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ORIGINAL PAPER

Automated constructability rating framework for concrete formwork systems using building information modeling

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Abstract

The main objective of this research is to develop an automated constructability rating framework for different concrete formwork systems that are commonly used for the construction of reinforced concrete residential buildings. Initially, various constructability criteria (cost, time, quality, safety and environmental sustainability) that are analogous to the concrete formwork construction are rationally characterized through an intriguing data acquisition mechanism (a complete process involving the collection, recording and processing of data) known as constructability survey. Withal, an unified 3D Building Information Modeling (BIM) Model (i.e., 3D Structural BIM Model and 3D BIM Formwork Family or Module) is developed to providence CONSTaFORM, an automated constructability assessment framework for concrete formwork systems. The CONSTaFORM is a supplementary Add-in for Autodesk Revit developed by a process called API-fication, i.e., customizing Revit API to provide additional functionalities and hence enhancing the capabilities of existing framework invariably. The optimal constructability scores of various concrete formwork systems obtained from the constructability survey are initially fed into their respective 3D BIM formwork families as shared parameters, which are later used for the computation of the overall constructability rating of the formwork systems involved in the entire project, using BIM via CONSTaFORM Add-in. To reinforce the profundity and advocacy of CONSTaFORM Add-in, a suitable case study is reported.

Keywords CONSTaFORM · Constructability · Concrete formwork systems · Building information modeling · Parametric model · Shared parameters · API-fication

Introduction

Concrete formwork systems are temporary framework systems which are used for the cast-in-situ or precast construction (providing structural shape and texture of the plastic concrete on hardening) of Reinforced Cement Concrete (RCC) structures. It plays a paramount role in the construction of RCC structures, precisely, the cost of formwork construction (forming cost) and construction time pertaining to erection and assembly of formwork systems (forming time) contributes to 10 and 50% of the overall cost and overall time of the entire construction project, respectively (Hanna 1999; Peurifoy and Oberlender 2010; Jha 2012; Hurd 2005). Besides both forming cost and forming time, other associated attributes like forming quality, forming safety and environmental sustainability, significantly influences the concrete formwork systems (Kannan and Santhi 2013a).

These intrinsic and interdependent characteristics which influence the profitability of formwork construction can be fragmented into five major criteria as cost, time, quality, safety and environmental sustainability. These five criteria are instantiated using a phenomenal construction project management technique known as 'Constructability'.

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Constructability

Construction Industry Institute (CII) (1986) defined constructability as "a system for achieving optimum integration of construction knowledge and experience in planning, engineering, procurement and field operations in the building process and balancing the various project and environmental constraints to achieve overall project objectives". ASCE, Construction Management Committee (1991) defines constructability program as "the application of a disciplined, systematic optimization of the construction-related aspects of a project during the planning, design, procurement, construction, test and start-up phases by knowledgeable, experienced construction personnel who are part of a project". Constructability is the only project management technique designed and developed solely by the construction industry for the construction industry (McGeorge et al. 2012). The concept and scope of constructability and buildability are synonymous similar and are used interchangeably by many researchers, however, for the sake of clarity, the term 'constructability' is monologously considered and used throughout this research. To integrate constructability efficiently and efficiently into overall phases of the project, a specialized classification system incorporating all the attributes or factors that influences constructability are to be identified and listed in a logical sequence (Hanlon and Sanvido 1995).

Constructability information model

Many researchers developed single-user classification systems for categorizing and storing the constructability information (Hanlon and Sanvido 1995). The classification systems developed by some of the researchers are highly unique (domain specific and predilection in the classification format) and does not cover the overall phases of the project comprehensively (Hanlon and Sanvido 1995). Hanlon and Sanvido (1995) described the prominence of the constructability information classification system that covers over all phases of the project since it is the prelude for constructability assessment. They developed a sophisticated framework called as Constructability Information Model (CIM) through which constructability information is classified, stored and retrieved accurately and efficiently throughout the project. The CIM comprises two parts, first is the categories of information and its associated attributes and other is the storage format of attributes (Hanlon and Sanvido 1995). To ease the process of the constructability, the classification of various concrete formwork systems augmenting this research is illustrated in Fig. 1 and ensnared schematically in Table 1, also, the constructability information scheme adapted for this research incorporating all the attributes traversing the concrete formwork construction is illustrated in Fig. 2 and tabulated in Table 5 of Appendix 'Constructability information scheme for concrete formwork systems'.

Constructability Assessment of Concrete Formwork Systems

The appreciable work on implementing the concept of constructability in concrete formwork design was initially carried out by Touran (1988). O'Connor and Davis (1988) and CRSI Report No. 32 (1989) depicted the importance of interaction between formwork contractor and Engineers for

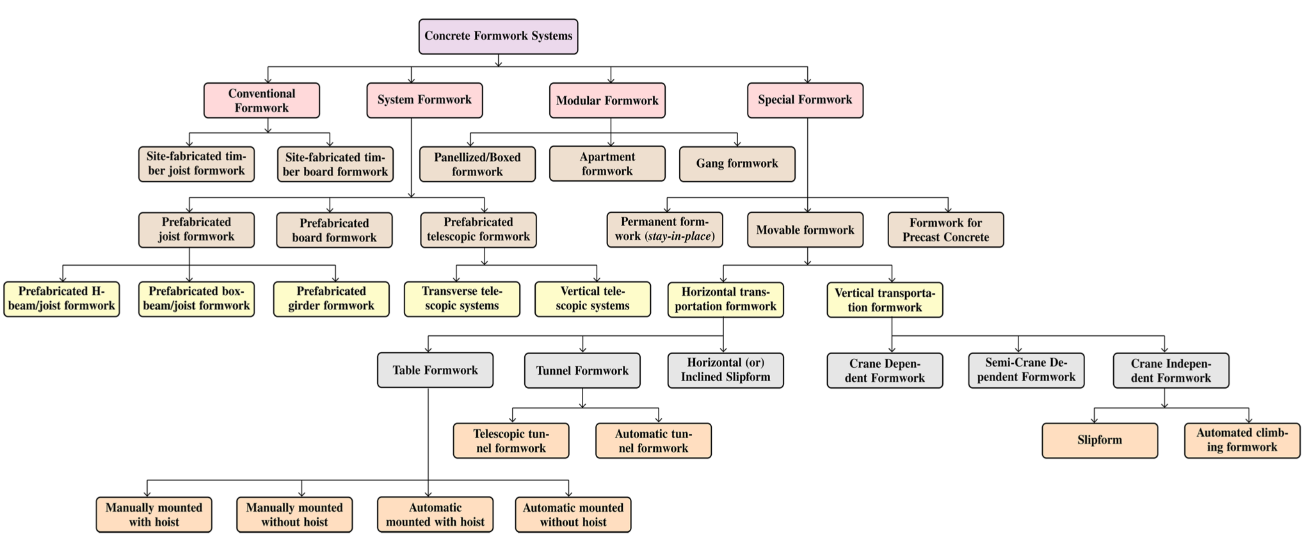

Fig. 1 Distinct classification of concrete formwork systems

Table 1 Nomenclature of concrete formwork systems

Alternative	Sub-alternative	Formwork	Notation
Conventional	Horizontal	Site-fabricated timber joist formwork	A_1
	Vertical	Site-fabricated timber joist formwork	A_2
	Inclined	Site-fabricated timber joist formwork	A_3
	Combined	Site-fabricated timber joist formwork	A_4
	Horizontal	Site-fabricated timber board formwork	A_5
	Vertical	Site-fabricated timber board formwork	A_6
	Inclined	Site-fabricated timber board formwork	A_7
	Combined	Site-fabricated timber board formwork	A_8
System	Horizontal	Prefabricated H-beam formwork	A_9
	Horizontal	Prefabricated box-beam formwork	A_{10}
	Horizontal	Prefabricated girder formwork	A_{11}
	Vertical	Prefabricated H-beam formwork	A_{12}
	Vertical	Prefabricated box-beam formwork	A_{13}
	Vertical	Prefabricated girder formwork	A_{14}
	Inclined	Prefabricated H-beam formwork	A_{15}
	Inclined	Prefabricated box-beam formwork	A_{16}
	Inclined	Prefabricated girder formwork	A_{17}
	Combined	Prefabricated H-beam formwork	A_{18}
	Combined	Prefabricated box-beam formwork	A_{19}
	Combined	Prefabricated girder formwork	A_{20}
	Horizontal	Prefabricated board formwork	A_{21}
	Vertical	Prefabricated board formwork	A_{22}
	Inclined	Prefabricated board formwork	A_{23}
	Combined	Prefabricated board formwork	A_{24}
	Horizontal	Prefabricated transverse telescopic formwork	A_{25}
	Vertical	Prefabricated vertical telescopic formwork	A_{26}
	Inclined	Prefabricated telescopic transverse and vertical formwork	A_{27}
	Combined	Prefabricated telescopic transverse and vertical formwork	A_{28}
Modular	Combined	Panellized/Boxed formwork	A_{29}
	Combined	Apartment or Half-Tunnel formwork	A_{30}
	Combined	Gang formwork	A_{31}
Special	Horizontal	Permanent formwork	A_{32}
	Vertical	Permanent formwork	A_{33}
	Inclined	Permanent formwork	A_{34}
	Combined	Permanent formwork	A_{35}
	Horizontal	Formwork for precast concrete	A_{36}
	Vertical	Formwork for precast concrete	A_{37}
	Inclined	Formwork for precast concrete	A_{38}
	Combined	Formwork for precast concrete	A_{39}
	Horizontal	Horizontally transported and manually mounted table formwork without hoist	A_{40}
	Horizontal	Horizontally transported and manually mounted table formwork with hoist	A_{41}
	Horizontal	Horizontally transported and automatically mounted table formwork with hoist	A_{42}
	Horizontal	Horizontally transported and automatically mounted table formwork without hoist	A_{43}
	Horizontal	Slipform	A_{44}
	Vertical	Slipform	A_{45}
	Inclined	Slipform	A_{46}
	Combined	Slipform	A_{47}
	Vertical	Crane dependent climbing formwork	A_{48}

Table 1 (continued)

Alternative	Sub-alternative	Formwork	Notation
	Inclined	Crane dependent climbing formwork	A_{49}
	Vertical	Semi-crane dependent climbing formwork	A_{50}
	Inclined	Semi-crane dependent climbing formwork	A_{51}
	Vertical	Automatic climbing formwork	A_{52}
	Inclined	Automatic climbing formwork	A_{53}

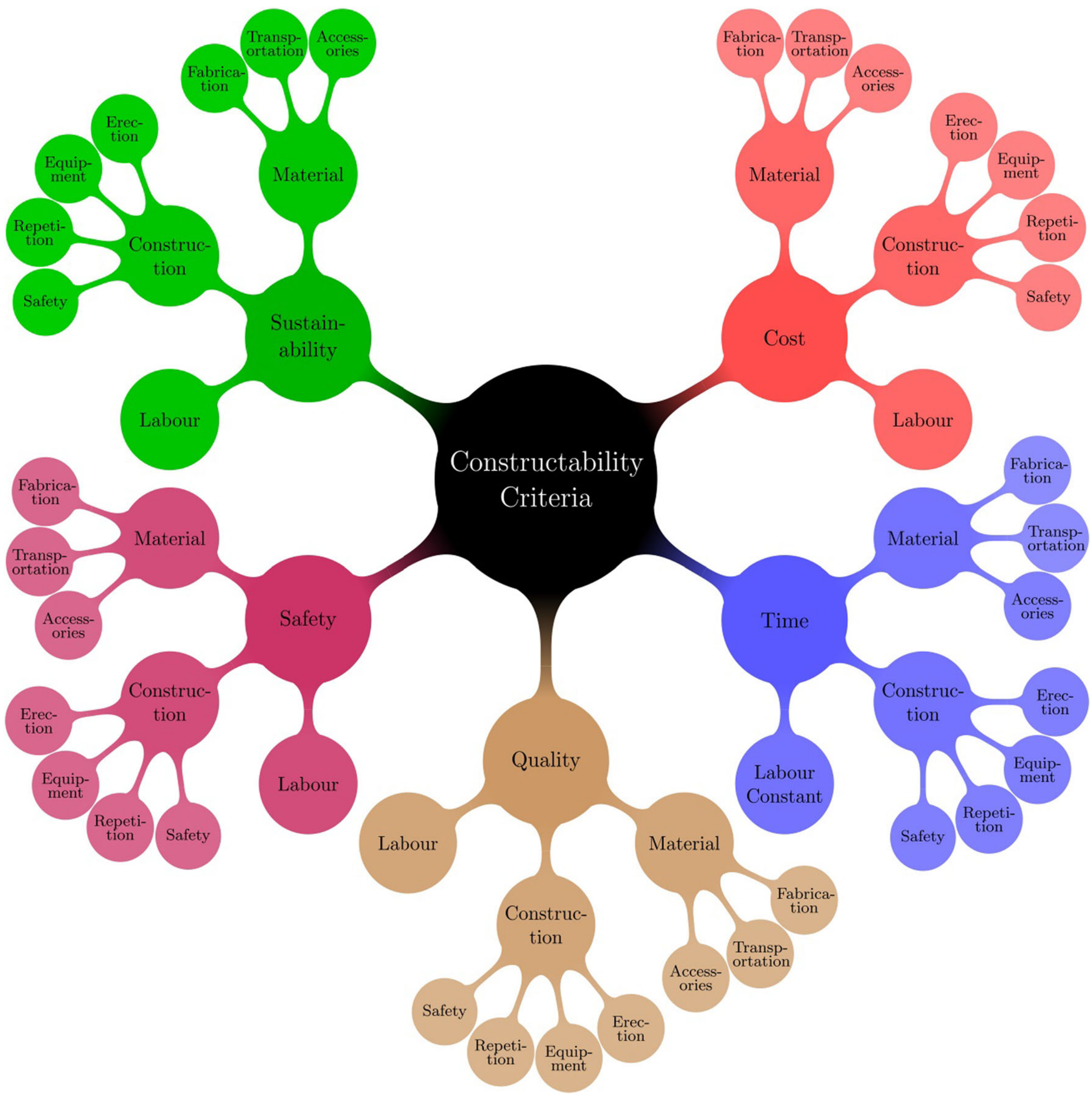

Fig. 2 Constructability information classification schema

attaining rapid construction cycle by virtue of performance-oriented specifications of formwork construction such as selection of suitable formwork systems (Gang formwork system and flying truss formwork system) for rapid cycle, strength and serviceability consideration of formwork systems and choice of shore-replacement methods: backshoring, reshoring and preshoring. Meanwhile, Fischer (1991) realized the importance of incorporating constructability even in the formwork planning phase for reinforced concrete construction projects. He also emphasized the importance of selection of appropriate construction crew for specialized formwork systems like self-climbing formwork, etc., as they are generally complex in nature requires highly skilled and qualified personnel and mostly custom-made systems demands a higher degree of planning garnering space adequacy, access for materials transport and crew during construction (Hanlon and Sanvido 1995) etc. Generally, to achieve these details, a well-documented framework or guide comprising set of rules/ criteria developed by expert members are employed. For this research, a comprehensive overview of all the constructability criteria pertaining to concrete formwork construction for performing constructability analysis, the promulgated ideas and information pertaining to the global concrete formwork construction by various experts are recorded through an intriguing mechanism known as 'Constructability Survey'.

Constructability survey

ASCE, Construction Management Committee (1991) emphasized that to enhance constructability into construction projects 'experienced construction personnel need to be involved with the project from the earliest stages to ensure that the construction focus and experience can properly influence the owner, planners, and designers, as well as material suppliers'. Experienced personnel mean persons having a full understanding of the nature of the project from start-to-finish and acquired knowledge from the previous and similar projects (Kartam and Flood 1997) which was done earlier rather than sticking with the project for a long period of time. More importantly, the experienced personnel should have deeper knowledge on modern or innovative construction process or methods (O'Connor and Miller 1994). These skills are generally acquired through a process called 'Constructability Survey'.

Kannan and Santhi characterized constructability survey as 'a process to acquire the knowledge and experience by adequate hands-on-training in a project (similar to the proposed project) for a particular period of time, in collecting work samplings, gathering information on work sequencing, productivity, contractual procedures and material handling function, etc., from the construction personnel/industry actually involved in the project' (Kannan and Santhi 2013b). For performing constructability analysis of concrete formwork systems, 173 residential construction projects was surveyed. The template used for the survey are given in Table 6 of Appendix 'Constructability survey template'. From the constructability survey, the weights assigned to compute constructability score of each concrete formwork systems are calculated using a technique known as Relative Importance Index (RII). Researchers characterize RII as a measure of the extent to which each variable contributes to the prediction of the criterion individually and in combination with the other variables contributing to the prediction (Johnson and LeBreton 2004; Somiah et al. 2015). It is also termed as 'relative weight' and is calculated using the expression as shown in the Eq. 1.

$$\mathrm{RII} = \frac{\sum_{i=1}^{N} w_i}{w_h \times N} (0 \le \mathrm{RII} \le 1) \tag{1}$$

where, w_i is the rating or weight of each factor (0–10), w_h is the highest rating or weight allocated to each factor (i.e., 10 for 0–10 rating scale, 11 point Likert scale) and N is the total number of responses recorded. For instance, RII for Forming cost, C_i is calculated as shown in the Eq. 2.

$$\mathrm{RII} = \frac{\sum_{i=1}^{173} w_i}{9.21 \times 173} = \frac{8.23 + 6.45 + \cdots + 9.21 + 7.71}{9.21 \times 173} = 0.9450 \approx 0.95 \tag{2}$$

Where, $\sum_{i=1}^{173} w_i$ is the values of the forming cost, w_h is the highest rating of forming cost (9.21), N is the total number responses (173). Similarly, the RII value of other constructability criteria are determined, the sum of all the RII values is 4.0. The weight of each constructability criteria is calculated using Eq. 3

$$w = \frac{\mathrm{RII}}{\mathrm{Total\ RII}} \tag{3}$$

For example, the weight of the constructability criteria, Forming cost, C_i is calculated as shown in Eq. 3 using Eq. 4.

$$w = C_i = \frac{\mathrm{RII}}{\mathrm{Total\ RII}} = \frac{0.95}{4.0} = 0.2375 \approx 0.24 \tag{4}$$

Similarly, the weights for other constructability criteria are also calculated using Eq. 3. The overall RII value and weight for each constructability criteria was calculated and ranked based on the higher value of the RII values as shown in the Table 2.

The application of RII in determining weights of these criteria is portentous than computing through commonly used statistical measures, i.e., median and mode of the sample distribution. Thus, the Constructability Score (CS) for concrete formwork systems can be computed using Eq. 5.

Table 2 RII value and weight for each constructability criteria

Constructability criteria	RII	Weight	Rank
Forming cost (C_i)	0.95	0.24	1
Forming Time (C_j)	0.92	0.23	2
Forming Quality (C_k)	0.79	0.20	3
Forming Safety (C_l)	0.69	0.17	4
Environmental sustainability (C_m)	0.65	0.16	5
Total	4.00	1.00	–

Table 3 Constructability survey report

Pro. no.	AreaConstr. (in sq.m)	No. storey	HghtConstr. (in m.)	ConstTime (in years)	CycleTime (in days/floor)	C_1	⋯	C_{20}	⋯	C_{30}	⋯	C_{40}	ConstScr. (Out of 10)
P1	9301–18600	07–15	25.1–65.0	2.1–4.0	04–07	8.10	⋯	8.50	⋯	8.20	⋯	7.80	8.38
P2	≥ 25001	46–85	185.1–345.0	4.1–6.0	01–03	6.84	⋯	6.52	⋯	5.88	⋯	6.42	6.96
P3	≥ 25001	46–85	185.1–345.0	4.1–6.0	01–03	6.84	⋯	6.52	⋯	5.88	⋯	6.42	6.96
P4	9301–18600	07–15	25.1–65.0	2.1–4.0	08–14	5.26	⋯	5.56	⋯	4.04	⋯	5.48	6.06
P5	≥ 25001	16–25	65.1–105.0	2.1–4.0	08–14	6.00	⋯	6.20	⋯	5.00	⋯	5.60	6.49
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
P50	5001–9300	07–15	25.1–65.0	2.1–4.0	08–14	6.28	⋯	NA	⋯	5.00	⋯	5.60	5.79
P51	2001–5000	≤ 06	≤ 25	2.1–4.0	08–14	5.26	⋯	5.56	⋯	4.04	⋯	5.48	6.06
P52	2001–5000	≤ 06	≤ 25	≤ 2	08–14	5.00	⋯	5.04	⋯	NA	⋯	5.44	4.90
P53	9301–18600	≤ 06	≤ 25	2.1–4.0	08–14	5.26	⋯	NA	⋯	NA	⋯	NA	3.97
P54	9301–18600	26–45	105.1–185.0	4.1–6.0	08–14	5.68	⋯	6.16	⋯	5.62	⋯	6.30	6.76
P55	9301–18600	26–45	105.1–185.0	4.1–6.0	08–14	5.68	⋯	6.16	⋯	5.62	⋯	6.30	6.76
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
P100	2001–5000	07–15	25.1–65.0	2.1–4.0	08–14	NA	⋯	5.04	⋯	3.92	⋯	5.44	5.76
P101	2001–5000	≤ 06	≤ 25	≤ 2	08–14	5.00	⋯	5.04	⋯	3.92	⋯	5.44	5.99
P102	5001–9300	≤ 06	≤ 25	2.1–4.0	08–14	6.28	⋯	5.90	⋯	5.00	⋯	5.60	6.39
P103	5001–9300	07–15	25.1–65.0	2.1–4.0	08–14	6.28	⋯	6.84	⋯	5.70	⋯	7.14	2.75
P104	9301–18600	07–15	25.1–65.0	2.1–4.0	08–14	5.26	⋯	5.56	⋯	4.04	⋯	5.48	6.06
P105	5001–9300	≤ 06	≤ 25	≤ 2	08–14	6.00	⋯	6.20	⋯	5.00	⋯	5.60	6.49
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
P170	5001–9300	16–25	65.1–105.0	2.1–4.0	08–14	5.00	⋯	5.04	⋯	3.92	⋯	5.44	5.99
P171	2001–5000	≤ 06	≤ 25	≤ 2	08–14	5.00	⋯	5.04	⋯	3.92	⋯	5.44	5.99
P172	5001–9300	16–25	65.1–105.0	2.1–4.0	08–14	6.00	⋯	6.20	⋯	5.00	⋯	5.60	6.49
P173	9301–18600	≤ 06	≤ 25	2.1–4.0	08–14	5.26	⋯	5.56	⋯	4.04	⋯	5.48	6.06

NA represents missing data

$$\text{CS} = \frac{0.24 \times \sum_{i=1}^{8} C_i + 0.23 \times \sum_{j=9}^{16} C_j + 0.20 \times \sum_{k=17}^{24} C_k + 0.17 \times \sum_{l=25}^{32} C_l + 0.16 \times \sum_{m=33}^{40} C_m}{8} \tag{5}$$

The constructability score of a comprehensive concrete formwork system (project specific system) and optimum constructability score (optimal constructability score obtained using Linear Programming) for individual formwork system that are used in the 173 projects are tabulated in Tables 3 and 4 respectively.

Constructability rating

Constructability scoring or rating of concrete formwork systems for determining optimal constructability score for simpler constructions can be performed manually and more accurately without any difficulties, but for the heavy construction projects due to its inherent difficulties and complexities associated with the projects, performing constructability rating is quite perplexing rather challenging and hence additional guides and tools are required. Many researchers developed computerized solution for constructability implementation for concrete formwork construction starting from integrated microcomputer packages (Christian and Mir 1987; Tah and Price 1997), 2D CAD and 3D CAD models to sophisticated 'Enterprise Design/Data Management' (EDM) and Building Information Modeling (BIM) for developing nD models (Kannan and Santhi 2013b; Kannan and Knight 2012; Lee et al. 2009; Kannan and Santhi 2013a, 2015; Jun and Yun 2011; Meadati et al. 2011; Neto and Ruschel 2015) and collaborative construction process using customized software tools (Multimedia constructability tool 1998; Ganah et al. 2005; Hijaji et al. 2009).

Building information modeling

BIM is a digital representation of physical and functional characteristics of the buildings developed in the pre-

Table 4 Constructability score for different formwork systems from the constructability survey

S. no.	Notation	Type	Category	Forming cost			Forming time			Forming quality			Forming safety			Sustainability			CS
				C_1	...	Avg	C_9	...	Avg	C_{17}	...	Avg	C_{25}	...	Avg	C_{33}	...	Avg	
1	A1	Con_Form	Horizontal	9.00	...	2.00	9.00	...	2.00	6.00	...	6.00	6.00	...	6.00	5.00	...	6.00	4.00
2	A2	Con_Form	Vertical	6.00	...	2.00	9.00	...	2.00	6.00	...	6.00	6.00	...	6.00	5.00	...	6.00	4.00
3	A3	Con_Form	Inclined	7.00	...	2.00	9.00	...	1.00	6.00	...	6.00	6.00	...	6.00	5.00	...	6.00	4.00
4	A4	Con_Form	Combined	8.00	...	2.00	9.00	...	1.00	6.00	...	6.00	6.00	...	6.00	5.00	...	6.00	4.00
5	A5	Con_Form	Horizontal	7.00	...	2.00	9.00	...	2.00	7.00	...	7.00	6.00	...	6.00	6.00	...	6.00	5.00
6	A6	Con_Form	Vertical	7.00	...	2.00	9.00	...	2.00	7.00	...	7.00	6.00	...	6.00	6.00	...	6.00	5.00
7	A7	Con_Form	Inclined	8.00	...	2.00	9.00	...	2.00	7.00	...	7.00	6.00	...	6.00	6.00	...	6.00	5.00
8	A8	Con_Form	Combined	8.00	...	2.00	9.00	...	2.00	7.00	...	7.00	6.00	...	6.00	6.00	...	6.00	5.00
9	A9	Sys_Form	Horizontal	8.00	...	2.00	9.00	...	2.00	8.00	...	7.00	6.00	...	7.00	6.00	...	7.00	5.00
10	A10	Sys_Form	Horizontal	6.00	...	4.00	9.00	...	2.00	8.00	...	7.00	6.00	...	7.00	6.00	...	7.00	5.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
20	A20	Sys_Form	Combined	7.00	...	4.00	9.00	...	2.00	9.00	...	7.00	6.00	...	7.00	6.00	...	7.00	5.00
21	A21	Sys_Form	Horizontal	6.00	...	3.00	10.00	...	1.00	9.00	...	9.00	9.00	...	9.00	8.00	...	8.00	6.00
22	A22	Sys_Form	Vertical	6.00	...	3.00	10.00	...	1.00	9.00	...	9.00	9.00	...	9.00	8.00	...	8.00	6.00
23	A23	Sys_Form	Inclined	7.00	...	3.00	10.00	...	1.00	9.00	...	9.00	9.00	...	9.00	8.00	...	8.00	6.00
24	A24	Sys_Form	Combined	7.00	...	3.00	9.00	...	1.00	9.00	...	9.00	9.00	...	9.00	8.00	...	8.00	6.00
25	A25	Sys_Form	Horizontal	5.00	...	3.00	10.00	...	1.00	10.00	...	9.00	9.00	...	9.00	8.00	...	8.00	6.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
30	A30	Mod_Form	Combined	7.00	...	4.00	7.00	...	4.00	10.00	...	10.00	10.00	...	10.00	10.00	...	10.00	8.00
31	A31	Mod_Form	Combined	7.00	...	4.00	7.00	...	4.00	10.00	...	10.00	10.00	...	10.00	10.00	...	10.00	8.00
32	A32	Spl_Form	Horizontal	9.00	...	3.00	10.00	...	1.00	10.00	...	10.00	9.00	...	10.00	9.00	...	9.00	7.00
33	A33	Spl_Form	Vertical	9.00	...	3.00	10.00	...	1.00	10.00	...	10.00	9.00	...	10.00	9.00	...	9.00	7.00
34	A34	Spl_Form	Inclined	9.00	...	3.00	10.00	...	1.00	10.00	...	10.00	9.00	...	10.00	9.00	...	9.00	7.00
35	A35	Spl_Form	Combined	9.00	...	3.00	10.00	...	1.00	10.00	...	10.00	9.00	...	10.00	9.00	...	9.00	7.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
50	A50	Spl_Form	Vertical	9.00	...	2.00	10.00	...	1.00	10.00	...	10.00	10.00	...	10.00	10.00	...	10.00	7.00
51	A51	Spl_Form	Inclined	9.00	...	2.00	10.00	...	1.00	10.00	...	10.00	10.00	...	10.00	10.00	...	10.00	7.00
52	A52	Spl_Form	Vertical	9.00	...	2.00	10.00	...	1.00	10.00	...	10.00	10.00	...	10.00	10.00	...	10.00	7.00
53	A53	Spl_Form	Inclined	9.00	...	2.00	10.00	...	1.00	10.00	...	10.00	10.00	...	10.00	10.00	...	10.00	7.00

construction stage or even during the conceptual stage (pre-design stage) of the project which provides provision for the participation of client, stakeholders, engineers and contractors in a single platform so as to eliminate all the possible errors that could probable occur in a project even at the beginning of the project so as to produce flawless diagrams and could be readily updated at any point of time, generally this features is called as 'parametric-change characteristics'.

The parametric change characteristics of 3D BIM formwork module was visualized and portrayed in detail by Kannan and Knight (2012). The parametric change capabilities of 3D BIM formwork module were further extended to account for the automatic layout and simulation of concrete formwork systems and to perform 4D and 5D constructability analysis by Kannan and Santhi (2013a). A detailed retrospective assessment of constructability analysis of three major types of climbing formwork systems, namely, crane-independent climbing formwork system, semi-dependent climbing formwork system and automatic climbing formwork system traversing the cost, time, attributes using 3D BIM was carried out by Kannan and Santhi (2013b). The 3D BIM formwork module proves to be an essential tool in checking for clashes with the associated 3D BIM architectural, structural and MEP models in the pre-construction stage of the construction project, which is commonly termed as 'clash detection' (Kannan and Santhi 2015) to identify and eliminate obstacles or prevent error, delays and cost over-run that could probably occur during construction. Thus, the interoperability characteristics of BIM plays a vital role in incorporating the constructability criteria of formwork construction (Kannan and Santhi 2013b, 2015; Hijaji et al. 2009; Kim and Cho 2015). In this research, the implementation of BIM for constructability assessment of concrete formwork systems is portrayed for the pre-construction visualization and decision-making phase of a project

This is achieved by developing an unique add-in functionality for Autodesk Revit known as 'CONSTaFORM'.

CONSTaFORM

For developing a comprehensive add-in for Constructability assessment of Concrete formwork systems in Autodesk Revit, a detailed formulation and fragmentation of unified 3D BIM Model (3D Structural BIM + 3D BIM Formwork Module) is necessitated and the manoeuvring process involved in accomplishing the same are delineated in the Figs. 3, 4, 5, 6, 7, 8 and 9. The detailed convoluted procedures are elaborated as follows: initially, 3D BIM Structural Model of a 20-storied building is created using the 2D BIM structural floor plan as in Fig. 3 and 2D BIM

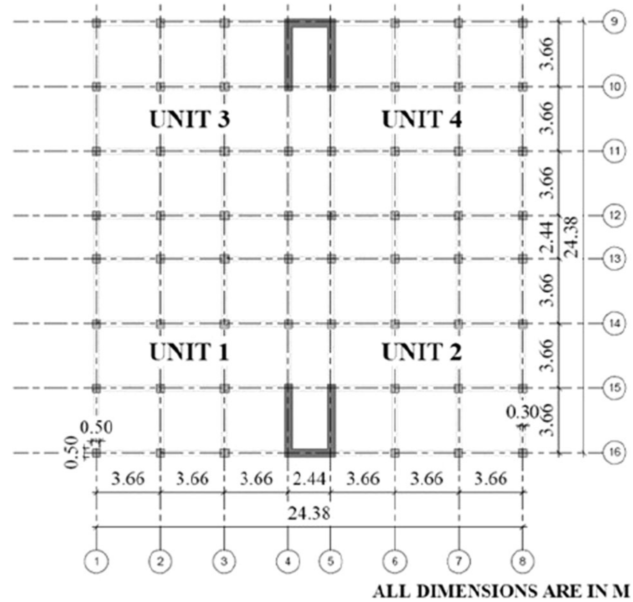

Fig. 3 Typical 2D structural floor plan of a 20-storied building

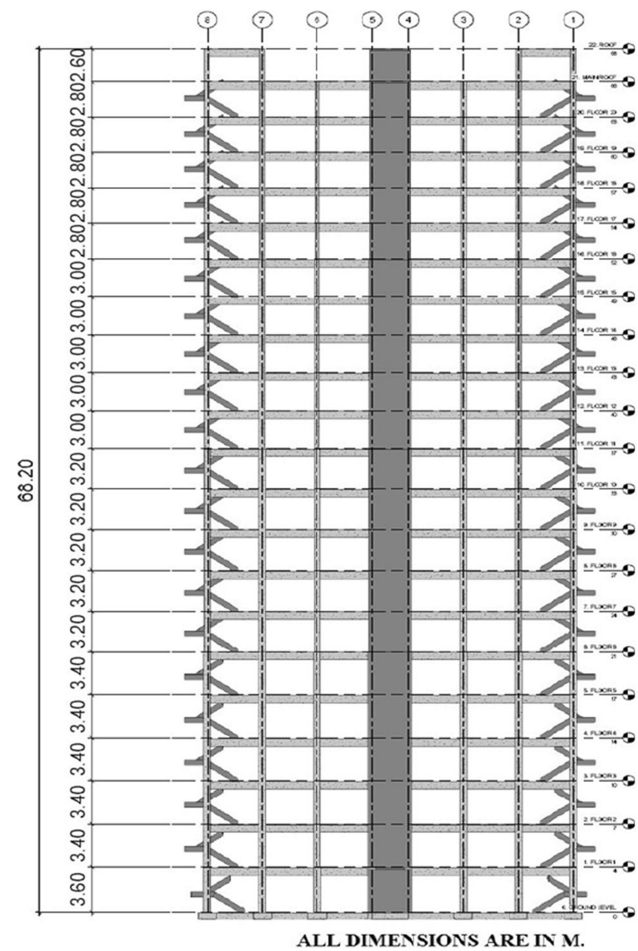

Fig. 4 Typical 2D structural elevation of a 20-storied building

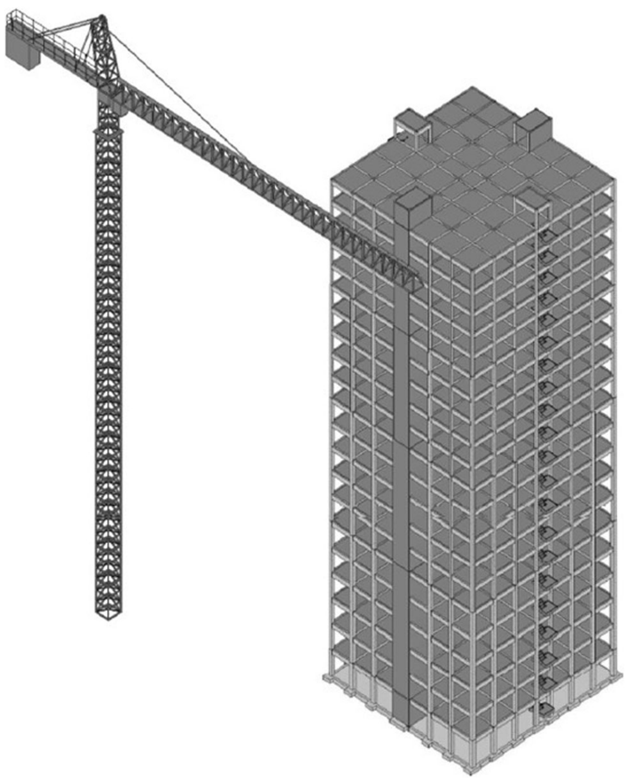

Fig. 5 Typical 3D BIM model of a 20-storied high-rise building

structural elevation as in Fig. 4 then, convert the solid 3D BIM Model as in Fig. 5, into wireframe 3D BIM model as shown in Fig. 6, which acts as a reference for 3D BIM Formwork Family insertion. Then 3D BIM Formwork Module are created separately as Component Family File, i.e., a type of Revit Family that is available for all the Revit projects and gets loaded into the projects when necessary as in Figs. 7 and 8. The detailed process of integration of the 3D BIM Structural Model and 3D BIM Formwork Module is illustrated in Fig. 9 (Kannan and Santhi 2013b, a, 2015).

The constructability score of each concrete formwork system from Table 4 is incorporated directly into its" respective 3D BIM formwork family file as 'shared parameters' (information of the parameters stored explicitly in each 3D BIM family file for accurate retrieval) is shown in Fig. 10.

This unified 3D BIM Model plays a key role in the development of 'CONSTaFORM', an Add-in for Autodesk Revit to perform constructability assessment of concrete formwork systems using BIM. This can be achieved through a cutting edge methodology known as 'API-fication'.

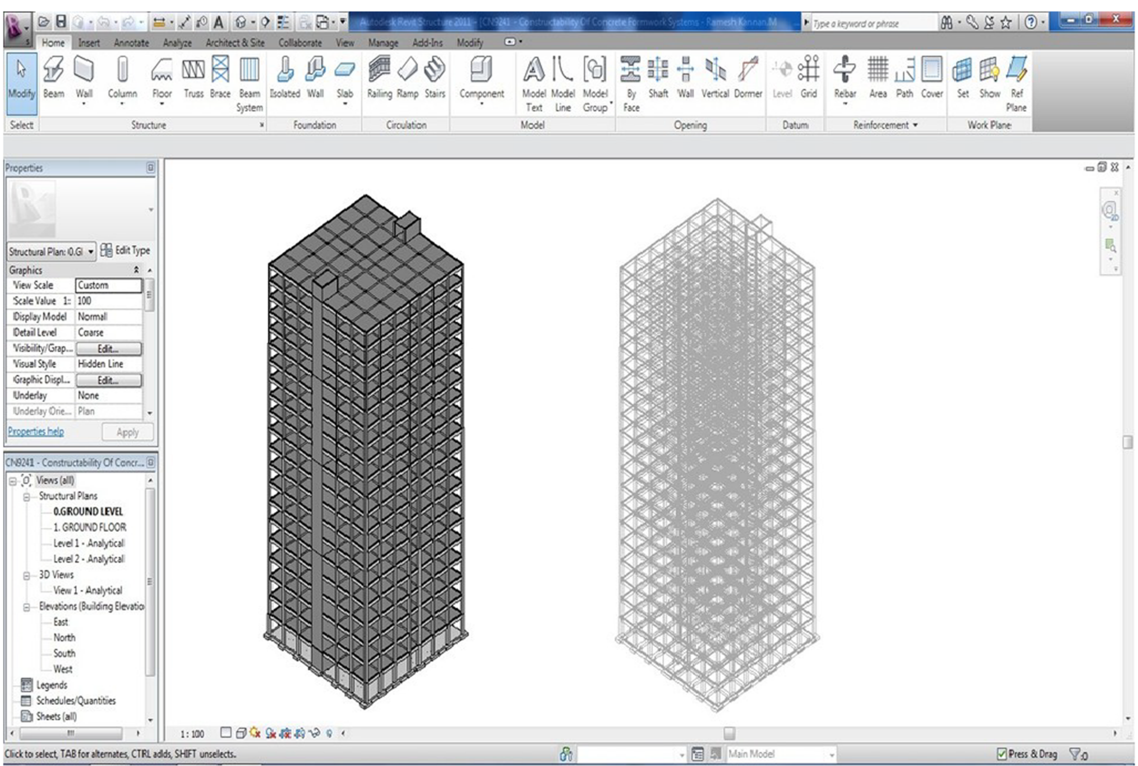

Fig. 6 Conversion of solid 3D BIM to wireframe 3D BIM model

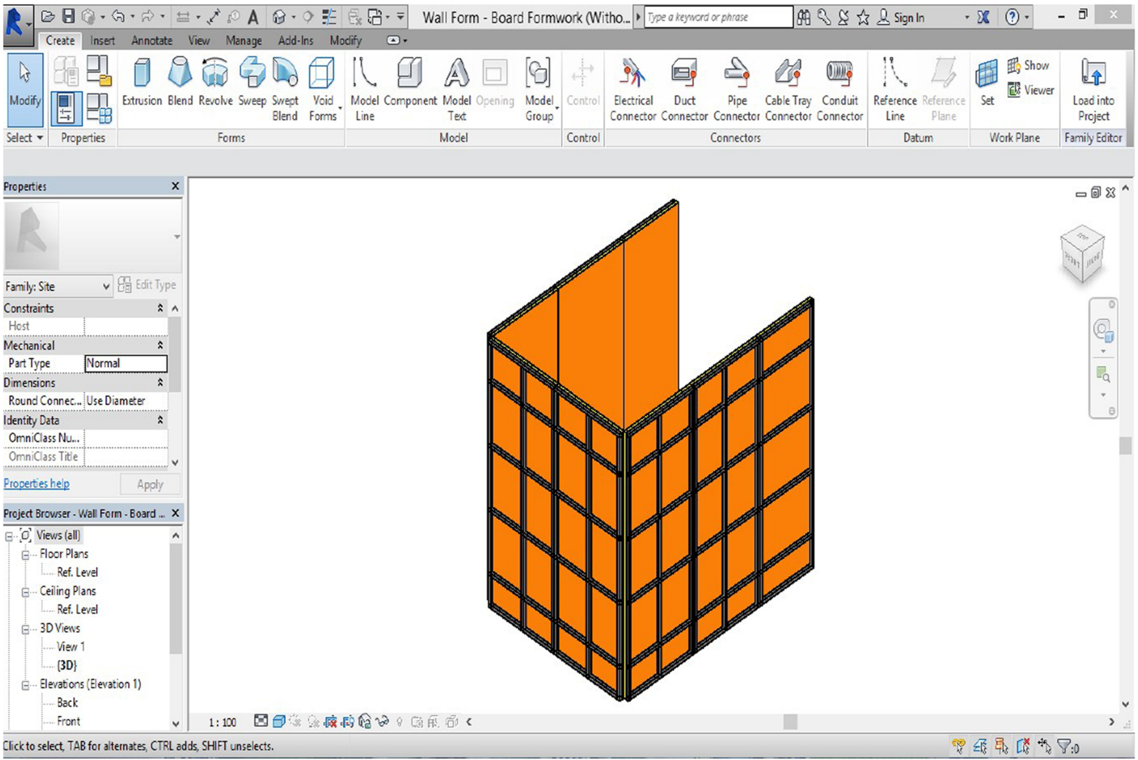

Fig. 7 3D BIM wall formwork Revit family file depicting a system wall formwork

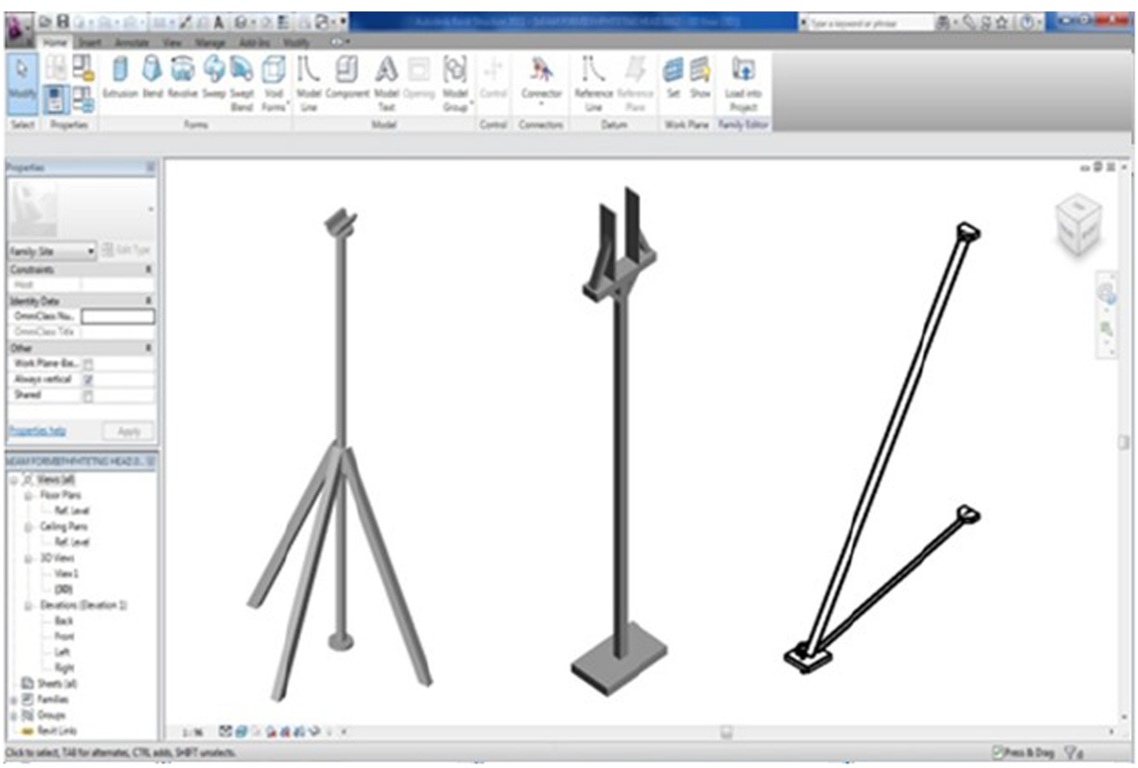

Fig. 8 3D BIM formwork accessories Revit families

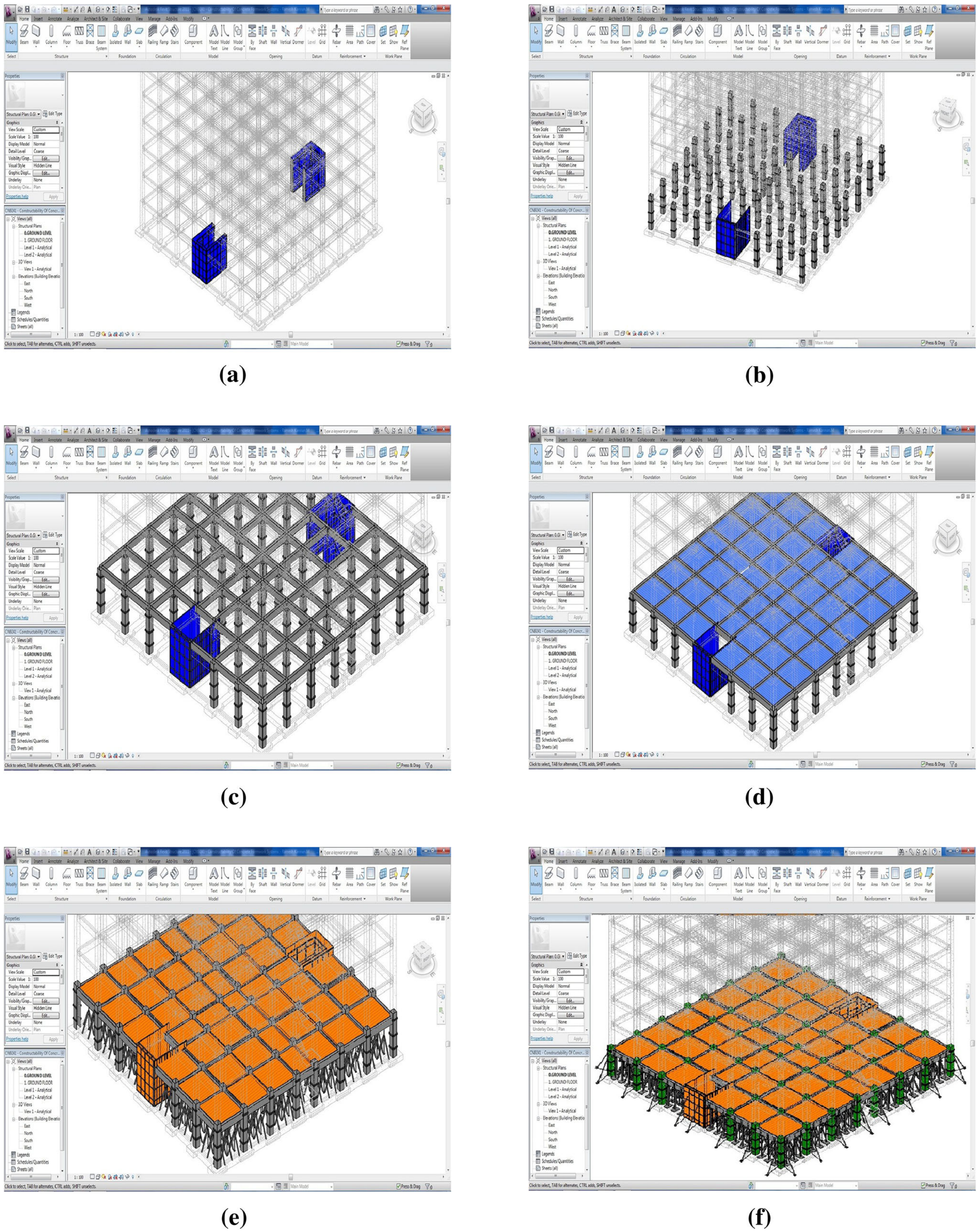

Fig. 9 Sequence representing the process of integration of 3D BIM formwork family with 3D BIM structural model, incorporation of **a** wall formwork, **b** column formwork, **c** beam formwork, **d** slab formwork, **e** formwork supporting element and **f** formwork accessories

API-fication

API is a short form of 'Application Programming Interface' is an all-embracing term related to computer programming, which is a set of protocols and tools used by developers for building application software and also in many cases, it used to enhance the functionality of the existing application software. Thus, the process of revamping the application software architecture by modification or alteration to enhance additional functionality is termed as API-fication. In this research, the CONSTaFORM Add-in is developed by customizing Revit API through both Revit Macro Manager (MM) as shown in Fig. 11 and Visual Studio software using C# language in .Net Framework (Rudder 2013). The detailed description of the development environment of the CONSTaFORM Add-in is given in the Algorithm 1.

Algorithm 1 Development environment for CONSTaFORM add-in in Autodesk Revit

```
procedure CUSTOMIZING REVIT API
create a new application → CONSTaFORM as in Fig. 11
create a new macro using C# Application (Compatible with Visual Studio)
    reference Microsoft .NET 4.0 Libraries RevitAPI.dll & RevitAPIUI.dll
        Copy Local → False
    imports namespaces Autodesk.Revit.UI & Autodesk.Revit.DB
    create a new class (*.vb) in Visual Studio
    create a TaskDialog
        add PushButton Control → RibbonPanel
    get ElementInfo
    ElementInfo → Constructability Score of that particular element
        if ElementInfo = Null
            modify designOption
        else return designoption
    get GeometryObjectFromReference
        pick surface
            pick entire surface in the project
            call Constructability score of all the surface as in Table 4
    use rule-based calling for computing constructability as in Fig. 12
    create custom ribbion CONSTaFORM → IExternalApplicationInteface
    run the application
    return Result.Succeeded as in Fig. 13
catch
```

The detailed description of the steps involved in the Algorithm 1 are as follows. To create CONSTaFORM add-in for Autodesk Revit, the initial process is to create a `application`, invariably to create a module named 'CONSTaFORM' using Revit Macro Manager (MM) as shown in Fig. 11. The programming language used in this research is C# language in .Net Framework, however, the customization can also be done using other programming languages like Ruby and Python. The customization of the Revit Macro can be done using the Revit's in-built Script, but for enhancing the versatility of the code editing, Visual Studio is used in this research. Initially, the two important libraries known as `RevitAPI.dll` (database library) and `RevitAPIUI.dll` (user-interface library) are referenced into the project with marking `Copy Local` to `False`, i.e., any customization of these libraries will not modify the parent or existing library files (Rudder 2013). Using, the referenced libraries, the class of elements known as `namespace elements` such as `Autodesk.Revit.DB` and `Autodesk.Revit.UI` are imported respectively, and then, a new class file, `CONSTaFORM.vb` is created in the Visual Studio. Then using the `Autodesk.Revit.UI` user-interface namespace, user-interface elements such as `TaskDialog` Box, `Ribbon Panel` and `PushButtons` are created for the CONSTaFORM Add-in. A sample 3D BIM formwork family file is loaded into a 3D BIM Structural Project, the details of the shared parameters corresponding to 3D formwork family is obtained using get `ElementInfo`. This process is carried out for other 3D BIM formwork family, to find out the 3D BIM formwork family files with missing parameters, provided `ElementInfo` = Null in the code, for displaying the missing parameters. For missing parameters, values are entered manually as in Fig. 10.

When all the 3D BIM formwork families are verified, the process of assembly of all the formwork systems required for a sample project is done as in Fig. 9 to get the information pertaining to the overall formwork systems using `GetObjectFromReference`. Using the pick `surface` function, the details of each formwork systems are obtained. Then, using pick `surface` for the entire project, selects the overall formwork systems used in the entire project, this is used to compute the overall constructability score of formwork systems used in the entire project. To be precise, the values of the formwork systems are initially stored in a directory as a relational database and the computation of the constructability score is carried out like in the Fig. 12 using Eq. 5. The output of the constructability score is visualized in a dialog box as shown in Fig. 13.

Results and discussion

From Fig. 13, we infer that, the CONSTaFORM Add-in provides a vivid display of the overall constructability score of concrete formwork systems used in the entire project, however, the CONSTaFORM Add-in should be checked for reliability of the final constructability scores, this is actually performed using an important functionality of BIM, known as parametric change characteristics as in Figs. 14 and 15.

The parametric change characteristics of the BIM not only accommodates the effective modification of the 3D BIM formwork families but also provides a semi-intelligent markup, i.e, when changing the 3D BIM system wall formwork family to 3D BIM conventional wall formwork family as in Fig. 14, the associated formwork accessories of the 3D BIM system wall formwork family are deleted instantaneously. This brings down some of the major complexities associated with the formwork planning.

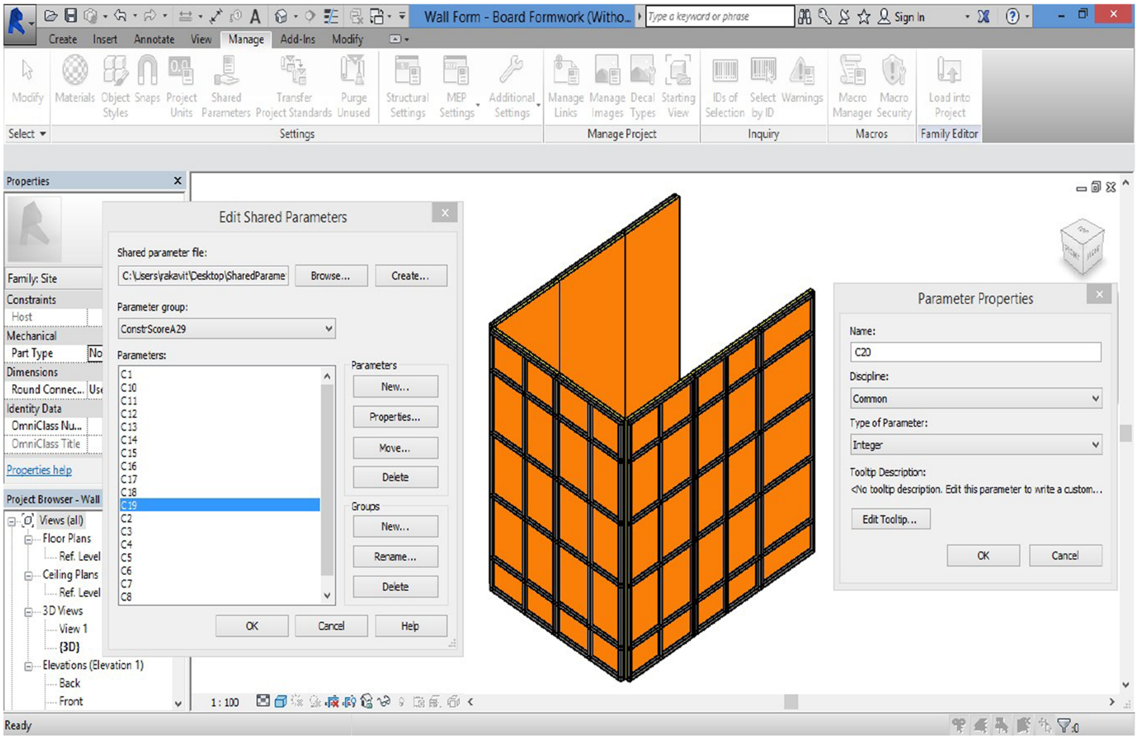

Fig. 10 Incorporating respective constructability score into the 3D BIM wall formwork family as shared parameter

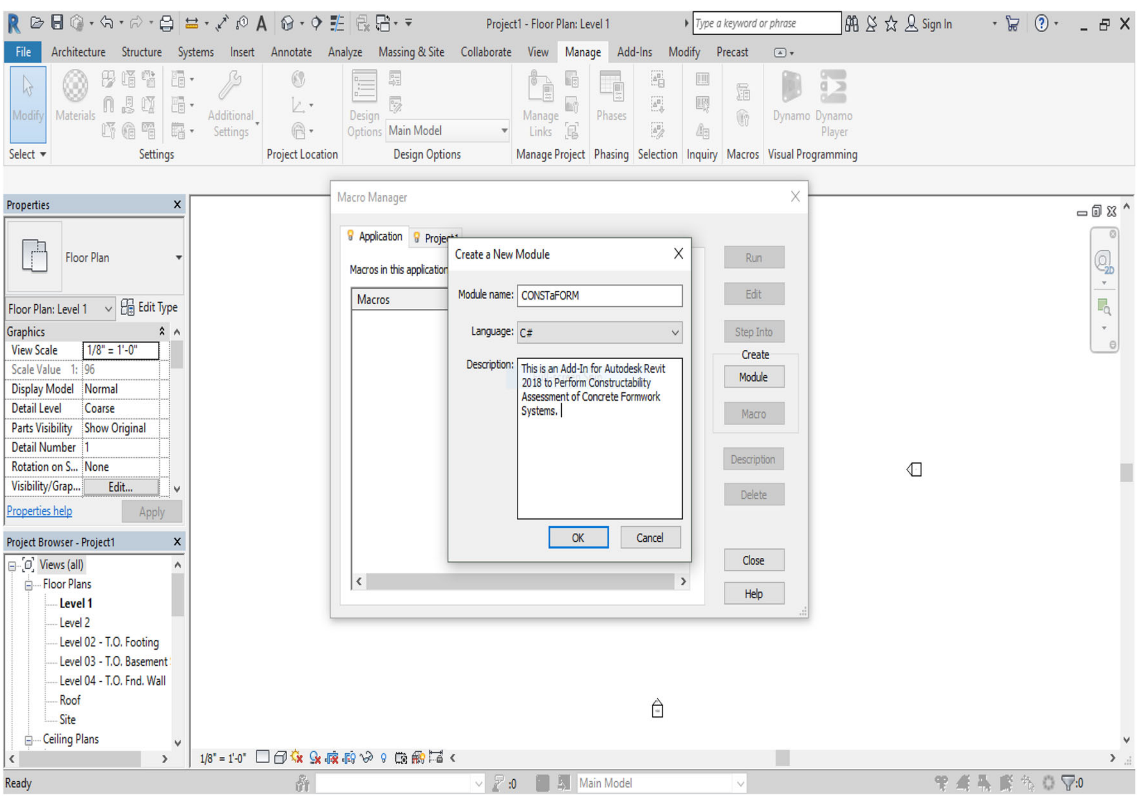

Fig. 11 Screenshot of the process of creating CONSTaFORM add-in using Revit Macro Manager (MM)

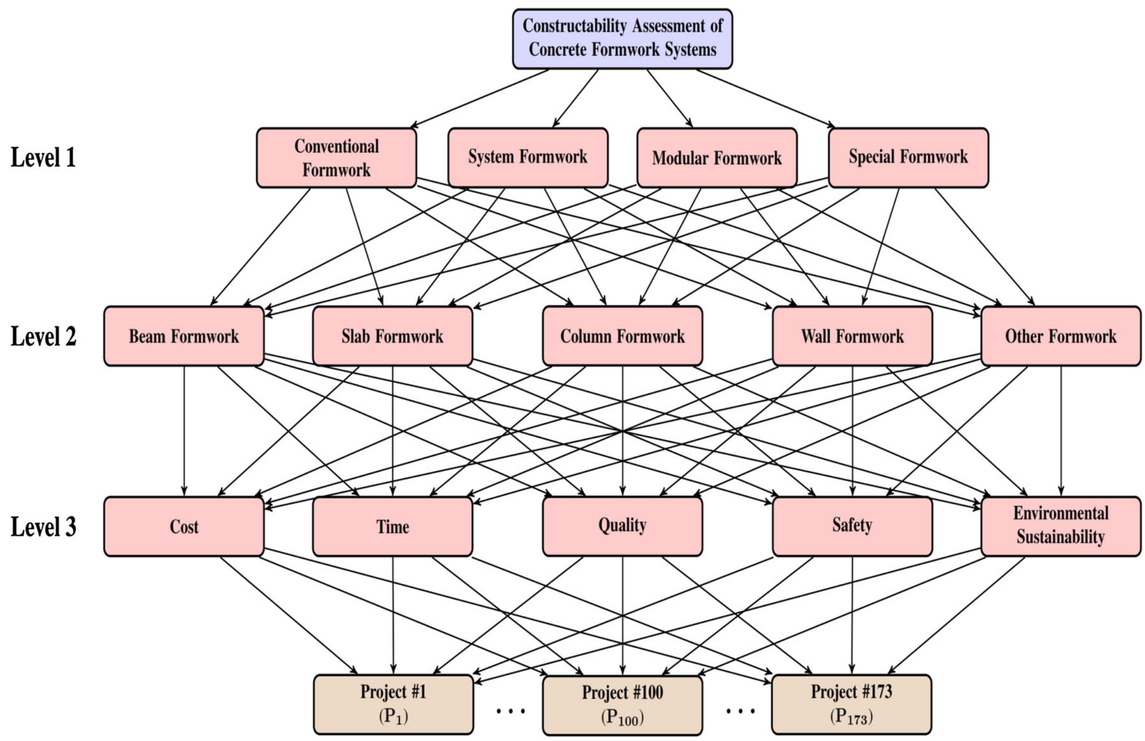

Fig. 12 Relational diagram for constructability assessment of concrete formwork system

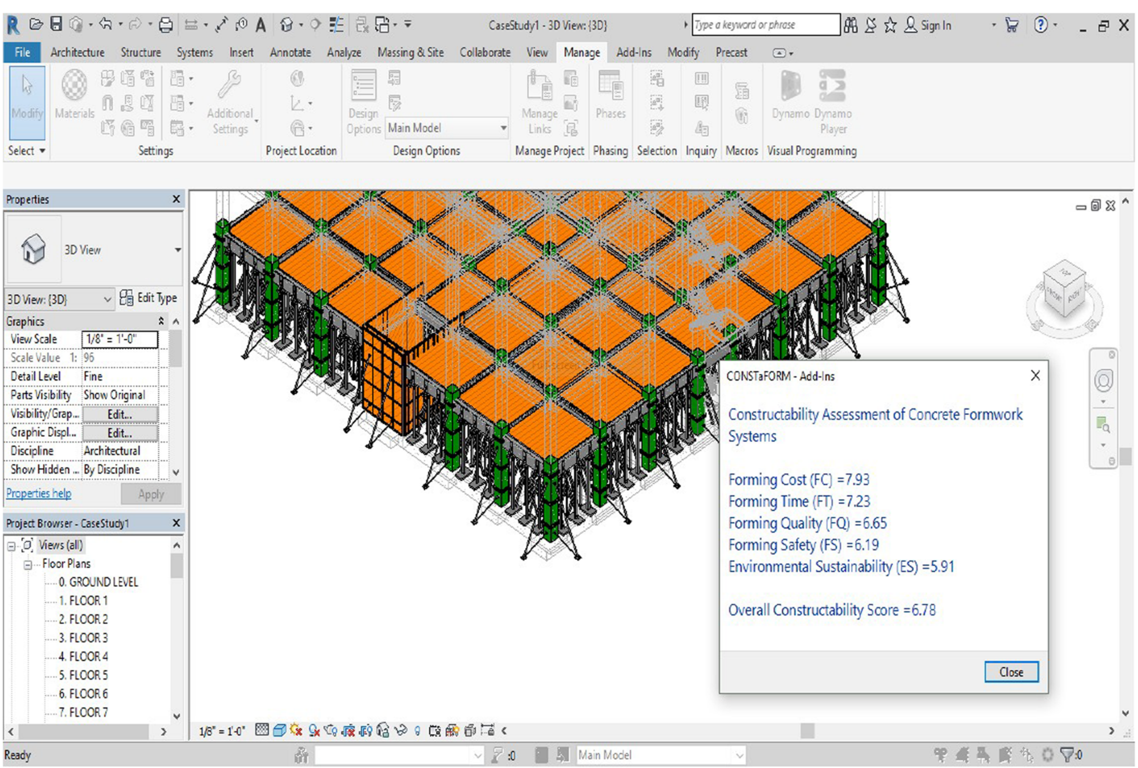

Fig. 13 Output of CONSTaFORM depicting the overall constructability score for the integrated 3D BIM Model

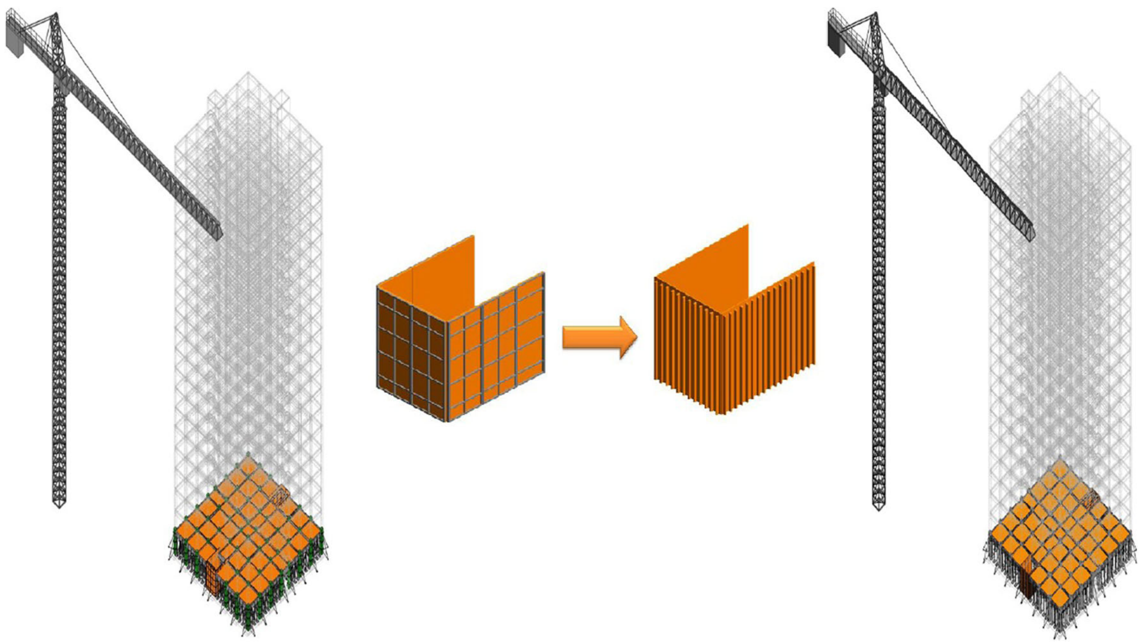

Fig. 14 Schematic illustration of parametric change characteristics of BIM

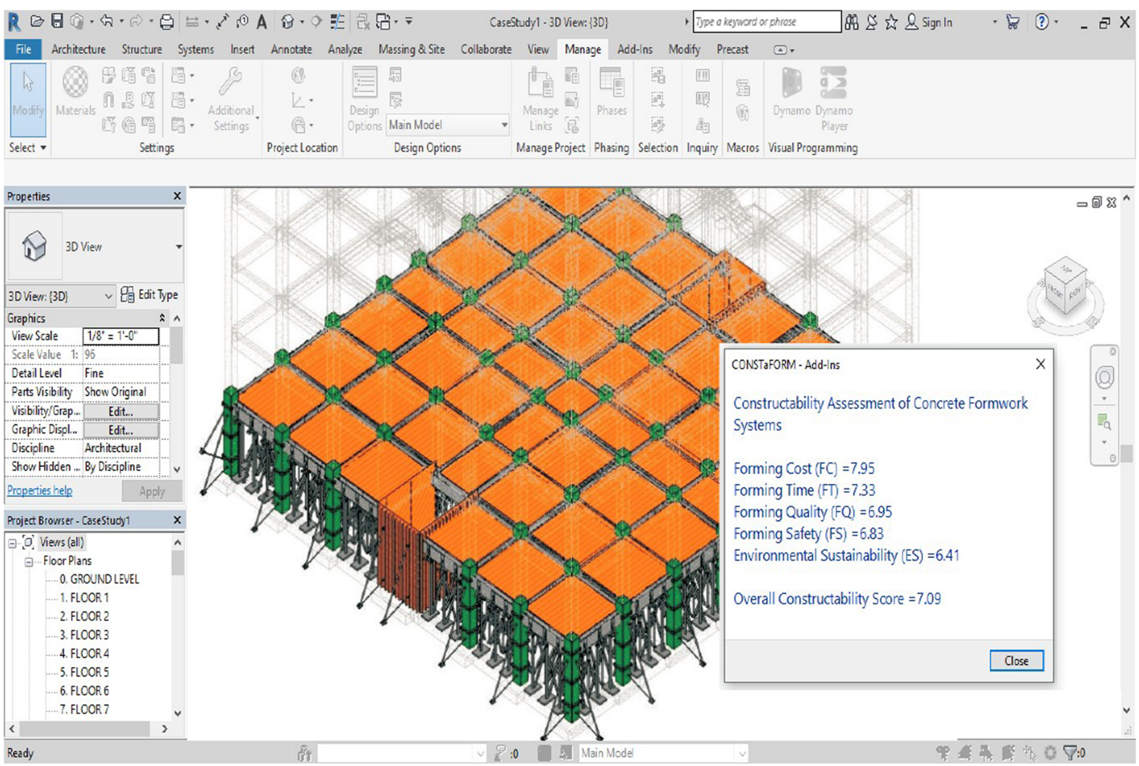

Fig. 15 Output of CONSTaFORM depicting the overall constructability score for the integrated 3D BIM Model after the parametric change

Moreover, for a greater understanding of the clashes between different 3D BIM Formwork families and 3D BIM structural model, a sophisticated process known as 'clash detection' is carried out using the same integrated 3D BIM model in a separate software, say, Autodesk Navisworks. Then, after resolution of the clashes in the integrated 3D

Fig. 16 Architectural elevation of the proposed high-rise residential building

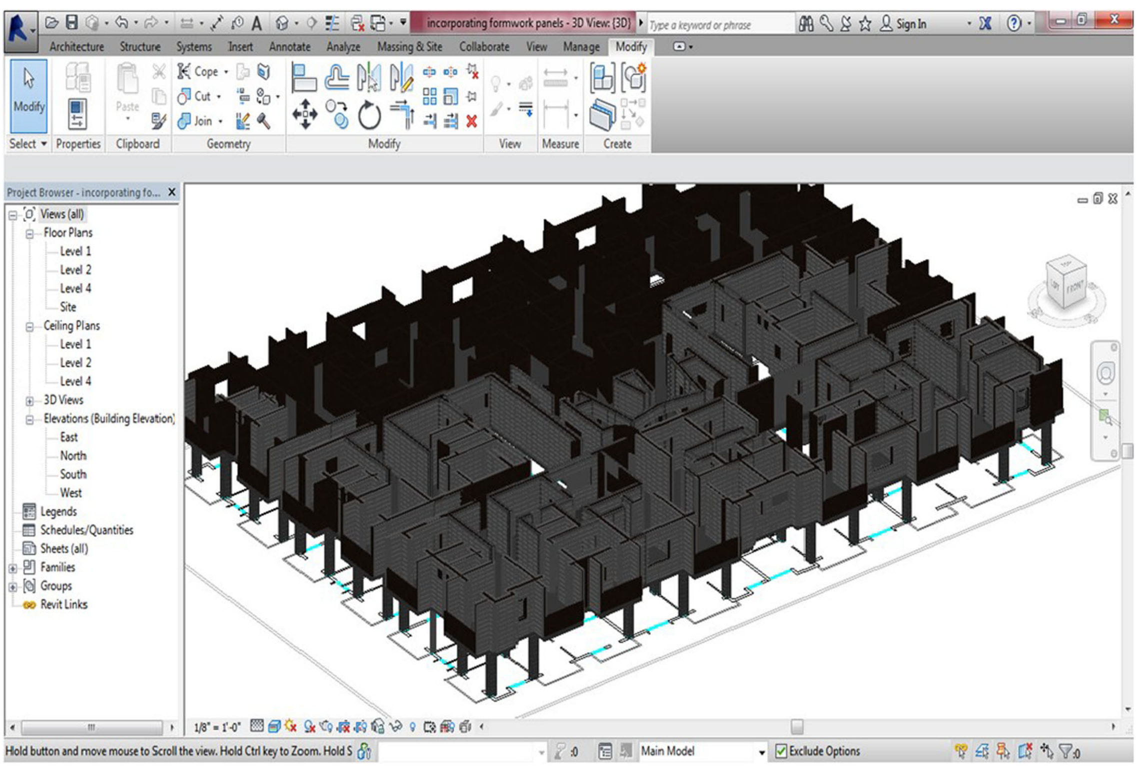

Fig. 17 Integrated 3D BIM model of the proposed high-rise residential building

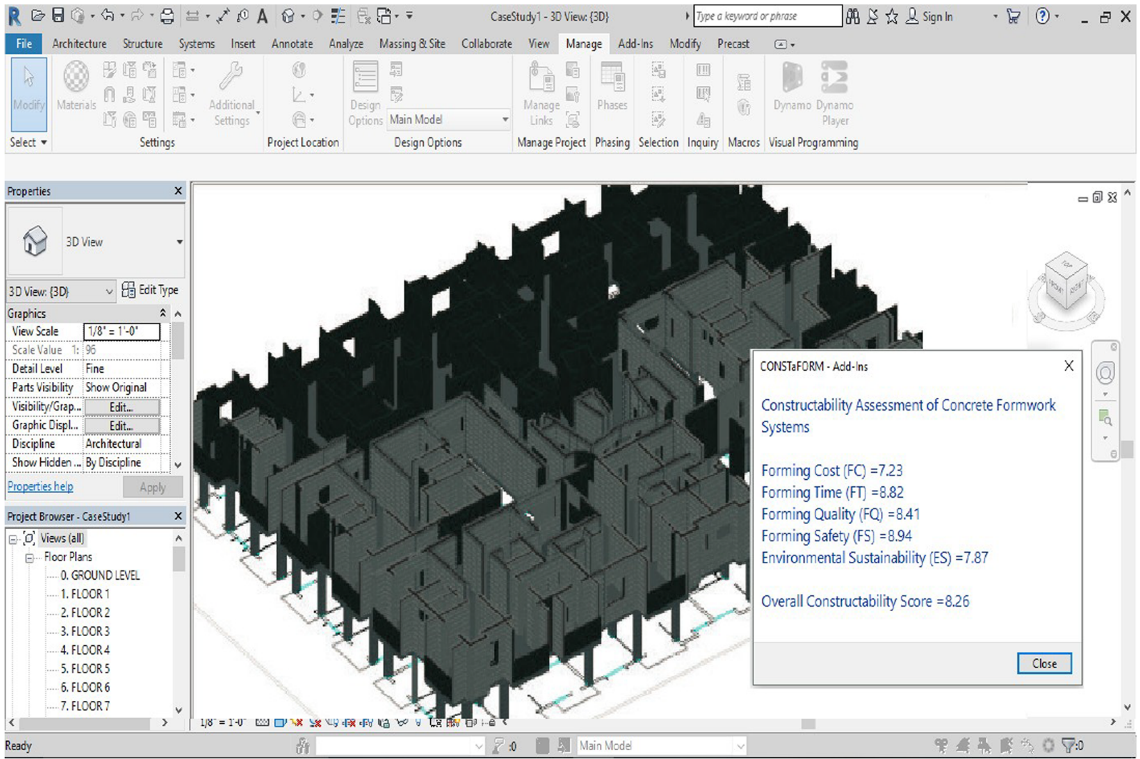

Fig. 18 Output of CONSTaFORM depicting the overall constructability score for the integrated 3D BIM Model for validation perspective

BIM Model, it is then transferred to Autodesk Revit for performing the constructability rating.

One of the advantages of the CONSTaFORM Add-in is that the outputs, i.e., the overall constructability scores as well as the constructability scores of each concrete formwork system can be exported to Microsoft Excel, MySQL and other database management systems for further data analysis.

In addition to the capabilities of incorporating parametric change characteristics, it should be incorporated in a real-time construction projects for actual advocacy and validation.

Validation

For validating the CONSTaFORM Add-in, an ad hoc testing in a real-time project is carried out. The following are some of the salient features of the real-time construction project considered for the analysis.

- 14-storied residential building as in Fig. 16
- Modular aluminium formwork system is used for the construction as illustrated in Fig. 17

The overall constructability score of concrete formwork systems for this project, obtained from the CONSTaFORM Add-in is shown in Fig. 18.

Conclusion

The CONSTaFORM Add-in developed in this research is an innovative automated constructability rating framework system for assessing constructability of different concrete formwork system. The developmental procedure adapted for CONSTaFORM Add-in, in this research, is based on various possible techniques and tools by trial and errors. From Figs. 13, 15 and 18, we infer that, the CONSTaFORM Add-in is capable of adapting in all the situations traversing from the 3D BIM models to a real-time project.

Further research

This research promulgates the interoperability of BIM for constructibility assessment of concrete formwork systems, withal this concept can be extended to incorporate in other modern reality technologies such as virtual reality, augmented reality and mixed reality so as to enhance and explore further functionalities of BIM (Boga et al. 2018). Additionally, the capabilities of BIM can be further enhanced by coupling with the open source graphical software like Dynamo (Griendling 2016), blender and so on. Additionally, the clash detection process of the 3D Integrated BIM Model (3D BIM structural + 3D BIM formwork module) is carried out externally using Autodesk Navisworks, thus, the API-fication process (customizing Navisworks API) can be incorporated in Autodesk Navisworks to synchronize with Revit API to perform the clash detection process of the integrated 3D BIM Model intermediately or simultaneously.

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Appendix

Constructability information scheme for concrete formwork systems

The detailed description of the constituents of the Constructability Information Scheme (CIS) developed for the research is given in the Table 5.

Table 5 Constructability information scheme

Criteria	Sub-criteria	Description	Notation	Category
Forming Cost (FC)				
Cost	Materials: Fabrication	This signifies the cost of fabrication of formwork systems (including cost of materials and payment to fabricators for the fabrication process) starting from the procurement of raw materials for fabrication to the final finished component/system. For example, the cost of fabrication of an engineered formwork is comparatively lesser than that of the conventional site-fabricated formwork, as the site-fabricated formwork demands maximum labour for fabrication, whereas engineered formworks are manufactured using machineries in a factory. Nowadays, robotic formwork production systems are deployed to ease the fabrication process and lower the cost of fabrication as a whole (Søndergaard 2014)	C_1 ($C\downarrow$)	Quantitative
	Materials: Transportation	This signifies the cost of transportation of materials for fabrication/assembly of formwork systems to a factory (in case of prefabricated or engineered formwork systems) or construction site (in case of site-fabricated or conventional formwork systems). The transportation cost for site-fabricated formwork systems is relatively lesser than that of prefabricated formwork systems as the latter demand alliance cost (cost of transportation of raw materials to factories) in addition to the cost of delivering the finished component/system to the construction site	C_2 ($C\downarrow$)	Quantitative
	Materials: Accessories	The cost of accessories associated with the formwork systems such as plywood sheathings, floor props, form-ties, spindles, yokes, and suspension cones. The conventional timber/wooden formwork systems require more accessories than the modular formwork systems, and hence, result in increased cost in terms of formwork accessories. However, the performance-based or special formwork systems necessitate specialized or custom-made accessories and hence, result in a drastic increase in the cost of formwork accessories	C_3 ($C\downarrow$)	Quantitative
	Construction: Erection	This signifies the cost of erection or assembly of the formwork systems within the construction premises. Engineered formwork systems are prefabricated and standardized formwork systems, and incur lesser cost as they provide maximum ease in the erection or assembly process owing to their modularization and reduced assembly components than the site-fabricated lumber formwork, which generally has additional components such as batter and yoke with unique dimensions	C_4 ($C\downarrow$)	Quantitative
	Construction: Equipment	This signifies the cost of equipment required for handling formwork systems during construction. Mechanized formwork systems (panelised formwork, gang formwork, etc.) are heavy and laborious, and hence require additional hoisting or lifting equipment as compared to lightweight aluminium modular formwork systems. In addition, the special formwork system, semi-automated climbing formwork, requires additional equipment such as a climbing cylinder and a bracket and movable spindle, besides the hoisting or lifting equipment; this increases the construction cost drastically	C_5 ($C\downarrow$)	Quantitative
	Construction: Reuse	This signifies the cost of reuse of formwork systems during the construction phase of the project. The cost of reuse for aluminium modular formwork systems is relatively much higher (100+ times) than that of the site-fabricated lumber formwork (4 times) and prefabricated timber H-Beam formwork (15 times) for constructing specified/equivalent dimensions of the same structural elements of a construction project.	C_6 ($C\downarrow$)	Quantitative
	Construction: Safety	This signifies the cost of safety or provision of a safe construction environment. The cost of safety for prefabricated formwork systems is higher than that for conventional formwork systems owing to additional provisions for safety requirements, such as inbuilt ladders and supporting decks or fall protections. However, for conventional site-fabricated formwork systems, these provisions are made separately and hence result in increased costs	C_7 ($C\downarrow$)	Quantitative
	Labour	This signifies the labour costs (wages or salaries) associated with the formwork construction. The cost of labour for engineered or mechanized formwork systems is relatively low as it requires fewer labourers for the formwork construction, whereas the number of labourers required for site-fabricated formwork is more; hence, the cost of labour for site-fabricated formworks is very high	C_8 ($C\downarrow$)	Quantitative

Table 5 (continued)

Criteria	Sub-criteria	Description	Notation	Category
Forming time (FT)				
Time	Materials: Fabrication	This signifies the time required for the fabrication of formwork systems at factories or construction sites. For example, the fabrication time required for panellised formwork systems is relatively lower than that for site-fabricated board/panel formwork systems as most of the engineered panellised formwork systems are manufactured by servo-controlled robots, which are capable of rapid prototyping; however, the site-fabricated board/panel formwork systems are generally manufactured with six carpenters per square meter of the formwork area	C_9 ($C \downarrow$)	Quantitative
	Materials: Transportation	This signifies the transportation time required for formwork systems from a factory (in case of prefabricated or engineered formwork systems) or within the construction site (in case of site-fabricated or conventional formwork systems). For site-fabricated formwork systems, the transportation time is relatively lower than that for prefabricated formwork systems as prefabricated formwork systems demand additional alliance time (time for transportation of raw materials to factory) besides the delivery time of the finished components/system to the construction site	C_{10} ($C \downarrow$)	Quantitative
	Materials: Accessories	This signifies the total time incurred in deploying accessories in the concrete formwork construction. The performance-based formwork systems, such as fabric formwork systems, consume relatively more time than modular formwork systems, owing to the increased number of components or accessories used during formwork construction. In addition, the site-fabricated formwork systems consider auxiliary accessories for safety requirements and hence consume a much longer time than engineered formwork systems, which have in-built safety accessories	C_{11} ($C \downarrow$)	Quantitative
	Construction: Erection	This signifies the total time required for the assembly or erection of formwork systems. The assembly or erection time required for modular formwork systems is comparatively much lower than that for the site-fabricated timber board formwork systems as they consider several auxiliary accessories and demand considerable effort in maintaining the verticality or eradicating plumb-off situations	C_{12} ($C \downarrow$)	Quantitative
	Construction: Equipment	This signifies the total time required for the equipment (assembly or erection equipment, lifting or hoisting equipment, and transportation equipment within the construction premises) involved in the construction of formwork systems. For constructing a slender shear wall, automatic climbing formwork systems are preferred over modular formwork systems because of their versatility in forming a large concrete surface not only monolithically (start-to-finish) but also in a relatively shorter time owing to their automation characteristics	C_{13} ($C \downarrow$)	Quantitative
	Construction: Reuse	Reuse time is one of the most important characteristics of formwork & falsework (temporary systems) construction. This signifies the total time involved in reusing (stripping from an already assembled structure for casting a structural element/unit to obtain assembled to another structural element/unit) the formwork systems within a construction project and vice versa. For casting a large-area slab structural element, table formwork systems are preferred over engineered shore-based slab formwork systems owing to their decreased shoring/stripping time and enhanced assembly and transportation capability	C_{14} ($C \downarrow$)	Quantitative
	Construction: Safety	This signifies the time involved in the stoppage of formwork construction due to unexpected incidents pertaining to the safety of equipment and labourers. There is no formwork system (ideal formwork system) whose degree of safety is 100%; each formwork system has some merits and demerits pertaining to safety, and the safety of the formwork systems is enhanced by the construction personnel based on their previous experience and knowledge through trial and error.	C_{15} ($C \downarrow$)	Quantitative
	Labour	This is also referred to as 'labour Constant', i.e., the total time, which includes primary (main), ancillary times (directly contributing to the progress of formwork construction and fitting of formwork systems, accessories and extra-time for recesses, and fixtures and stop-ends), and other contingency allowances. For example, for a specified dimension of slab formwork construction, the labour constant for the table formwork system is 0.20–0.26 h/m^2, while that for the H-beam slab formwork system is 0.36–0.45 h/m^2. The increased labour constant of the H-beam slab formwork system is due to the additional time required to assemble/strip individual H-beam elements in a panel	C_{16} ($C \downarrow$)	Quantitative

Table 5 (continued)

Criteria	Sub-criteria	Description	Notation	Category
Forming quality (FQ)				
Quality	Material: Fabrication	The quality of fabrication of formwork elements depends on not only the quality of the raw materials deployed but also the techniques used in the manufacturing of formwork elements. The formwork elements manufactured in the factory, known as 'engineered formwork' show superior quality in comparison to the site-fabricated formwork elements owing to the increased degree of homogeneity in manufacturing of formwork systems in a factory	C_{17} ($B\uparrow$)	Qualitative
	Material: Transportation	This signifies the quality of the transportation process of materials/elements (including transportation of raw materials, assembly/erection, and hauling) for concrete formwork construction. For example, the quality of transportation of mechanized gang formwork construction is very high in comparison to that of engineered formwork systems as it is generally transported as a single unit	C_{18} ($B\uparrow$)	Qualitative
	Material: Accessories	The quality of the forming accessories in-turn increase the fixity and stability of the overall formwork systems, which invariably enhances the structural integrity and provides the maximum factor of safety during formwork construction. For example, the quality of the suspension cone, an accessory used for climbing formwork systems, alone contributes to the maximum structural integrity, and despite the cost, its significance is irreplaceable during vertical formwork construction	C_{19} ($B\uparrow$)	Qualitative
	Construction: Erection	The quality of the erection process of the concrete formwork systems depends on the utilization of highly mechanized transportation and lifting or hoisting equipment. For example, the verticality of the slender concrete structural elements depends mainly on the erection process than the actual forming surface of the formwork systems; thus, monolithic formwork systems are used predominantly for casting symmetrical multiple segments rather than other engineered formwork systems	C_{20} ($B\uparrow$)	Qualitative
	Construction: Equipment	The use of automated equipment in formwork construction results in maximum quality of the finalized concrete structural elements. For example, an automated climbing formwork system produces higher-quality finished slender concrete structural systems (e.g., shear walls) for multi-storied buildings than other formwork systems owing to its in-built impeccable automation characteristics	C_{21} ($B\uparrow$)	Qualitative
	Construction: Reuse	The quality of reuse describes the quantum of effective repetition/utilization of the formwork systems for the construction of similar structural elements in a project. The grade of the finished concrete surface formed using modular formwork systems is superior to that of other gang formwork systems because a modular formwork exhibits high versatility in terms of repetition (reuse) and unblemished operation	C_{22} ($B\uparrow$)	Qualitative
	Construction: Safety	This signifies the creation of a no-harm environment in formwork construction, indicating that the proliferation of construction accidents can be deliberately minimized by paying careful attention to potential harmful, damage, rework, and invariably safety aspects pertaining to the project (Wanberg et al. 2013; Love et al. 2016). Despite the cost, the quality of safer working conditions provided by the system formwork makes it unique and superior in comparison to other conventional formwork systems	C_{23} ($B\uparrow$)	Qualitative
	Labour	Quality of labour does not mean that the employment of skilled labour in formwork construction enhances the quality of construction. It is generally circumscribing the utilization of labour for formwork construction. For example, light-weight aluminium modular formwork systems require fewer labourers and produces higher-quality finished concrete structural elements owing to the inherent characteristics of the formwork systems to accelerate the ease of handling for the labourers as compared to other formwork systems	C_{24} ($B\uparrow$)	Qualitative
Forming safety (FS)				
Safety	Material: Fabrication	This signifies the incorporation of safer techniques or methods in the fabrication of formwork systems and accessories. Besides the application of digital prototyping and lean manufacturing in engineered (factory-made) formwork systems, it produces highly safe formwork systems or accessories to be used in multifarious formwork construction. Despite the ergonomics, the serviceability and durability of engineered metallic gang formwork systems are very high in comparison to those of modular formwork systems	C_{25} ($B\uparrow$)	Qualitative

Table 5 (continued)

Criteria	Sub-criteria	Description	Notation	Category
	Material: Transportation	This signifies safety in the process of transportation of formwork systems via inter- and intra-construction project locations (sites). The process of transportation within the construction site plays a crucial role as it has a direct relation with most other in situ formwork constructions. The mechanized formwork systems play a crucial role in the transportation of formwork systems; at present, movable formwork systems have gained much popularity over carried or hoisted formwork systems owing to their ease of operation and transport (Kim et al. 2014)	C_{26} ($B\uparrow$)	Qualitative
	Material: Accessories	This signifies the safety pertaining to the accessories or supplementary elements associated with the main formwork systems. Safety of the formwork system accessories is very important and crucial as most formwork failures reported are due to malfunctioning or defects in the accessories or components rather than the design or structural failure of entire formwork systems. For instance, the size of the suspension cone is negligible when compared to the entire size of the climbing formwork; however, it is the prime accessory that carries both the massive formwork system and the immense loads that can possibly encounter the formwork systems; thus, failure of this would certainly result in disproportionate collapse, and hence, safety consideration of this accessory is highly contemplated	C_{27} ($B\uparrow$)	Quantitative
	Construction: Erection	This signifies the safety pertaining to the assembly or erection process of formwork systems. An automated or mechanised engineered formwork system is much safer than a conventional manually assembled formwork system owing to its reduced complexity and dexterity in the assembling process	C_{28} ($B\uparrow$)	Qualitative
	Construction: Equipment	This signifies the safety pertaining to the choice and use of equipment for formwork construction. Thus, for the construction of vertical slender structural elements, an automated climbing formwork system is preferred over a hoisted climbing formwork for not only increasing the forming time but also incorporating safety (avoiding 'fall from height') in the forming process	C_{29} ($B\uparrow$)	Qualitative
	Construction: Reuse	This signifies the safety aspects pertaining to the reuse of the formwork systems. A formwork system not has high reuse value but also holds good for safety aspects pertaining to it in comparison to conventional formwork systems	C_{30} ($B\uparrow$)	Qualitative
	Construction: Safety	This signifies the overall safety aspects of the formwork construction. It is a prime factor that can influence the cost and quality aspects of the overall formwork construction	C_{31} ($B\uparrow$)	Qualitative
	Labour	The safety of labourers demarcates the potential criteria of construction injuries or accidents (rate of injury or accidents, level of intensity of the accidents, etc.) associated with the working of various formwork systems. In addition to the stoppage time in formwork construction due to an injury or accident, an unsafe working condition for labourers will have a negative propensity toward the overall productivity of the formwork construction. The modular formwork system exhibits higher productivity over other formwork systems owing to its provision of safer working conditions to the labourers	C_{32} ($B\uparrow$)	Qualitative
Environmental sustainability (ES)				
Sustain-ability	Material: Fabrication	The process of fabrication, which involves less wastage of raw materials and other related materials, is considered an environmentally sustainable process since it deceases the negative environmental impacts and enhances the 6Rs (Reuse, Recover, Recycle, Redesign, Reduce, and Remanufacture) strategy (Chen et al. 2010)	C_{33} ($B\uparrow$)	Qualitative
	Material: Transportation	The process involves minimum total fuel used for the entire transportation process (including material handling, hauling, and other logistics) of the formwork systems. The amount of transportation fuel required for modular formwork construction is much lesser than that required for site-fabricated timber formwork systems owing to increased construction efficiency by modularization and decreased back-shoring	C_{34} ($B\uparrow$)	Qualitative
	Material: Accessories	The increased number of auxiliary accessories in formwork systems does not only result in increased complexity of formwork construction but also conceives maximal wastage. For example, the increased sustainability of heavy formwork construction by gang formwork systems in comparison to a system formwork is because of fewer accessories	C_{35} ($B\uparrow$)	Qualitative
	Construction: Erection	This deals with the sustainability aspects involved in the assembly/erection process of concrete formwork systems. For example, the sustainability of aluminium modular formwork systems is much higher than that of metallic steel gang formwork systems owing to its increased degree of operability and maintainability	C_{36} ($B\uparrow$)	Qualitative

Table 5 (continued)

Criteria	Sub-criteria	Description	Notation	Category
	Construction: Equipment	The process of deploying main and auxiliary equipment depends purely on the complexity and dexterity of formwork construction itself. The application of equipment for formwork construction demands additional fuel and other required resources, and hence, decreased degree of sustainability. For example, the automatic climbing formwork systems suffer seriously on sustainability aspects of formwork construction in comparison to gang formwork systems due to increased mechanization	C_{37} ($B\uparrow$)	Qualitative
	Construction: Reuse	An increased number of reuse of formwork systems leads to a decreased degree of wastage. For example, aluminium formwork systems appear to be costlier than site-fabricated timber formwork systems, but when considering the reuse characteristics, the amount of reuse is much higher, and hence, results in decreased wastage/scraps	C_{38} ($B\uparrow$)	Qualitative
	Construction: Safety	This describes the nature of safety pertaining to sustainability aspects of concrete formwork constructions. For example, the light-weight aluminium adjustable shore slab formwork systems help in achieving superlative workmanship and increased ergonomics for construction workers than those working with the conventional metallic shore slab formwork systems	C_{39} ($B\uparrow$)	Qualitative
	Labour	Provision of a safer environment is necessary for any construction worker. However, the nature of the construction environment is highly unpredictable and the degree of safety inbuilt inside the formwork systems, which eradicates such unsafe working condition by itself, is highly regarded. For example, the degree of safety of the formwork system is much higher than that of site-fabricated timber formwork systems owing to increased inbuilt safety provisions	C_{40} ($B\uparrow$)	Qualitative

Constructability survey template

The Table 6 is an actual reproduction of the form/template entitled ‘Constructability Survey’ used to obtain responses and collate intuitive feedback from various construction personnel associated with structural and formwork construction at various construction sites for this research purpose.

Table 6 Constructability Survey-Form

1.	Name of the Respondent (Optional)	:	____________________
2.	Designation	:	□ Architect □ Fabricator □ Planning ○ Construction ○ Formwork □ Engineer □ Design ○ Structural ○ Formwork □ Const. ○ Structural ○ Formwork □ Contractor ○ Construction ○ Formwork □ Other
3.	Name of the Company or Organization (Optional)	:	____________________
4.	Name of the Construction Project	:	____________________
5.	Location of the Construction Project	:	____________________
6.	Type of Construction	:	□ Cast-in-situ Construction □ Prefabricated Construction
7.	Total Area of Construction (in m^2)	:	□ ≤ 2,000 m^2 □ 2,001 to 5,000 m^2 □ 5,001 to 9,300 m^2 □ 9,301 to 18,600 m^2 □ 18,601 to 25,000 m^2 □ ≥ 25,001 m^2
8.	Total Number of Storey (in Nos.)	:	□ ≤ 06 □ 07 to 15 □ 16 to 25 □ 26 to 45 □ 46 to 85 □ ≥ 86
9.	Total Height of Structure (≈ in m)	:	□ ≤ 25.0 m □ 25.1 m to 65.0 m □ 65.1 m to 105.0 m □ 105.1 m to 185.0 m □ 185.1 m to 345.0 m □ ≥ 345.1 m
10.	Total Construction Time (in years)	:	□ ≤ 2.0 years □ 2.1 to 4.0 years □ 4.1 to 6.0 years □ 6.1 to 8.0 years □ 8.1 to 10.0 years □ ≥ 10.1 years
11.	Construction Cycle Time (in days per floor*)	:	□ < 1 day/floor □ 1 to 3 days/floor □ 4 to 7 days/floor □ 8 to 14 days/floor □ 15 to 21 days/floor □ > 21 days/floor
12.	Type of Formwork Systems	:	(Refer Fig. 1 & Table 1)
a)	For structural beam elements	:	____________________
b)	For structural slab elements	:	____________________
c)	For structural column elements	:	____________________
d)	For structural wall elements	:	____________________

Table 6 continued

e)	For other structural elements (eg: structural foundations, staircases (inclined), modular & monolithic structural elements and so on.)	:	______________________
Please rate the following constructability criteria & sub-criteria on a eleven points rating scale as follows: 0 - Extremely Low, 1 - Very Low, 2 - Low, 3 - Moderately Low, 4 - Slightly Low, 5 - Neutral, 6 - Slightly High, 7 - Moderately High, 8 - High, 9 - Very High and 10 - Extremely High			
13.	Forming Cost (FC)†		
i)	Material: Fabrication	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
ii)	Material: Transportation	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
iii)	Material: Accessories	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
iv)	Construction: Erection	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
v)	Construction: Equipment	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
vi)	Construction: Reuse	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
vii)	Construction: Safety	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
viii)	Labour	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
14.	Forming Time (FT)†		
i)	Material: Fabrication	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
ii)	Material: Transportation	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
iii)	Material: Accessories	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
iv)	Construction: Erection	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
v)	Construction: Equipment	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
vi)	Construction: Reuse	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
vii)	Construction: Safety	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
viii)	Labour	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
15.	Forming Quality (FQ)‡		
i)	Material: Fabrication	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
ii)	Material: Transportation	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
iii)	Material: Accessories	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
iv)	Construction: Erection	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
v)	Construction: Equipment	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
vi)	Construction: Reuse	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
vii)	Construction: Safety	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
viii)	Labour	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
16.	Forming Safety (FS)‡		
i)	Material: Fabrication	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
ii)	Material: Transportation	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
iii)	Material: Accessories	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
iv)	Construction: Erection	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
v)	Construction: Equipment	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
vi)	Construction: Reuse	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
vii)	Construction: Safety	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
viii)	Labour	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
17.	Environmental Sustainability (ES)‡		
i)	Material: Fabrication	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
ii)	Material: Transportation	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
iii)	Material: Accessories	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
iv)	Construction: Erection	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
v)	Construction: Equipment	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
vi)	Construction: Reuse	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
vii)	Construction: Safety	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10
viii)	Labour	:	□ 0 □ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10

*Considering a standard floor area of 1000 m^2 in every project as a benchmark for the comparison and computation

†Refers to Cost Criteria, higher the value in the scale corresponds to the level of minimization in consideration of Cost Criteria since lower the better and vice-versa

‡Refers to Benefit Criteria, higher the value in the scale corresponds to the level of maximization in consideration of Benefit Criteria since higher the better and vice-versa

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