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REVIEW

Critical perspective of design collaboration: A review

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Abstract
This study reviews the issue of collaboration with respect to the manner by which it has become increasingly important in promoting a contemporary design approach. Moreover, the study aims to critically review relevant core research articles and establish the perspective of design collaboration. Furthermore, the study uses a qualitative content analysis method on 94 selected research articles that discuss the concept of design collaboration. The content analysis finds four key themes, namely, *teamwork*, *building information modeling* framework, *evidence-based design* practice, and *modality supported collaboration design*, as the proposed subjects for the examination. Further analysis reveals that majority of articles on design collaboration have focused on interdisciplinary design collaboration and teamwork using digital modalities. Meanwhile, design collaboration concentrates on the manner by which multiple designers can perform various key cognitive design characteristics, such as links, functions, behavior, structure, frame, move, evaluation, abduction, induction, and deduction. Furthermore, the main contributions, recommendations, and implications of the article are graphically presented using a statistical graph method. Finally, the study concludes that a definitive framework is lacking on the constituent parameters of design collaboration.

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Contents

1. Introduction

Contemporary conditions have encouraged growth-oriented measures that associate digital-supported collaboration with improving the efficiency of an architectural design process (Azmi et al., 2018). Accordingly, the building industry has vigorously considered the digital-supported collaboration as a remedy to the notorious profligacy of the sector. In reality, design collaboration is problematic because of the complex nature of a multidimensional cognitive interaction (Bråthen, 2015; Luyten, 2015). Thus, design collaboration might imbue highly differentiated types of strategy through which designers can constructively share their differences and environment to search for a common goal that is beyond individual vision. This article focuses on a critical perspective of digital-supported collaboration practice in a highly complex cognitive activity, such as design.

Design is considered a highly cognitive process (Goldschmidt and Weil, 1998; Lawson, 1979, 1997, 2002, 2004 and 2006; Schön, 1983; Valkenburg and Dorst, 1998; Dorst, 2011; Goel, 1994). Issues pertaining to design collaboration might imbue highly differentiated types of approach that can support integrated framing, reflecting, critical moving, behavior, and reasoning among designers in search of a common design goal. Migilinskas et al. (2013) highlighted that the rigidity of team problem-solving of the digital modalities is the major barrier to the successful integration of digital-supported collaboration into a silo-oriented design practice. Many authors have underlined that the new approach is still obscured due to the flexible nature of a conventional method and significant investments required (Leonard-Barton, 1992; Oxman, 2006; Eadie et al., 2013; Azmi et al., 2018). Even though Jonson (2005) reported that the speed of the millennium will offer a more friendly digital design practice, many players still question the flexibility of digital-supported collaboration in cognitive design activities. By contrast, most research efforts support the method adoption in design practice even though the approach has no clear explanation on the effect and implication of digital-supported collaboration on various crucial design activities, such as reflecting, critical moving, behavior, and reasoning. For example, Froese (2010) stressed that digitalization and collaboration have a direct effect on the speed, accuracy, and efficiency of the design. Similarly, Garber (2014) attested that digital modalities and collaboration can enhance conventional building design practice. Succar (2009) articulated that insufficient effective digitalization and collaboration in the conventional design process significantly affect quality, efficiency, and productivity. Similarly, Bryde et al. (2013) acknowledged that digitalization and collaboration during design stages are the ultimate contemporary catalysts that can enhance building design processes.

One of the major problems of the contemporary design approach is the manner by which conventional design activities can digitally and collaboratively be overhauled (Vaishnavi and Kuechler, 2015; Preece et al., 2015; Hardin and McCool, 2015; Kasali and Nersessian, 2015). This condition implies that digital-supported design collaboration has not been critically reviewed and integrated, specifically in terms of different complex issues, such as group cognitive action, reasoning, and sharing of tacit knowledge. The study focuses on the need to critically review issues in design collaboration, especially the position of various conventional cognitive design activities, such as sketching, thinking, and reasoning in the collaborative ecosystem. The privation of this effect preempts the earlier assumptions that digital-supported collaboration presumes improving building design (Mazlan et al., 2015; Preece et al., 2015). Thus, the present study conducted a critical review of 100 selected articles that have discussed issues that inculcate existing and preferred perspectives of design collaboration.

2. Method

The study aims to critically review the articles that have discussed the issues of design collaboration. More than 100 major articles on design collaboration were reviewed to assimilate and integrate their views into a collective and concise perspective. Only articles that maintain, deviate from, or propose a standpoint on the issue of design collaboration were included in the study. After a careful selection process, only 94 articles within a publication period of 32 years (1986-2018) met the selection criterion. Majority of the selected articles were downloaded under the Universiti Teknologi Malaysia ScienceDirect license access. The selected materials were reviewed and analyzed using content analysis strategy. During the content analysis, each article was coded under a theme that best describes the focus of the issue being discussed. For example, articles on loners and design teams were coded under *teamwork*. Additionally, other articles on collaboration and information

Table 1 Analysis of extant literature on perspectives of collaboration in the context of design.

Author	Year/Publisher	Research perspective	Themes	Sub-themes	Design Stage
Achten, H.H.	2002, H. Timmermans (ed.), Sixth DDSSAUP Netherlands.	Requirements for collaborative design in architecture	Teamwork	Activity	Detail
Austin, S., Steele, J., Macmillan, S., Kirby, P., & Spence, R.	2001, Design studies	Mapping the conceptual design activity of interdisciplinary teams	Teamwork	Activity	Concept
Azmi, N. F., Chai, C. S., and Chin, L. W.	2018, 21st ISSACMRE	Building Information Modeling (BIM) in AEC Case Study in Malaysia	BIM	Management	Detail
Boud, D., Cohen, R. and Sampson, J.	1999, Assessment & evaluation in higher education	Peer learning and assessment	Teamwork	Activity	Concept
Bråthen, K.	2015, Procedia Economics and Finance	Collaboration with BIM - Learning in the Norwegian Industry	BIM	Management	Detail
Bryde, D., Broquetas, M., & Volm, J. M.	2013, International journal of project management	The project benefits of building information modeling (BIM)	BIM	Management	Detail
Chau, K. W., Anson, M., & Zhang, J. P.	2005, Automation in construction,	4D dynamic construction management and visualization software	MSCD	Activity	Detail
Chen, P. H., Cui, L., Wan, C., Yang, Q., Ting, S. K., & Tiong, R. L.	2005, Automation in construction	Implementation of IFC-based web server for collaborative building design	MSCD	Activity	Detail
Cheng, N. Y. W.	2003, Automation in Construction	Approaches to design collaboration research	Teamwork	Activity	Detail
Cheng, N., & Kvan, T.	2000, Fifth ICCDDSSA, Ampt van Nijkerk	Design collaboration strategies	Teamwork	Activity	Detail
Chiu, ML.	2002, Design studies.	An organizational view of design communication in design collaboration	Teamwork	Activity	Detail
Chung, J. K., Kumaraswamy, M. M., & Palaneeswaran, E.	2009, Automation in construction	Improving megaproject briefing through enhanced collaboration with ICT	MSCD	Activity	Detail
Craig, D. L., & Zimring, C.	2002, Automation in construction	Support for collaborative design reasoning in shared virtual spaces	MSCD	Activity	Detail
Cross, N., & Cross, A. C.	1995, Design studies	Observations of teamwork and social processes in design	Teamwork	Activity	Concept
Danfulani, B. I., & Anwar, M. K. K.	2015, Advanced Science Letters	Design-Based Learning a Dichotomy of Problem-Based Learning	Teamwork	Activity	Concept
Dave, B., and Koskela, L.	2009, Automation in construction	Collaborative knowledge management - A construction case study	Teamwork	Activity	Detail
Dong, A.	2005, Design Studies	The latent semantic approach to studying design team communication	Teamwork	Activity	Detail
Eadie, R., Browne, M., Odeyinka, H., McKeown, C., and McNiff, S.	2013, Automation in Construction	BIM implementation throughout the UK construction project lifecycle	BIM	Management	Detail
Eris, O., Martelaro, N., and Badke-Schaub, P.	2014, Design Studies	A comparative analysis of multimodal communication during design sketching	MSCD	Activity	Detail
Feast, L.	2012, CoDesign	Professional perspectives on collaborative design work	Teamwork	Activity	Detail
Fernando, T. P., Wu, K. C., and Bassanino, M. N.	2013, Journal of Information Technology in Construction	Designing a novel virtual collaborative environment to support collaboration in design review meetings	MSCD	Activity	Detail
Froese, T. M.	2010, Automation in construction	The impact of emerging information technology on project management for construction	MSCD	Activity	Detail

Fruchter, R.	2003, Proceedings 2nd Social Intelligence Design	Degrees of Engagement in Interactive Workspaces	MSCD	Activity	Detail
Gabriel, G. C., and Maher, M. L.	2002, Automation in construction	Coding and modeling communication in architectural collaborative design	Teamwork	Activity	Detail
Gabriel, G., & Maher, M. L.	2000, Springer, London.	An analysis of design communication with and without computer mediation	MSCD	Activity	Detail
Garber, R.	2014, John Wiley and Sons.	BIM Design: Realising the Creative Potential of Building Information Modeling	BIM	Management	Detail
Garner, S., & Mann, P.	2003, Automation in construction	Interdisciplinarity: perceptions of the value of computer-supported collaborative work in design	MSCD	Activity	Detail
Goldschmidt, G.	1995, Design Studies	The designer as a team of one	Teamwork	Activity	Concept
Grilo, A., & Jardim-Goncalves, R.	2010, Automation in Construction	Value proposition on interoperability of BIM and collaborative working environments	BIM	Management	Detail
Gross, M. D., Do, E. Y. L., McCall, R. J., Citrin, W. V., Hamill, P., Warmack, A., & Kuczun, K. S.	1998, Automation in Construction	Collaboration and coordination in architectural design: approaches to computer mediated team work	MSCD	Activity	Detail
Gu, N., Kim, M. J., & Maher, M. L.	2011, Automation in Construction	Technological advancements in synchronous collaboration in 3D virtual worlds and tangible user interfaces on architectural design	MSCD	Activity	Detail
Gül, L. F., & Maher, M. L.	2007, Proceedings IASDR 2007	Understanding design collaboration: Comparing face-to-face sketching to designing in virtual environments	MSCD	Activity	Concept
Hamilton, D. K.	2003, Healthcare Design	The four levels of evidence-based practice	EBD	Management	Concept
Han, Z., Lei, C., & Yang, J.	2006, Data Analysis and Knowledge Discovery	Finding the Potential Opportunities for Collaboration between Two Organizations by Noninteractive Literature-based Knowledge Discovery	Teamwork	Activity	Detail
Hardin, B., & McCool, D.	2015, John Wiley & Sons	BIM and construction management: proven tools, methods and workflows	BIM	Management	Detail
Hong, S. W., Jeong, Y., Kalay, Y. E., Jung, S., & Lee, J.	2016, CoDesign	Enablers and barriers of the multi-user virtual environment for exploratory creativity in architectural design collaboration	MSCD	Activity	Concept
Hord, S. M.	1986, Educational Leadership	A synthesis of research on organizational collaboration	Teamwork	Activity	Detail
Huxham, C.	1996, Ed. Sage.	Creating collaborative advantage	Teamwork	Activity	Detail
Ibrahim, R., & Rahimian, F. P.	2010, Automation in Construction	Comparison of CAD and manual sketching tools for teaching architectural design	MSCD	Activity	Concept
Idi, D. B., & Khaidzir, K. A. M.	2016, World Applied Sciences Journal	Collaborative Facets in Design Learning for Potential Adoption in the Architectural BIM Studio	BIM	Management	Detail
Isikdag, U., and Underwood, J.	2010, Automation in Construction	Two design patterns for facilitating Building Information Model-based synchronous collaboration	BIM	Management	Detail
Jeng, T. S., & Eastman, C. M.	1998, Automation in Construction	A database architecture for design collaboration	MSCD	Activity	Detail
Johansson, P., & Popova, S.	1998, Springer, Berlin, Heidelberg.	Case-based design process facilitating collaboration and information evolution.	MSCD	Activity	Detail
Jutraž, A., & Zupančič, T.	2014, IGRA Ustvarjalnosti (IU)/Creativity Game (CG)–Theory and Practice of Spatial Planning	The Role of architect in Interdisciplinary Collaborative Design Studios	Teamwork	Activity	Detail
Kalay, Y. E.	1998, Automation in construction		MSCD	Activity	Detail

Table 1 (*continued*)

Author	Year/Publisher	Research perspective	Themes	Sub-themes	Design Stage
		P3: Computational environment to support design collaboration			
Kalay, Y. E.	2001, Automation in Construction	Enhancing multi-disciplinary collaboration through semantically rich representation	MSCD	Activity	Detail
Kalay, Y. E., Khemlani, L., and Choi, J. W.	1998, Automation in construction	An integrated model to support distributed collaborative design of buildings	MSCD	Activity	Detail
Kan, J. W. and Gero J. S.	2010, international conference of CAADRIA	Studying Designers' Behavior in Collaborative Virtual Workspaces Using Quantitative Methods	MSCD	Activity	Concept
Kan, W. T., and Gero, S. J.	2011, Proceedings of the 3rd ICORD Bangalore, India,	Learning to Collaborate During Team Designing: Quantitative Measurement	Teamwork	Activity	Concept
Kasali, A., & Nersessian, N. J.	2015, Design Studies	Architects in interdisciplinary contexts: Representational practices in healthcare design	Teamwork	Activity	Detail
Kvan, T.	2000, Automation in construction	Collaborative design: what is it?	MSCD	Activity	Detail
Kvan, T., Vera, A., & West, R.	1997, Proceedings of 2nd CSCW, International Academic Publishers, Beijing	Expert and situated actions in collaborative design	Teamwork	Activity	Concept
Lahti, H., Seitamaa-Hakkarainen, P., and Hakkarainen, K.	2004, Design Studies	Collaboration patterns in computer-supported collaborative designing	MSCD	Activity	Detail
Lee, J., and Jeong, Y.	2012, Computer-aided design	User-centric knowledge representations based on ontology for AEC design collaboration	MSCD	Activity	Detail
Leon, M., Laing, R., Malins, J., and Salman, H	2015, WIT Transactions on The Built Environment	Making collaboration work: application of a Conceptual Design Stages Protocol for pre-BIM stages	BIM	Management	Concept
Leonard-Barton, D.	1992, Strategic management journal,	Core capabilities and core rigidities: A paradox in managing new product development	Teamwork	Activity	Detail
Luyten, L.	2015, Real Time-Proceedings of the 33rd eCAADe, Vienna	CAAD and Conceptual Design Collaboration between Architects and Structural Engineers	MSCD	Activity	Concept
Maher L. M., Anna Cicognani, and Simeon Simoff.	1998, International Journal of Design Computing	An experimental of computer mediated collaborative design	MSCD	Activity	Detail
Maher, M. L., Liew, P. S., Gu, N., & Ding, L.	2005, Automation in Construction	An agent approach to supporting collaborative design in 3D virtual worlds	MSCD	Activity	Detail
Mathews, M.	2013, Journal of Engineering, Design and Technology	BIM collaboration in student architectural technologist learning	BIM	Management	Detail
Mazlan, K. S., Khoo, L. M. S., & Jano, Z.	2015, Asian Social Science	Designing an eportfolio conceptual framework to enhance written communication skills among undergraduate students	MSCD	Modality	Concept
McCall, R., & Johnson, E.	1997, Automation in Construction	Using argumentative agents to catalyze and support collaboration in design	MSCD	Activity	Detail
McMillan, J. H., and Schumacher, S.	2010, MyEducationLab Series. Pearson	Research in Education: Evidence-Based Inquiry	EBD	Management	Concept
Migilinskas, D., Popov, V., Juocevicius, V., and Ustinovichius, L.	2013, Procedia Engineering	The benefits, obstacles and problems of practical BIM implementation	BIM	Management	Detail

Mitcham, C.	1995, Science and Engineering Ethics	Computers, information and ethics: A review of issues and literature	MSCD	Activity	Detail
Neghab, A. P., Etienne, A., Kleiner, M., & Roucoules, L.	2015, Computers in Industry	Performance evaluation of collaboration in the design process: Using interoperability measurement	MSCD	Activity	Detail
Oh, M., Lee, J., Hong, S. W., and Jeong, Y.	2015, Automation in Construction	Integrated system for BIM-based collaborative design	BIM	Management	Detail
Olatunji, O. A.	2011, Journal of Financial Management of Property and Construction	Modeling the costs of corporate implementation of building information modeling	BIM	Management	Detail
Plume, J., & Mitchell, J.	2007, Automation in Construction	Collaborative design using a shared IFC building model - Learning from experience	MSCD	Activity	Detail
Preece, J., & Rombach, H. D.	1994, International journal of human-computer studies	A taxonomy for combining software engineering and human-computer interaction measurement approaches: towards a common framework	MSCD	Activity	Concept
Preece, J., Sharp, H., Rogers, Y.	2015, John Wiley & Sons.	Interaction Design-beyond human-computer interaction	MSCD	Activity	Detail
Rahimian, F. P. and R. Ibrahim	2011, Design Studies	Impacts of VR 3D sketching on novice designers' spatial cognition in collaborative conceptual architectural design	MSCD	Activity	Concept
Rahman, N., Cheng, R., and Bayerl, P. S.	2013, Design Studies	Synchronous versus asynchronous manipulation of 2D-objects in distributed design collaborations: Implications for the support of distributed team processes	MSCD	Activity	Concept
Ren, Z., Yang, F., Bouchlaghem, N. M., and Anumba, C. J.	2011, Automation in Construction	Multi-disciplinary collaborative building design - A comparative study between multi-agent systems and multi-disciplinary optimisation approaches	MSCD	Activity	Detail
Rosenman, M. A., Smith, G., Maher, M. L., Ding, L., and Marchant, D.	2007, Automation in Construction	Multidisciplinary collaborative design in virtual environments	MSCD	Activity	Detail
Rosenman, M., & Wang, F.	2001, Automation in Construction	A component agent-based open CAD system for collaborative design	MSCD	Activity	Detail
Schmitt, G.	1998, In Artificial Intelligence in Structural Engineering Springer, Berlin, Heidelberg.	A new collaborative design environment for engineers and architects	MSCD	Activity	Detail
Skopp, N. A., Workman, D. E., Adler, J. L., & Gahm, G. A.	2015, International Journal of Human-Computer Interaction	Analysis of Distance Collaboration Modalities: Alternatives to Meeting Face-to-Face	MSCD	Activity	Detail
Sonnenwald, D. H.	1996, Design studies	Communication roles that support collaboration during the design process	Teamwork	Activity	Detail
Stahl, G.	2006, Scripting computer-supported collaborative learning	Scripting group cognition: The problem of guiding situated collaboration	Teamwork	Activity	Concept
Stempfle, J., and Badke-Schaub, P.	2002, Design studies	Thinking in design teams - an analysis of team communication	Teamwork	Activity	Concept
Succar, B.	2009, Automation in construction	Building information modeling framework: A research and delivery foundation for industry stakeholders	BIM	Management	Detail
Tang, M. X., & Frazer, J.	2001, Automation in Construction	A representation of context for computer supported collaborative design.	MSCD	Activity	Detail
Vaishnavi, V. K., & Kuechler, W.	2015, Crc Press.	Design science research methods and patterns: innovating information and communication technology	MSCD	Activity	Detail
Valkenburg, R. and K. Dorst	1998, Design Studies	The reflective practice of design teams	Teamwork	Activity	Concept
Veeramani, D., Tserng, H. P., & Russell, J. S.	1998, Automation in Construction	Computer-integrated collaborative design and operation in the construction industry	MSCD	Activity	Detail

Table 1 (continued)

Author	Year/Publisher	Research perspective	Themes	Sub-themes	Design Stage
Vera, A. H., Kvan, T., West, R. L., & Lai, S.	1998, SIGCHI ACM Press/Addison-Wesley Publishing	Expertise, collaboration and bandwidth	Teamwork	Activity	Detail
Wang, J., Chong, H. Y., Shou, W., Wang, X., and Guo, J.	2014, ICCDVE Springer International Publishing.	BIM-Enabled Design Collaboration for Complex Building	BIM	Management	Detail
Wang, X., & Dunston, P. S.	2013, Visualization in Engineering	Tangible mixed reality for remote design review: a study on understanding user perception and acceptance	MSCD	Activity	Detail
Wiltschnig, S., Christensen, B. T. and Ball, L. J.	2013, Design Studies	Collaborative problem-solution co-evolution in creative design	Teamwork	Activity	Concept
Woo, S., Lee, E., & Sasada, T.	2001, Automation in Construction	The multiuser workspace as the medium for communication in collaborative design	MSCD	Activity	Detail
Xue, X., Shen, Q., Fan, H., Li, H. and Fan, S.	2012, Automation in Construction	IT supported collaborative work in A/E/C projects: A ten-year review	MSCD	Activity	Detail
Yan-chuen, L., Phil, M., & Gilleard, J. D.	2000, Automation in construction	Refurbishment of building services engineering systems under a collaborative design environment	MSCD	Activity	Detail
Zolin, R., Hinds, P. J., Fruchter, R., & Levitt, R. E.	2004, Information and Organization	Interpersonal trust in cross-functional, geographically distributed work: A longitudinal study	MSCD	Activity	Detail

production, management, and implementation were coded under *building information modeling (BIM)*. Furthermore, four themes (perspectives) of design collaboration emerged after conducting the content analysis on all the selected articles. As shown in Table 1, the four themes identified are *teamwork*, *BIM*, *evidence-based design* (*EBD*) practice, and *modality supported collaboration design* (*MSCD*). As stipulated in the aim of the study, the established themes represent the current perspectives of extant literature on design collaboration.

However, in some instances, one article repeatedly discussed more than one theme. In such a situation, the article had two themes. Thus, detailed description and implications of each theme are presented in the next section. As shown in the coded themes, one of the more distinctive perspectives of the literature on design collaboration is computer support followed by teamwork. However, a direct reference to several issues regarding the definition of design collaboration, such as the need for computer support and collective teamwork, is particularly basic because it was unable to indicate the abilities required in design collaboration. Consequentially, the results (themes) are critically reviewed in the subsequent sections. A summary of the results provides our perspective on the reviewed literature and the actual abilities needed in design collaboration.

The identified themes include some sub-themes and the design phase, as shown in the fourth and fifth columns of Table 1. The sub-themes are *design activity and design management process*. The design phase includes concept and detail. For example, articles that focus on *activities* or *modality* or both in an article are mostly working design *teamwork*. Similarly, most articles on design collaboration in the BIM framework emphasize on the *design management process* aspects of design collaboration. Moreover, articles on issues of EBD practice are associated with the management of design collaboration, such as conferences, workshops, seminars, and peer reviewing in design practice. Finally, the overall context of the articles is premised on either the concept or detailed design phase.

3. Findings

Here, the outcome of the content analysis is presented in line with the four themes identified. Each section of the findings covers one of the identified themes. At the end of each section, a summary of the theme on the abilities needed in design collaboration is presented. A graphical illustration is also presented to depict the review exercise at the end of each section.

3.1. BIM — a collaboration design framework

The BIM is one of the themes identified with respect to the issues of design collaboration during the content analysis of the selected articles, as shown in Table 1. The word "collaboration" in the BIM framework is defined as a process in which different actors collaboratively manage the production information of a building. The major function of the BIM concept is collaborative information management using technology. The collaborative process is supported by a software platform that allows different stakeholders to work simultaneously on a single building information model. The information model holds multidimensional digital data that are embedded within the production information of the building. Various integral software functions, such as single digital modeling, fabrication, and assembly, are referred to as BIM authoring, and animation and simulation are denoted as BIM analysis. Authoring and analysis are the major functions of software technologies according to the BIM practice (Garber, 2014). These authoring and analysis software technologies are described as the major game-changers for the new design and construction practices.

Mitcham (1995) attested that the software technologies provide hyper-computer mediated authoring and analysis approaches for virtual information processing and management during integrated project delivery (IPD). During the IPD, stakeholders have to resolve issues as if they were working on the real one. All the building design and construction processes are virtual models similar to real-life conditions. Many BIM-based scholars share the views of Mitcham by considering the ability to integrate and support multiple stakeholders into the main function of the BIM-based collaborative design practice (Vaishnavi and Kuechler, 2015; Preece et al., 2015; Hardin and McCool, 2015). Mathews (2013) analyzed the potential of collaboration supporting technologies in a studio learning environment. The research explored the potential benefits of collaborative learning supported by a BIM application in studio-based learning using a qualitative case study methodology for six architectural students and one design tutor working for 12 weeks. The study provides evidence that supports the creation of a single digital building model by a student and group in a studio-based learning environment. Jutraž and Zupančič (2014) determined the importance of interdisciplinary collaborative design studios in terms of whether architects learn anything new through interdisciplinary collaboration; and the manner by which collaboration could be improved. A total of 21 students from the architecture, engineering, and construction disciplines divided into three groups working for 6 months were observed. Result shows that incorporating interdisciplinary courses for architecture students is necessary. Isikdag and Underwood (2010) proposed a system using the BIM-based approach to facilitate a shared environment for the entire lifecycle of the building. Chung et al. (2009) improved the efficiency and reliability of shared environment during a project briefing for ICT-based megaprojects. Garber (2014) classified collaboration in BIM design into three stages, namely, architect–client collaboration, collaboration for submission, and collaboration for design check (Fig. 1).

A certain developmental process is carried out in each collaboration stage. The input and output of each collaboration stage aim to determine the layers and level of development requirements. The designer–client collaboration is the relationship among the architect, client, and design, normally at the conceptual design phase. During this phase, the designers and client have to agree on a particular model. The collaboration for submission is the next stage required for the BIM design after the client approves the model. Sharing of digital models among design teams using a technology setup allows central files to network among stakeholders wherever they may be. The concept provides a technology that enables multiple users to have input on a single shared file at one time. Each user will work on their local files before integrating those documents and checking them and finally have an integrated model that represents all individual designs. Then, the integrated model can be shared among stakeholders for updates, comments, and necessary adjustments. Thus, all BIM-based software should provide this sharing function. The collaboration for submission level incorporates a multidisciplinary file sharing of objects with accurate geometrical representation with a specific system, object, or assembly. Information related to quantity, size, shape, location, and orientation is also determined. The global model can adequately provide precise information that is required by other professionals, such as architects; civil, structural, mechanical, electrical, and plumbing (MEP) system engineers; builders; manufacturers; and project owners, who can extract and generate views and information according to their needs for further analysis and simulations on every element and system of the proposed design.

Furthermore, the object should be set for further tasks related to collaboration at this stage, such as coordination and clash detections. Moreover, the architecturally detailed model with windows and doors, which is considerably more

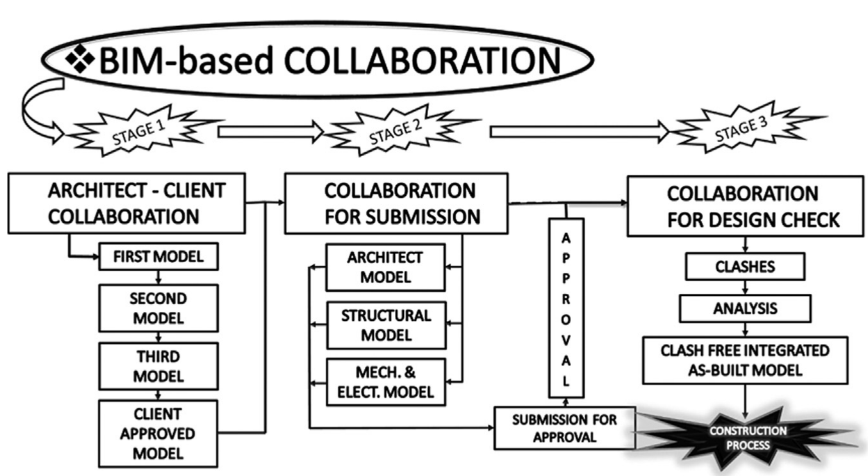

Fig. 1 BIM-based assumption of architectural collaboration design.

complex than its preceding counterpart, will be shared with other stakeholders so that they can produce their own design with accurate modeling and shop drawings, where elements are defined with specific assemblies and precise quantity, size, shape, location, and orientation. In addition, non-geometric information can be attached to the model elements. The collaboration for design check is the ability to virtually integrate architectural and structural and MEP system engineering models. The design check can detect several interdisciplinary issues, such as structural stability and construction efficiency. Checking the proposed integrated model to prevent clashes is necessary to save time, money, and waste. The design check assists in eliminating the effect of clashes before construction resumes. Similarly, the design check also analyzes issues related to energy consumption, environmental effect, and structural stability. The energy consumption through heating, cooling, lighting, and equipment operations of the proposed building can be analyzed during the design process. Buildings require adequate water for drinking, cooking, washing, cleaning, flushing toilets, and landscaping purposes. All of these water functions require high energy treated water. Additionally, the water exits from the building need substantial energy treatment. For example, the two streams of water flow, the inlet water flow into the building as input to the building ecosystem, can be analyzed and perfected during the design process. The various environmental effects, such as daylight, sun radiation, rainfall, temperature, and heat gain, on the building can also be analyzed during the design process through BIM analysis. The magnitude of environmental effect on buildings differs depending on location and orientation. Moreover, the BIM on the location and orientation of the building can be analyzed and perfected during the design process. Finally, the BIM can analyze the structural stability of the proposed building before construction.

The BIM has been a major area in the study of design collaboration on the basis of extensive literature review under this section. However, majority of BIM-based design collaboration research has been inclined to emphasize on technology and multidisciplinary team activities. Nevertheless, Garber (2014) exerted efforts to describe the role of client and designer collaboration during the conceptual design phase and reported that issues, such as the manner by which technology and collaboration affect conventional design activities (e.g., cognitive actions, reasoning, and visual transformation), also need to be further understood in line with the BIM concept.

3.2. Teamwork activities in collaboration design

Teamwork is among the themes identified during the content analysis. Studies on teamwork in design include Sonnenwald (1996) exploration on the role of design collaboration. Sonnenwald used a retrospective analysis to investigate the teamwork activities of four teams from the architectural, computer, telecommunications, and engineering disciplines. Study results have established that knowledge about communication support provides insights on the functionality of methods and tools of multidisciplinary design collaboration. Goldschmidt (1995) used a protocol study to investigate the teamwork cognitive activities of a lone designer (Dan) and a three-member design team. Goldschmidt found no significant differences between the individual and the team in the way they bring their work to fruition. Thus, the author concluded that teams have no significant advantage over individuals with regard to fulfillment of design. Cross and Cross (1995) investigated the applicability of cognitive processes during a design teamwork practice for a working period of 2 h. The study found a significant social interaction process between technical and cognitive processes among designers during design teamwork.

Valkenburg and Dorst (1998) used the protocol data of nine teams of four designers to investigate the structure of reflective practice during teamwork. The study established a reflective practice pattern of design teamwork on the basis of naming, framing, moving, and reflecting. Danfulani and Anwar (2015) described design teamwork through collaborative design learning facets in a typical design-based learning environment. Chiu (2002) conducted a comparative case study analysis on four architectural firms and four architectural design studios. Moreover, the author established that design teamwork in architectural organizations is better structured in practice than studios. Dong (2005) established that language similarities can bridge an indirect relationship in designers' minds, which then lead to a constructed and shared mental representation of design artifacts during design teamwork. Stempfle and Badke-Schaub (2002) identified the basic elements of thinking in design teamwork using protocol analysis (content and process-oriented approaches) of three design teams of six mechanical engineering students. Rahman et al. (2013) provided clear indications that the phase-specific usage of a shared object is better in a synchronous setting than in an asynchronous setting during design teamwork. Feast (2012) used 23 professional designers from 13 disciplines to develop a social interactive problem-solving support for professional teamwork.

A protocol study has been used to investigate issues of teamwork in design on the basis of extensive literature review under this section. However, various matters, such as common design teamwork goals, have not been properly investigated. Most studies were unable to extend beyond communication, technology, and environmental approaches to the design teamwork. Apart from communication, cognitive actions, thinking, and environment, studies on teamwork in design should also acknowledge transformations that emerge from stakeholders' interaction.

3.3. EBD — a collaboration design practice

The EBD practice has also been identified as a contemporary strategy that supports design collaboration (Fruchter, 2003; Zolin et al., 2004). At this level of practice, identified evidence intended for use in design is collaboratively discussed as reports or publications during various activities, such as conferences, seminars, and workshops. McMillan and Schumacher (2010) defined EBD as "the process of generating decisions based on certain evidence of information that suggests the fulfillment of the requirement of the subsequent decision-making." An evidence-based method can be used for all forms of decision-making, including design. Although most of the recent evidence-based literature has come from healthcare research, evidence-based practice is widely needed across different decision-making domains, such as design, management, and organizational and financial performance. The role of EBD is to help various stakeholders, such as design professionals, healthcare planners, and organizational managers, identify research evidence that will support the hypotheses associated with their projects. This role will help the stakeholders to identify the knowledge needed to solve their project problems. An evidence-based method can be used for all forms of decision-making, including design.

Design collaboration based on the EBD concept provides the opportunity to integrate data from various aspects, such as environmental, socio-ecological, political, and other sources during design work. This condition can lead to natural evidence-based decisions among designers and clients. Notably, the outcome of the project resembles the initial decision due to the evidence-based decisions taken by designers and clients. Designers can improve their knowledge on materials, technology, environment, and functions through EBD. Such knowledge gives them the ability to determine the various concepts that have been tested and also to understand the data and results needed in each particular design situation. This situation will allow many designers to have a foundation on which to base important decisions taken during the design process. Moreover, this condition can give designers the ability to use their understanding and findings from different domains, such as psychology, sociology, anthropology, economics, management, engineering, industrial design, client-related internet, press, industry data, conferences, and other related sources, to be integrated into their designs. Designers can adopt the research methods by deeply understanding a design, thereby producing high-quality projects with measurably excellent results to satisfy clients seeking exquisite performance from costly projects. This strategic approach to convince decision-makers to invest time and money to "build it right" can be a competitive advantage for the client and designer. Hamilton (2003) identified four levels of EBD practice, with each successive stage requiring more rigor and commitment. Fig. 2 illustrates the EBD levels of design collaboration.

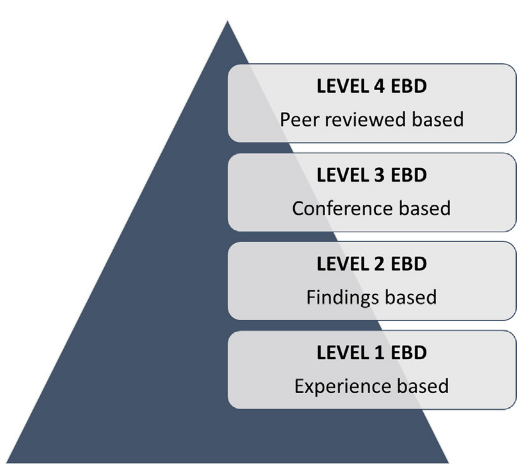

Fig. 2 EBD levels of collaboration in design.

The first level of EBD practice relies on literature to interpret evidence related to the project at hand. In this case, designers make use of design-based decisions. Moreover, designers are learning from others and developing new examples for others. The second level of EBD practice involves designers' ability to understand the research, interpret the implications, and create a chain of logic connecting the study findings and decisions. The third level of EBD practice includes designers' collaboration based on feedback from conferences or published articles. The last level of EBD practice follows all of the steps previously mentioned but attempts to obtain the research published in peer-reviewed journals. This level generally requires a licensed designer to collaborate with scholars in academic or professional settings who understand the rigor of the necessary requirements to obtain an article accepted by a journal. This study is the type of research that advances the field of evidence.

Some concerns exist that the EBD concept can limit designers' creativity and innovation due to its focus on known evidence. This situation is due to the negligence of some aspects of inventing cognitive responses with emerging evidence-based results and new facts that require no imaginative and ever-changing interpretations. Another concern is that EBD could lead to rules and limitations. However, research in design offers complex and sometimes contradictory findings and encourages continuous testing of new ideas until the best solution is achieved.

3.4. MSCD — a review

The MSCD has the highest number of publications on the issue of design collaboration. An example of such articles includes Gabriel and Maher's (2002) development of computer-mediated and communication tools for collaborative design by coding and modeling of correspondence in computer-mediated collaborative design. Gül and Maher (2007) analyzed the effect of designing in virtual collaborative design environments. The study concludes that changes in design behavior can be categorized into two: the effect of being in the same location and the effect of the type of external representation. Rahimian and Ibrahim (2011) used protocol analysis of three peers of novice architectural designers to discover that 3D haptic-based sketching technique interfaces can improve designers' cognitive and collaborative activities. Gu et al. (2011) found that technological advancements in synchronous collaboration and the effect of 3D virtual worlds, such as smart board and tangible user interfaces (TUIs), support the production of considerable perceptual events during synchronous collaboration design activities. Ibrahim and Rahimian (2010) found that computer-aided design (CAD) tools are advantageous for detailed engineering design but hinder the creativity of novice designers during collaborative design.

Kalay (1998) provided computational methods of shared environment for the construction industry using semantically-rich computational representation through the World Wide Web. Moreover, Kalay et al. (1998) developed an integrated model that supports a distributed shared environment to replace the sequential communication norm. McCall and Johnson (1997) produced the first milestone technique that supports a shared environment in design. The technique uses argumentative agents, namely, the PHIDIAS hyper-CAD system, as catalysts that support the production of a shared environment system for design collaboration. McCall and Johnson (1997) used the argumentative agents with a media facility that supports the sharing of time and place during collaboration. Similarly, Schmitt (1998) developed a new shared environment platform for engineers and architects using conventional and artificial intelligent (AI) communication systems to support the large distribution of data among multiple users. After a comparative investigation between conventional and AI communication media, the study finally developed a new media for sharing information between engineers and architects during design. Similarly, Johansson and Popova (1998) used a case-based design issue to test the manner by which sequential traditional work methods using 3D visualization techniques support effective cooperation among architects and structural designers. After comparing the case-based issue with the quality, cost, and outcome of the product, the study establishes that sequential traditional work methods using 3D visualization techniques have high quality and low cost for cooperation among architects and structural designers. Furthermore, comparative studies on real life/virtual environment or same/remote location were conducted (Jeng and Eastman, 1998; Kalay, 1998; Kalay et al., 1998; Veeramani et al., 1998). Gross et al. (1998) investigated the effect of a computer-mediated shared environment on designers during long-term distributed interactions. Veeramani et al. (1998) estimated that in 25 years, the computer-integrated technologies would dominate the building construction industry due to the emergence of Internet-Intranet technologies that create new mechanisms for the shared environment that were previously impossible, the same with the manufacturing sector 25 years ago.

Yan-chuen et al. (2000) investigated the refurbishment of building services under two shared environment media (i.e., active and passive model making). Comparatively, the study was unable to establish any significant differences between the two media. Gabriel and Maher (2000) established that the use of computer-mediated media does not necessarily mean emulating close-proximity environments. Cheng and Kvan (2000); Kvan (2000) established some of the needed strategies for the application of technology-supported environments to promote shared environment in design. Rosenman and Wang (2001) evaluated a component agent-based open CAD system for a shared environment, whereas Tang and Frazer (2001) assessed the role of the representation of design context in a computer-supported shared environment. Similarly, Woo et al. (2001) investigated the manner by which a multi-user workspace facilitates adequate communication among stakeholders during collaboration to ensure that collaborative work progresses smoothly among participants in the aforementioned workstation. Finally, the study developed a multi-user workspace that influences communication in a shared environment. Additionally, Kalay (2001) examined the manner by which the bonds of interaction suffer from low-grade communication, arguments, misunderstanding, errors, and dissatisfaction. Moreover, the study presents some solutions on the basis of the explicit representation of reference and frame-of-reference to resolve issues of misunderstanding during design collaboration. Austin et al. (2001) mapped out the conceptual design activity of interdisciplinary teams. The study successfully tracks and frames the iterative nature of the conceptual design activities and provides a coding scheme as a basis for modeling and understanding communication in design collaboration.

Chiu (2002) described in detail the role of organizational surroundings in communication in a shared environment. The study used architectural practice and design learning studios to investigate the effects of communication between the two environments. Moreover, the study suggests that the structure of the team's organization of each environment can facilitate design communication and contribute to the success of the design project. The outcome of the empirical case studies within the two design experiments also suggests that a structured organization can improve design communication during collaboration and consequently contribute to the success of the design project. Craig and Zimring (2002) stressed the role of verbal and graphic communications in the shared design environment. The study investigated the role that verbal and graphic communications play in a shared virtual space. The result shows that an immersive discussion tool (IDT) allows collaborators to reason 3D models over the Internet using view-dependent and view-independent diagrammatic marks, dynamic simulations, geometric design surrogates, and text annotations. Finally, the study concludes by emphasizing the need to support the virtual space. In a similar study, Craig and Zimring (2002) established the significant influence of Internet-based shared media and Virtual Reality Modeling Language (VRML) Java-based interface shared media on verbal and graphical communications. However, Gabriel and Maher (2002) argued that successful computer-mediated collaborative design does not necessarily mean emulating communication in close-proximity environments. Nevertheless, the study does indicate the parameters that justify the argument. Stempfle and Badke-Schaub (2002) analyzed the generation, exploration, comparison, and selection activities of design collaboration through team communication. The analysis proposes a two-process-theory of thinking in design teams that can explain the results from the empirical investigation, which also affirm the theory of the psychology of human information-processing and decision-making. Achten (2002) supported the need for a CAD-shared environment for an architectural-focused design environment. Thus far, most studies are still focused on the nature of the shared environment and tools that support the virtual workspace.

Cheng (2003) surveyed and compared the interface and interactive artwork media. The study identifies that the TUI shared environment has a strong potential for innovations and concludes that issues of shared media need further research. Garner and Mann (2003) found that the computer supported collaboration work systems improve project management information exchange among team members. However, this idea has a divided consensus among specialists. Similarly, Lahti et al. (2004) used conventionally written text and sketching in virtual learning media to examine the computer-supported shared environment support on design learning. The study found that coordination, cooperation, and collaboration are key characteristics of the environment. The findings indicate that designers tend to be collaborative during the conventional process. Likewise, Maher et al. (2005) demonstrated an agent approach that supports shared environment in the 3D virtual world. The study developed an integrated shared design media (3D virtual environment and CAD systems) using a common data model to support design collaboration of the 3D virtual worlds. Moreover, the study created a multi-agent virtual design collaborative system (MAVDCS) that allows active data sharing by integrating the two media. Chen et al. (2005) successfully developed and implemented an industry foundation class (IFC)-based web server for developing a shared environment between architects and structural engineers. Dong (2005) used design team communication to measure designers' construction knowledge. The results of the latent semantic analysis of language-based communication revealed that language similarity supports indirect relations among components of designers' tacit knowledge, thereby resulting in developed shared mental representation of a designed artifact. On the basis of Plume and Mitchell (2007), more research is needed to further explore the nature of the multidisciplinary shared environment using the IFC building model specification when dealing with design analysis. Rosenman et al. (2007) stressed the need to support relationships in a multidisciplinary shared environment in the virtual workspace. Furthermore, Han et al. (2006) evaluated the use of collaborative virtual organization software for the shared environment during construction project management. According to reviews, issues of computer-supported technology are dominant. An example of a typical MSCD is illustrated in Fig. 3.

Wang and Dunston (2007) surveyed user perspectives on mixed reality tabletop visualization and face-to-face (F2F) shared environment during design review. The study found that the mixed reality tool facilitates effective problem-solving patterns. Moreover, Gül and Maher (2007) compared the similarities and differences between F2F sketching and designing in the virtual environment. The empirical results show some similarities and differences between F2F sketching media and remote designing using virtual media. For example, designers behave differently in the two media. Furthermore, Dave and Koskela (2009) established a method of using information and communication technologies to offer some answers to implement knowledge management solutions in a shared environment.

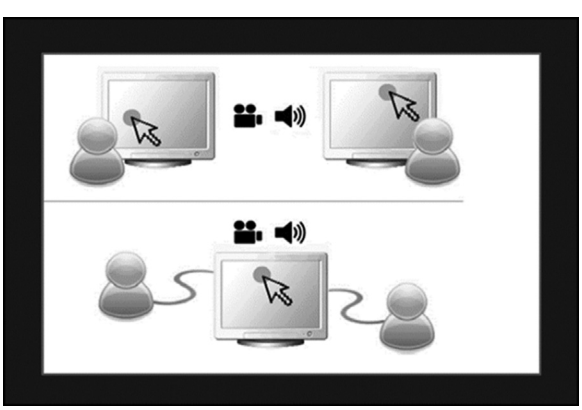

Fig. 3 Typical example of MSCD (Rahman et al., 2013).

Kan and Gero (2010) compared the behavior of designers in a shared 3D virtual workspace with those in a real F2F shared environment using quantitative tools. The study found that the 3D environment increases a designer's rate of effective communication (structural activities) over the real F2F shared environment. However, the virtual reality (VR) 3D environment proved otherwise when Ibrahim and Rahimian (2010) studied the effects of VR 3D sketching on novice designers' spatial cognition in conceptual architectural design. The study found that the conventional CAD tools lack intuitive design activities, whereas VR 3D sketching has a significant effect on novice designers' cognitive actions for design creativity. Therefore, the study concludes that conventional CAD media cannot effectively support various conceptual architectural design processes, such as haptic-based VR 3D sketching media. Similarly, compared shared environment technologies for architectural design, such as the effect of 3D virtual media and TUI on architectural design collaboration. The study successfully identified and established some key recommendations for future development of mixed media technologies for shared architectural design. Ren et al. (2011) recommended a multi-agent system environment for optimizing shared environment approaches to design. Xue et al. (2012) presented a comprehensive 10-year literature review (2000–2009) on the implementation of information technology (IT) in a shared environment. Rahman et al. (2013) compared the manipulation of 2D-objects in synchronous and asynchronous distributed shared environments. The study examined changes in the usage of the shared object across design phases in the distributed shared environment. The findings of the study clearly indicate phase-specific usage of the shared object in the synchronous setting. The two settings also show varying usefulness depending on the design stage, thereby indicating the disparate effect of synchronous and asynchronous settings on collaboration quality in disparate design phases.

According to Lee and Jeong (2012), the user-centric knowledge representations of the design collaboration have failed due to disciplinary differences among the participants. The failure is also due to the lack of understanding of the nature of multidisciplinary design and tools that can support them. The study establishes a suitable model for a machine-mediated tool to support knowledge representation in multidisciplinary design collaboration. To the best of the researchers' understanding, only two studies have been conducted on knowledge in design teams on the basis of the abovementioned discussions. The first is the study of user-centric knowledge representations of design collaboration by Lee and Jeong (2012). Ren et al. (2011) used a performance measuring matrix to measure the strength and weakness of communication activities in the shared design environment. The study summarizes the strengths and weaknesses of a shared design environment and suggests suitable responsive actions for improving communication activities in design collaboration. Chau et al. (2005) reported a method for the design of an adapted visualization for 4D applications in a shared environment. Moreover, Fernando et al. (2013) developed a virtual shared environment to support review meetings in design collaboration. Another study by Wiltschnig et al. (2013) analyzed problem solution co-evolution in a creative design collaboration. The outcome reveals that co-evolution episodes occur regularly and embody various directional transitions between problem and solution spaces (creative activities). This result affirms the view that co-evolution is the mechanism of creativity in design collaboration. In another comparative study, Eris et al. (2014) compared multimedia communication during distributed design sessions. On the basis of comparative analysis of sketching in co-located and distributed environments, when gesturing reduces, graphical communication increases and vice versa, and verbal communication is continuous in both environments. Wang et al. (2014) established that BIM-enabled complex building shared environment technology significantly shortens design time and improves design performance. Skopp et al. (2015) analyzed distance shared media (DSM), which is a reasonable alternative to meeting F2F.

Hong et al. (2016) investigated the enablers of and barriers to multi-user virtual media (MUVM) and sketching media in F2F and remote collaborations. The study found that the co-presence in the sketching media promotes the emergence of creative solutions, while the MUVM prevents creative solutions. Finally, the study confirms that most of the previous studies have concentrated on the efficiency of the shared digital media. Neghab et al. (2015) measured the performance evaluation of collaboration in the design process using interoperability measurement. Kasali and Nersessian (2015) observed that architects allow distributed disciplinary expertise to morph into a new form of interdisciplinary expertise to solve problems in situ. Leon et al. (2015) demonstrated technologies of communication for a conceptual design stage protocol for pre-BIM stages. Luyten (2015) studied computer aided architectural design and conceptual shared environment between architects and structural engineers. Oh et al. (2015) developed an

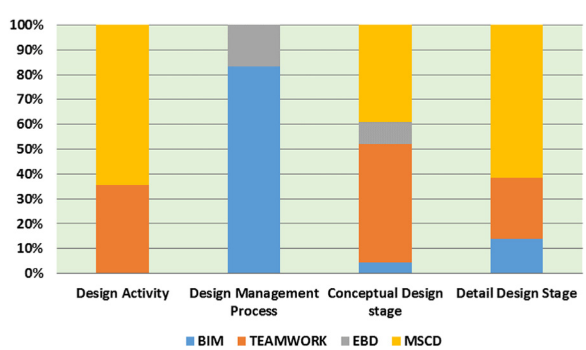

Fig. 4 Summary of data source output from content analysis.

integrated system for the BIM-based shared environment. The extensive review has shown that the majority of the studies have focused on the digital media (AI, VRML Java, 3D-VW, CAD, IDT, MAVDCS, 3D-VRS, TUI, CMCD, DSM, and MUVM), with limited studies focusing on investigating established grounded design modalities, such as sketching, which has proven to be one of the most successful design media since classical times. The sketch remains the designers' thinking tool. Moreover, the research of Lee and Jeong (2012) is in contrast to this study because their work viewed design collaboration from the perspectives of symbolic and latent semantic meaning derived from a shared design environment. However, the studies by Gül, Maher (2007); Kan and Gero (2011) have focused on the nature and pattern of design characteristics that are exhibited in a design that is performed collaboratively by more than one designer.

A form of unique shared operational media that can provide the needed collaboration is necessary because collaboration is a unique process that consists of different people and environments. The shared media is a tool by which the collaboration operates. Here, the tools are determined on the basis of the influence of existing design tools on collaborative media. As a general note in most cases, collaboration is a technique that assists stakeholders that are geographically separated or F2F to have an interaction, either concurrently or retrospectively. Thus, this approach can be achieved using various technological tools and media, such as graphical user interface (GUI), TUI, VR, and augmented reality (AR) for the interaction (Gu et al., 2011) or real life F2F medium. For example, this method can be a medium that can support different times and same place interaction in a real or virtual condition. Most of the time, this type of collaboration relies on computer-mediated and collaborative-distributed technologies, such as computer hardware, software applications, and smart board (Gu et al., 2011). In most cases, this type of collaboration assists stakeholders who are geographically separated to have an interaction in a semi-same place environment. Thus, this collaboration can only be achieved using various technological tools and media, such as GUI, TUI, VR, and AR, for the interaction (Gu et al., 2011). In real-time and same time, such as F2F brainstorming, media (e.g., online chatting, video conferencing, and real-time verbalization) are applicable.

Kan and Gero (2010) explored quantitative methods to examine design activities in a collaborative virtual environment. The case study shows that the 3D virtual environment slows down the design activities and may favor certain design

Table 2 Summary of data source output from content analysis.

Themes	Sub-Themes			
	Design Activity	Design Management Process	Conceptual Design stage	Detail Design Stage
BIM	-	10	1	9
TEAMWORK	27	-	11	16
EBD	-	2	2	-
MSCD	49	-	9	40

activities. The study found that 3D media encourage a loosely coupled design process. Accordingly, the empirical result of the protocol analysis of the virtual shared environment shows that 3D media slow down design activities, whereas F2F media support higher design activities. Similar to the early research understanding on the concept of design collaboration, the extensive review so far shows that most of the studies still focused on shared environment (virtual or real) and tools that support the virtual workspace (computer and technology-supported tools). However, none of the studies have looked into the core operational properties of design characteristics in the shared environment virtually. Moreover, the strategies and actions that facilitate designing collaboratively in a shared environment are unexplored.

4. Conclusion

As shown in Fig. 4 and Table 2, the issues of the design activities that occur during design collaboration have been seldom discussed in the BIM framework and EBD practice. The results further indicate that on the basis of the studies reviewed so far, the BIM framework of design collaboration has mainly focused on information and project management. This outcome reveals that research on design collaboration in the BIM framework was unable to focus on various issues of design teamwork, such as sharing, discussing, interacting, socializing, and conceptualizing design ideas during conceptual architectural collaboration design. This result affirms that the BIM framework of design collaboration excludes the human conceptual design aspects of communicating and transforming tacit knowledge into explicit building products. Hence, improving research investigation in conceptual architectural collaboration design under the BIM framework is necessary. Moreover, the results indicate that the MSCD is a particularly important parameter with regard to design collaboration. This condition can be observed from the frequencies of MSCD under concept, detail, and activity.

On the basis of the review of critical perspectives of design collaboration based on teamwork, BIM framework, EBD practices, and MSCD, interdisciplinary design collaboration using digital building structure in a virtual environment is one of the major approaches in all the four themes. Evidently, many studies have considered that the multidisciplinary approach, higher level of technology, communication, information sharing, error detection, and speed are the ultimate objectives of the modern design and construction method (Succar, 2009; Bryde et al., 2013; Grilo and Jardim-Goncalves, 2010; Olatunji, 2011; Isikdag and Underwood, 2010; Mitcham, 1995; Bryde et al., 2013; Vaishnavi and Kuechler, 2015; Preece et al., 2015; Hardin and McCool, 2015). On the contrary, Olatunji (2011) pointed out that design collaboration cannot accurately deliver key and reliable design characteristics because it mostly focuses on detailing, technology, clashes, and multidisciplinary work. This condition indicates over-concentration on issues of high-tech information technology and lack of focus on actual design activities when dealing with design collaboration. For example, design ideas are mostly conceptualized at the early stage of the process, whereas majority of multidisciplinary activities are at the final stage of the process. Therefore, the definition of the BIM collaboration framework, with the two stages of design, is obscured, and the method is mostly focused on improving every aspect of the traditional document-centric construction process. The BIM concept of design collaboration can be acknowledged because it provides a sufficient technology-supported platform for effective interaction and information management during design. However, the BIM concept of design collaboration is unable to consider the human dimension of design, which role is clearly explained in design theories, processes, methods, and knowledge. This study assumes that focusing on technology and other descriptive explanations of design collaboration is slightly out of the human context of design. Therefore, collaboration in design might not necessarily refer to only technology and multidisciplinary processes, but a framework in which all parameters are also considered. On the basis of the literature reviewed so far, critically investigating the design collaboration is necessary to fully comprehend it. Thus, the key characteristics of design specifically related to theory, process, method, and tacit knowledge that were excluded in the BIM framework should be investigated.

Design collaboration might not always be necessarily related to the multidisciplinary approach, technology, communication, information management, error detection and elimination, and speed; it can also be related to the design theories, processes, methods, tacit knowledge, and human aspects of design. Design theories have gained substantial attention since the technical rationality era. The technical rationality era and design science have viewed design as a rational search process, while the reflective theory views design as a reflective practice. This study concurs that design is a reflective practice collaboration and should also include various parameters, such as cognitive actions, reasoning, visual transformation, design goal, shared environment, teamwork, MSCD, EBD, BIM, and knowledge transformation. However, no research observation is available on the nature and characteristics of design collaboration. Moreover, design research has yet to generate new understanding and explanation on possible new design approaches. Therefore, understanding of design collaboration is insufficient. Thus, this research advocates for a research observation on design collaboration, where multiple designers share or transform their tacit knowledge during integrated work. Moreover, emphasizing on technology also contradicts the grounded nature of the cognitive aspect of design that has been unanimously considered by the design research community as the most flexible concept that is difficult to access, evaluate, and externalize. Therefore, updating the digital design with some properties of the sketch model is necessary so that it can be more design and tacit knowledge friendly.

On the basis of the reviewed literature, these four themes are the unique features of design collaboration, which constitute various areas, such as the team, activities, task, tools, strategy, requirements, technology, speed, accuracy, management, materials, investigation, and evidence. The task represents the nature and characteristics of the requirements and outcome. Moreover, the task explains the pros and cons of characteristics and attributes of interaction during teamwork. The MSCD influences the main structure, scope, and boundary by which the collaboration operates. The design team is composed of stakeholders that engage in shared tasks with a common goal, purpose, performance aim, and approach for which they hold themselves mutually responsible. The work covers individuals involved in collective and interdependent tasks, which are subsequently integrated as part of intra- and inter-group collaboration. We have included understanding from co-located teams (i.e., teams that are distributed in time and space and those in which one or more members use mobile, including remote agents). The team interaction is mostly between two or more individuals. Therefore, individual social and technical performance is crucial to the presentation of teams. Some of the major components of the individual discussed in the theoretical framework include skills, psychology, and well-being. The strategy facilitates coordination, communication, and decision-making among stakeholders. Future research can focus on detailed explanations and reviews of the theoretical framework of design collaboration.

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