0.049,0.122,0.370)	(0.052,0.128,0.384)	(0.056,0.138,0.402)	(0.058,0.143,0.411)	(0.068,0.146,0.385)	(0.033,0.105,0.340)	(0.076,0.162,0.413)	(0.073,0.157,0.406)
KPI 12	(0.046,0.115,0.353)	(0.049,0.120,0.368)	(0.053,0.130,0.385)	(0.055,0.134,0.393)	(0.033,0.107,0.353)	(0.029,0.097,0.324)	(0.073,0.154,0.395)	(0.071,0.150,0.389)
KPI 13	(0.031,0.100,0.339)	(0.033,0.105,0.353)	(0.037,0.115,0.370)	(0.070,0.150,0.394)	(0.051,0.125,0.370)	(0.047,0.114,0.341)	(0.057,0.139,0.396)	(0.040,0.120,0.375)
KPI 14	(0.045,0.113,0.343)	(0.032,0.103,0.342)	(0.035,0.112,0.359)	(0.054,0.133,0.383)	(0.066,0.139,0.359)	(0.063,0.129,0.331)	(0.040,0.122,0.370)	(0.054,0.133,0.378)
KPI 15	(0.044,0.105,0.329)	(0.045,0.109,0.342)	(0.064,0.133,0.357)	(0.033,0.105,0.349)	(0.045,0.111,0.342)	(0.010,0.071,0.285)	(0.034,0.108,0.351)	(0.033,0.105,0.346)
KPI 16	(0.044,0.105,0.334)	(0.045,0.109,0.347)	(0.048,0.117,0.363)	(0.032,0.104,0.355)	(0.029,0.096,0.332)	(0.010,0.071,0.290)	(0.034,0.108,0.357)	(0.034,0.105,0.352)

	KPI 9	KPI 10	KPI 11	KPI 12	KPI 13	KPI 14	KPI 15	KPI 16
KPI 1	(0.028,0.089,0.301)	(0.044,0.104,0.325)	(0.048,0.117,0.353)	(0.031,0.097,0.320)	(0.006,0.036,0.207)	(0.021,0.063,0.233)	(0.008,0.062,0.261)	(0.013,0.076,0.299)
KPI 2	(0.050,0.119,0.344)	(0.032,0.103,0.339)	(0.069,0.149,0.385)	(0.053,0.129,0.366)	(0.007,0.059,0.242)	(0.022,0.070,0.253)	(0.028,0.090,0.302)	(0.034,0.106,0.344)
KPI 3	(0.069,0.141,0.358)	(0.051,0.125,0.369)	(0.058,0.143,0.402)	(0.073,0.153,0.382)	(0.008,0.047,0.237)	(0.007,0.058,0.248)	(0.062,0.127,0.330)	(0.054,0.130,0.374)
KPI 4	(0.055,0.131,0.370)	(0.053,0.130,0.381)	(0.076,0.164,0.415)	(0.075,0.158,0.395)	(0.009,0.066,0.261)	(0.008,0.046,0.242)	(0.048,0.116,0.340)	(0.072,0.150,0.386)
KPI 5	(0.036,0.111,0.355)	(0.068,0.145,0.382)	(0.075,0.162,0.416)	(0.041,0.125,0.380)	(0.043,0.098,0.293)	(0.042,0.095,0.290)	(0.015,0.083,0.311)	(0.053,0.130,0.385)
KPI 6	(0.013,0.060,0.277)	(0.029,0.092,0.317)	(0.049,0.120,0.360)	(0.047,0.115,0.342)	(0.007,0.054,0.227)	(0.021,0.065,0.238)	(0.009,0.065,0.267)	(0.030,0.094,0.321)
KPI 7	(0.048,0.113,0.338)	(0.031,0.098,0.333)	(0.052,0.128,0.379)	(0.036,0.109,0.346)	(0.022,0.071,0.252)	(0.006,0.037,0.219)	(0.028,0.087,0.297)	(0.065,0.132,0.353)
KPI 8	(0.072,0.149,0.371)	(0.053,0.132,0.382)	(0.077,0.167,0.416)	(0.075,0.160,0.395)	(0.010,0.068,0.262)	(0.008,0.062,0.258)	(0.032,0.102,0.326)	(0.057,0.137,0.387)
KPI 9	(0.019,0.072,0.291)	(0.033,0.103,0.349)	(0.055,0.134,0.396)	(0.053,0.129,0.376)	(0.007,0.058,0.247)	(0.006,0.039,0.230)	(0.013,0.075,0.296)	(0.051,0.122,0.368)
KPI 10	(0.052,0.124,0.361)	(0.018,0.077,0.310)	(0.057,0.141,0.405)	(0.070,0.150,0.385)	(0.057,0.110,0.286)	(0.039,0.090,0.281)	(0.046,0.110,0.333)	(0.052,0.127,0.377)
KPI 11	(0.057,0.138,0.392)	(0.041,0.124,0.390)	(0.032,0.111,0.378)	(0.076,0.165,0.418)	(0.042,0.102,0.307)	(0.025,0.082,0.289)	(0.048,0.121,0.360)	(0.058,0.141,0.409)
KPI 12	(0.070,0.146,0.376)	(0.052,0.130,0.387)	(0.060,0.148,0.422)	(0.026,0.095,0.338)	(0.024,0.081,0.280)	(0.008,0.061,0.262)	(0.031,0.099,0.331)	(0.055,0.133,0.391)
KPI 13	(0.037,0.114,0.360)	(0.069,0.147,0.388)	(0.076,0.165,0.423)	(0.058,0.143,0.401)	(0.011,0.052,0.235)	(0.041,0.095,0.293)	(0.047,0.115,0.345)	(0.039,0.119,0.377)
KPI 14	(0.036,0.111,0.349)	(0.069,0.146,0.377)	(0.076,0.163,0.410)	(0.041,0.125,0.374)	(0.043,0.099,0.289)	(0.010,0.047,0.223)	(0.014,0.082,0.305)	(0.037,0.115,0.365)
KPI 15	(0.033,0.102,0.334)	(0.032,0.102,0.344)	(0.053,0.132,0.391)	(0.051,0.127,0.371)	(0.006,0.057,0.245)	(0.006,0.055,0.242)	(0.012,0.057,0.258)	(0.049,0.119,0.363)
KPI 16	(0.033,0.102,0.339)	(0.047,0.117,0.365)	(0.053,0.132,0.397)	(0.051,0.127,0.377)	(0.007,0.058,0.249)	(0.022,0.071,0.261)	(0.044,0.104,0.326)	(0.016,0.071,0.306)

Table 10 Crisp total relation matrix

	KPI 1	KPI 2	KPI 3	KPI 4	KPI 5	KPI 6	KPI 7	KPI 8	KPI 9	KPI 10	KPI 11	KPI 12	KPI 13	KPI 14	KPI 15	KPI 16
KPI 1	0	0	0	0	0	0	0	0.143	0	0	0.153	0	0	0	0	0
KPI 2	0	0	0.165	0.143	0	0	0.146	0.157	0.152	0	0.182	0.164	0	0	0	0
KPI 3	0.146	0	0	0.176	0	0	0.168	0.151	0.171	0.16	0.179	0.184	0	0	0.155	0.165
KPI 4	0	0	0.166	0	0.157	0.142	0.174	0.181	0.164	0.165	0.196	0.189	0	0	0.147	0.181
KPI 5	0	0.153	0.163	0.155	0	0.155	0.172	0.154	0.147	0.176	0.195	0.162	0	0	0	0.166
KPI 6	0	0	0	0.145	0	0	0.147	0	0	0	0.157	0.15	0	0	0	0
KPI 7	0	0	0	0.153	0	0	0	0.152	0.147	0	0.166	0.145	0	0	0	0.164
KPI 8	0	0.157	0.167	0.183	0.159	0	0.187	0	0.177	0.166	0.198	0.191	0	0	0	0.171
KPI 9	0	0.146	0.155	0.159	0	0	0.174	0.159	0	0	0.172	0.165	0	0	0	0.158
KPI 10	0	0	0.145	0.15	0	0	0.167	0.164	0.158	0	0.178	0.182	0	0	0.143	0.163
KPI 11	0.156	0.163	0.174	0.179	0.177	0	0.194	0.19	0.172	0.161	0.152	0.197	0	0	0.153	0.177
KPI 12	0.149	0.156	0.166	0.171	0.144	0	0.186	0.182	0.176	0.166	0.186	0	0	0	0	0.17
KPI 13	0	0	0.152	0.183	0.16	0.146	0.174	0.157	0.15	0.179	0.198	0.178	0	0	0.148	0.156
KPI 14	0.146	0	0.148	0.168	0.169	0.156	0.158	0.167	0.146	0.176	0.195	0.161	0	0	0	0.152
KPI 15	0	0.144	0.165	0.142	0.146	0	0.145	0	0	0	0.17	0.163	0	0	0	0.156
KPI 16	0	0.145	0.154	0.143	0	0	0.146	0.143	0	0.154	0.171	0.164	0	0	0	0

Table 11 Crisp values of R_i, C_j, $R_i + C_j$ and $R_i—C_j$

	R_i	C_j	$R_i + C_j$	$R_i - C_j$
KPI1	2.064	1.839	3.903	− 0.225
KPI2	2.191	2.158	4.35	− 0.033
KPI3	2.404	2.337	4.742	− 0.067
KPI4	2.518	2.442	4.96	− 0.076
KPI5	2.265	2.409	4.674	0.143
KPI6	1.984	1.9	3.884	− 0.084
KPI7	2.579	2.07	4.649	− 0.509
KPI8	2.5	2.476	4.975	− 0.024
KPI9	2.363	2.199	4.561	− 0.164
KPI10	2.438	2.306	4.743	− 0.132
KPI11	2.849	2.625	5.474	− 0.224
KPI12	2.66	2.45	5.11	− 0.211
KPI13	1.584	2.464	4.048	0.88
KPI14	1.512	2.399	3.911	0.89
KPI15	2.02	2.158	4.177	0.138
KPI16	2.474	2.173	4.647	− 0.301

Indicators (MCKPI) or most critical causal factors like KPI 11, KPI 12, KPI 8, KPI 4, KPI 10, KPI 3, KPI 5, KPI 7 and KPI 16. These most critical causal factors related to rework, speed and delivery after IPD adoption, improvement in productivity through BIM and IPD, enhancing collaborative effort, progress efficiency monitoring, early involvement of the stakeholders, effect of IPD and BIM implementation on the overall life cycle cost of the project and satisfaction of the client after implementing BIM and IPD need to be taken utmost care by the project authorities and wherever required suitable corrective and preventive mitigation measures need to be adopted. Finally the results

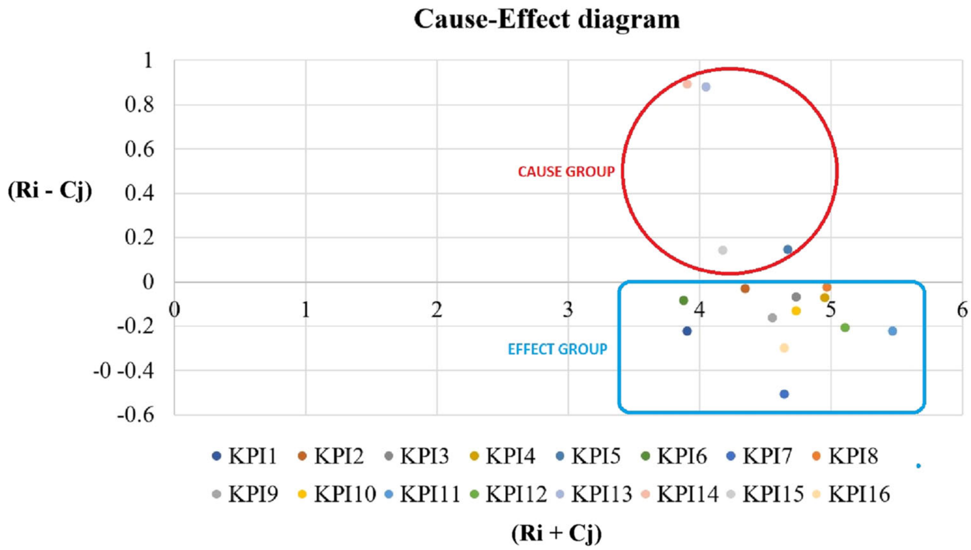

Fig. 2 Casual diagram highlighting the cause-and-effect groups of the evaluated KPIs for IPD and BIM adoption

of the FCM and fuzzy DEMATEL approach can be made more robust and the validation of test results can be done through sensitivity analysis. Thereby, it can be concluded that combined FCM and fuzzy DEMATEL methodology is effective decision-making tool which can be used in most of the industry sectors that need group decision making in a fuzzy environment.

Scope for Future Research

The methodology and the concepts applied in the present research is generic in nature and thereby may be applied for other infrastructure projects like highways, bridges, ports, power plants, dams etc. These concepts can be applied to all projects across the nation and also globally. Sensitivity analysis can be applied to validate the results of the fuzzy DEMATEL. The present research has been carried out with triangular membership function and 5-point scale. Further research may be carried out by exploring the possibilities of application of trapezoidal membership function and 7-point scale.

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