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Clash Detection or Clash Avoidance? An Investigation into Coordination Problems in 3D BIM

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Abstract: Early collaboration is crucial if the final design is to be clash-free, and automation processes through Building Information Modelling (BIM) have the capacity to reduce clashes through 3D design coordination. Yet, current design practices are still dependent on clash detection and contemporary literature presents several reasons for this. This paper investigates the root causes of clashes with respect to achieving "clash avoidance" as proposed in PAS 1192-2 design phase specifications for BIM in the UK. Empirical data from BIM coordinators around the world was collected and analyzed using explanatory sequential mixed-methods. It was found that: (i) isolated working was the prime cause of high occurrences of clashes linked to mechanical, electrical and plumbing (MEP) 3D BIM systems; (ii) there is a link between non-BIM specific training (or the professional qualifications) of design practitioners with the high incidence of clashes; and (iii) the current structure of cloud-based common data environments (CDEs) does not facilitate clash avoidance and in fact, encourages isolated working in the early design stage by creating "digital information silos". A conceptual framework for an open work in progress (OWIP) has been proposed to address this problem. These findings point to the need for more transparency during collaboration through CDE where designers from multidisciplinary backgrounds can engage in concurrent co-creation. This transparent and inclusive process could have consequences on how future architectural, engineering and construction (AEC) professionals are trained.

Keywords: clash detection; clash avoidance; design coordination; MEP coordination; co-creation; common data environment

1. Introduction

Current design practice and construction delivery has traditionally suffered from poor coordination and irregularities in the way that multi-disciplinary teams manage and exchange project lifecycle data. However, Information Communication and Technology (ICT) enabled collaboration through building information modeling (BIM) particularly the 3D modeling aspect has potentials to innovate, transform and foster the process of information exchange and cross-disciplinary collaboration. However, exploiting the full potential of BIM requires tools, protocols and open standards for collaborative working hence in the United Kingdom (UK), a cloud-based shared workspace also called a Common Data Environment (CDE) is required for Level 2 BIM to facilitate seamless transfer and sharing of data across the multi-stakeholder environment. Starting from April 2016, all public-sector projects were required to comply with Level 2 BIM specifications and the benefits of specific requirements are still unclear. What is obvious is that the process is still replete with knock-backs including inter-system and intra-system clashes [1]; with the increased marketing of clash detection software, whose success at finding clashes are touted by their developers and users. This is despite a requirement in PAS 1192-2 [2] for clash avoidance to be used as a proactive measure in place of the reactive clash detection process. In fact, according to researchers, clash detection is so crucial for delivering a clash-free 3D BIM model that dedicated meetings are held for this sole intent [3,4] or jointly with general "design coordination" meetings where clashes are identified and resolved [1,5]. The importance attached to these meetings signifies that clash avoidance is not practiced or perhaps even feasible currently.

A search conducted within peer reviewed databases (and general web search) did not reveal any specific tool designed to assist professionals achieve clash avoidance. This search was carried out because multifarious benefits of ICT software to successfully impact on the construction project delivery have been widely acknowledged in literature. These include but not limited to evaluating and simulating alternative construction schedules [6], improving communication of project participants [7], improving site logistics, layout and work execution space [8], supporting management tasks [9] and improving multi-team collaborative planning [10]. What is clear from these studies is that the introduction of digital systems improves coordination, collaboration and communication among the sundry design disciplines involved in a project. However, even though the collaborative ingredient of 4D modeling processes is often used as a commercial justification by proprietary BIM software vendors [11]; the significant number of clashes identified by clash detection tools employed in the project is still seen as a benefit of the clash detection process as highlighted in previous studies (for example [12,13]). However, arguably, the proliferation of clash detective tools makes it harder for design practitioners to achieve clash-free designs (clash avoidance). Moving beyond clash detection tools and investigating the real roots of design clashes could unearth existing cultural and work practices inhibiting clash avoidance.

2. Background and Frameworks

Traditional collision detection applied in computer graphics and robotics is a precursor to today's clash detection practice in 3D BIM. Several studies document the algorithms developed for these collision detection activities to include Oriented Bounding Boxes or OBB-trees method [14]; a realism approach adopting the Sphere-trees method [15]; Approximate polyhedra with spheres [16] and Bounding volume hierarchy [17]. Essentially, these algorithms determined the proximity of two or more objects and whether their geometries collide in virtual space. The practice of examining 3D BIM components for clashes or predicting how objects react to collisions or "collision response" can be traced to studies like Sullivan and Dingliana [18]. More recently, researchers like Helm et al. [19] have categorized clash detection algorithms into: (1) comparing shapes; (2) comparing axis aligned bounding boxes; (3) the Ray triangle intersection; and (4) the industry foundation classes (IFC) structure method. Each of these is influenced by the choice between accuracy and speed and although speed may be more important for gaming purposes, accuracy prevails for a building design [19].

These studies highlight how the subject of collision detection has fascinated researchers for decades but there appears to be a marked change in focus; a shift in the appropriate time and phase to clash-detect as clash detection practice has progressively changed from an on-site activity (reactive) to preconstruction design phase (proactive). Nowadays, the process of clash detection or interference checking in 3D BIM involves identifying the encroachments or conflicts in a 3D BIM environment which is achieved by conducting pair-wise comparison checks among the set of selected elements [20]. This usually occurs between the design models of interdisciplinary stakeholders including those of sub-contractors and specialist tradesmen. Clashes have also been categorized into hard clashes, soft clashes and time clashes [21,22]. These are the most popular among several classifications of clashes in the architectural, engineering and construction (AEC) industry. Evidently, the need for accuracy in multi-disciplinary designs makes clash detection software powerful tools in design coordination, which prompted researchers [3,23] to quantify the cost benefits of clash detection. In these studies, coordination and clash detection enhancements were hailed as strong reasons to push for the adoption of 3D and 4D BIM by industry practitioners. However, despite significant endeavors at improving clash detection algorithms of software, clash detection tools throw up large amounts of irrelevant clashes requiring time and resources to sort and causing some to question the real benefits of automated clash detection tools [24]. Leite et al. [4] also stated that it is cheaper to have more recalls due to false positives than paying for experienced professionals to carry out detailed review/coordination with traditional 2D drawings. It can be argued that avoiding design clashes could free up more time for design specialists to focus more on coordinating management activities involved in multidisciplinary coordination. Few studies exist which explore proactive methods of avoiding clashes and the focus currently paid on the practice of clash detection (with its negative repercussions for design practice) is among the motivations for this research.

2.1. Scoping the Research

Several frameworks have been proposed each designed to facilitate and enhance multidisciplinary collaboration. Some of the frameworks have employed the use of graphical annotation elements to aid both text and graphical communication [25] while others have highlighted the perspectives that need to be considered in facilitating an effective 3D BIM coordination framework. For example, studies by Kassem et al. [26] highlighted Technology, Process and Policy BIM fields as been crucial while Succar [27] and Zahiroddiny [28] both considered a fourth dimension; People. These frameworks share similarities to the one proposed by Benning et al. [29] which proposed an open and flexible three-level collaboration framework namely: the organizational level, the process level and the tool level in which clash detection is located within a coordination and management zone.

It is evident from these frameworks that technology that facilitates collaboration is crucial in integrating diverse project teams involved in interdisciplinary collaboration. In addition, central to all these frameworks is the objective of dealing with design coordination using a process that pays attention to the wider issues encountered during project coordination to minimize clash detection. For instance, the need to exchange and manage information accurately and efficiently between project participants is being frequently emphasized in coordination frameworks as evident in NBIMS [30]. Hence, Korman and Simonian [31] developed a composite knowledge and reasoning framework, which combined metrics in the aspects of crucial design measure, construction issues and operations and maintenance requirements to identify and resolve multiple types of interferences in mechanical, engineering and plumbing (MEP) systems. They then detail their "heuristic matching process" for resolving coordination issues. However, Benning et al. [29] have argued that the best way to deal with clashes is by ensuring clash avoidance and they proposed more direct communication between designers to resolve clashes if they occur. Therefore, they conceptualized a framework to enhance interdisciplinary coordination by proposing a bottom-up and then a top-down approach. Their bottom-up approach was intended to give principal attention to the project organization by specifying and detailing the organizational culture while the least priority was given to the tool level after addressing other organizational issues.

2.2. Frameworks and Tools Promoting Clash Avoidance

Over the years, frameworks and protocols aimed at improving process workflows have emerged. For instance, the process protocol widely used by AEC practitioners is targeted at giving priorities to the work processes involved in delivering a product. A process-driven framework has been used in the Analytical Design Planning Technique or ADePT, which is a collaborative design planning tool developed to break the traditional silo "over-the-wall" approach of project delivery and is fixed along interdisciplinary team lines instead of the work processes involved in delivering the project [32]. The design-planning tool prioritizes decision making using a design structure matrix (DSM) which makes a distinction between critical, important and nice to have activities and optimizes approach to early decision making at the design phase of the project.

Another framework is the Evolution-Sensitivity Architecture [33], which is a conceptual approach for overlapping activities. They provided a mechanism for tackling crucial issues that arise when deciding on an effective strategy for multi-disciplinary integration of activities and information exchange. Areas of interest were: when information should be exchanged between two activities and frozen between project participants and how overlapping can be done between an upstream and a downstream activity that requires information from it. This framework is especially suitable for project activities that are multi-disciplinary in nature and it is irrelevant whether some design information is available before others (e.g., information on architectural designs are available before information on specific MEP components). The Evolution-Sensitivity Framework is adaptable to design practitioners in the AEC industry.

These frameworks and especially the bottom-up concept may have informed current guidelines developed to facilitate interdisciplinary working in the AEC industry. For instance, the Avanti toolkit [34] contains standard methods and procedures (SMP) to coordinate and facilitate design information exchange among multidisciplinary project stakeholders with key focus on People, Process and Technology. The toolkit also developed stage gates for approval of information to minimize design errors. Indeed, the AEC (UK) BIM protocol [35] later developed for the AEC industry is in many respects like the Avanti toolkit. It aimed to improve three aspects of design coordination namely: production of design information, exchange of the information and finally management of the information that is exchanged. A common data environment (CDE) i.e., a cloud-based shared workspace is also required to facilitate systematic information exchange and achieve a clash-free model (or clash avoidance).

3. A Review of Causes of Clashes and Clash Avoidance Strategies

A systematic review of the drivers influencing hard and soft geometric clashes in a BIM model and the impacts clashes have on achieving an efficient design have been summarized in Table 1 below.

Table 1. Summary of the causes of hard/soft clashes.

Causes of Clashes	Authors
Use of wrong or low level of detail	[4]
Design uncertainty/use of Placeholders	[21]
Failing of design rules	[21]
Accuracy versus deadline	[21]
3D model objects exceeding allowable clearance	[21]
Designers working in isolation from each other	[25,36,37]
Design complexity	[21,31,38]
Insufficient time	[29,38]
Use of 2D instead of 3D models	[4,24,39]
Design errors	[13,21,40]
Use of different file formats	[41]
Lack of experts	[4,38,41–44]

From the summary of the causes of clashes in Table 1, scarcity of experts appears to be more common as it received the most mentions as the main cause of clashes. Also, the summary of the studies presented in Table 1 suggests that *Designers working in isolation, design complexity, use of 2D instead of 3D models and design errors* are all-important considerations when examining the primary causes of clashes. While clashes resulting from the "use of 2D instead of 3D models" can be directly addressed by mandating designers to adhere to a 3D standard, frequently reported design errors were of more serious concern to the authors of this paper due to the proliferation of clash detective software to check design errors which are mainly reactive approaches. Attempts to identify the cause(s) of design errors in a BIM project prompted the formulation and testing of the null hypothesis: *Professional errors by designers are not related to their non-BIM specific training.*

Froese [37] earlier argues that creating fixed specialist roles with minimal interdependence with one another creates an overall project that is unoptimized and more complex. Design complexity appears to be more frequent with MEP systems as is evident in literature.

3.1. Building Components Involved in Clashes: Importance of MEP Systems

Various studies have associated MEP systems with complexity and coordination issues related to BIM [12,21,31,38,45,46]. MEP systems are also more expensive to procure relative to the total cost of the entire building system [12,45] making them critical to the presence of clashes. According to Bloomberg and Burney [47], a preliminary clash detection run at the schematic phase can be between six pairs of major building elements while a clash detection run at the design development phase can be up to as many as between twenty pairs of major and minor building elements (e.g., architectural and heating, ventilation and air conditioning (HVAC); structural and HVAC, etc.). In addition, Tommelein and Gholami [21] argue that in the concept and design development phase, complex building systems with elements in areas subject to changes may promote clashes since other designers' solutions may already be fixed or shown as design intents in those problematic areas. This agrees with Korman and Simonian [31] who highlight that the complexity of building spaces and the necessity for many MEP specialty contractors (e.g., HVAC and structure, HVAC and piping, HVAC and electrical etc.) to be involved in a single coordination exercise is a reason for MEP clashes in building models.

Evidently, complexities of MEP components and coordination issues, or lack of them, are identified in literature as primary causes of clashes but this cannot be validated. The need to provide a statistical validation prompted the formulation of the null hypothesis (*The high incidence of MEP-related clashes in 3D BIM are not related to isolated-working*) to test whether isolated working and therefore MEP clashes is the result of poor coordination of the multifaceted disciplines involved in design coordination. There is also the need to investigate existing coordination platforms to test whether they promote isolated working or achieve clash avoidance through co-design. This will be validated using the research objective: *To what extent will the CDE facilitate interdisciplinary coordination and clash avoidance among design teams in the way they deal with clashes?*

3.2. Clash Avoidance and Early Design Coordination

The need for designers to coordinate effectively at early design phase has regularly been highlighted by researchers. Garrett [48] identified concurrency and shared understanding as general requirements for effective decision making in collaborative frameworks. Bloomberg and Burney [47] argued that project coordination must start during the early design phase and must be continuous but this advice seems contrary to the provisions of PAS 1192-2 [2] which although mentions clash avoidance, has specified that the Work-In-Progress (WIP) containers is for in-house design teams only. Arguably, the WIP encourages isolated working and negates the principle of early collaboration and crucially, feedback. Likewise, Ashcraft [38] assert that collaboration in BIM can only be effective when stakeholders agree to jointly develop and improve a model and recommends coordination through reliance on the information model rather than tightly defining roles and responsibilities which creates independence (and by extension, less collaboration). Collaborating jointly is further reinforced by Leon and Lang [42] who preferred the term "co-design" again implying that developing a model jointly for participants to achieve a common aim [29] should be emphasized beyond merely developing a model collaboratively. Although clashes between building systems might be inevitable in certain complex projects, the problem of designing in isolation instead of co-creating must be tackled as suggested by Adamu et al. [49]. This concept requires revising the structure of the CDE since online workspaces are viewed as essential for bringing teams together.

Existing literature on clash avoidance have highlighted typical solutions to clashes to include: (i) imposing BIM on traditional contracts [5,36,50,51]; concurrently integrating Engineering, Procurement and Construction (E, P and C) at a functional level as obtains in the manufacturing industry [52]; (ii) improvement in software detection algorithms [24,53]; (iii) co-creation among designers in a shared workspace [29,36,42,54,55]; (iv) designers working with more information provided by other specialists [54,56,57]; (v) designers being more accurate with their own model output [13,21,29,58,59]; and (vi) coordination of design through a common data environment as suggested in BS 1192 [60] and PAS 1192 [2]. These solutions to minimizing clashes in design practice are summarized in Table 2.

Table 2. Summary of clash avoidance strategies by researchers.

Clash Avoidance Strategies	Authors
Impose BIM in traditional procurement	[5,36,50,51]
Integrating Engineering, Construction and Procurement	[52]
Improvement in software detection algorithms	[24,53]
Co-creation among designers in a shared workspace	[29,36,42,54,55]
Designers working with more information provided by other specialists	[54,56,57]
Designers being more careful/accurate with their own model output	[13,21,29,58,59]
Design coordination in a common data environment (CDE)	[2,60]
Shared situational awareness	[49,61–63]

It is evident from previous studies (summarized in Table 2) that the creation of error-free models by designers is essential to achieving clash avoidance. This is in addition to suggestion that designers need more "complete" design information. One plausible explanation about the scarcity of design information is isolated working or "over-the-wall" collaboration, thus the convergence of views among researchers that co-creation in a shared workspace might promote clash avoidance in the AEC industry. This notion is gaining traction as lately Autodesk, a leading design technology provider has continued to encourage cloud-based designing through its "Collaboration for Revit" and "BIM 360" platforms [64]. In summary, co-designing synchronously in shared platforms should allow for information verification, identifying contradicting information, and acknowledging action points. In addition, production of information whenever needed by another party as well as sufficient demonstration of situational awareness by all participants [49] can be helpful. With regards to co-creation, a closer look at the work-in-progress (WIP) aspect of a CDE is necessary to appraise its suitability for online co-creation.

3.3. The Structure of a Common Data Environment (CDE)

A CDE in principle should allow project data to be shared freely between project participants and should include emailing, application sharing, collaborative platform, document management and task and workflow management [21]. This based on the need for projects to be able to harness the capabilities of stakeholders and should promote open, dependable and expedient communication protocols [38]. Lack of such capabilities, will be detrimental to project success. According to Quigley [65], it would be counter-productive to overall project objectives if design participants are confined to spaces or if a design team attempts to "claim space" in spatial planning meetings. It is argued therefore that such practices must be discouraged by all project participants if true collaboration is desired. Consequently, it is crucial that BIM coordination progresses from concept design to detailed design via concurrent multidisciplinary design imposed through deliberate coordination [21]. To promote open coordination protocols, researchers have sought to replace clash detection with clash avoidance strategies. Cloud-based CDEs that are implemented as Software-as-a-Service (SaaS) provide an opportunity to achieve model coordination and document control. Available BIM standards and specifications [2,60] specify four stages in the document and data management repository of a CDE to include: (i) the Work-In-Progress (WIP) containers (folders); (ii) the SHARED folder; (iii) the PUBLISHED folder; and (iv) the ARCHIVED folder.

Figure 1 shows the structure of a typical CDE based on the specifications of PAS 1192 [2]. The CDE fosters based on strict discipline-based commitments by the design team participants and it ensures that project information is only produced once and then synchronously accessed by all relevant project partners. For this study, an interesting segment of the CDE; the so-called "Work-In-Progress" area is overviewed in the next section.

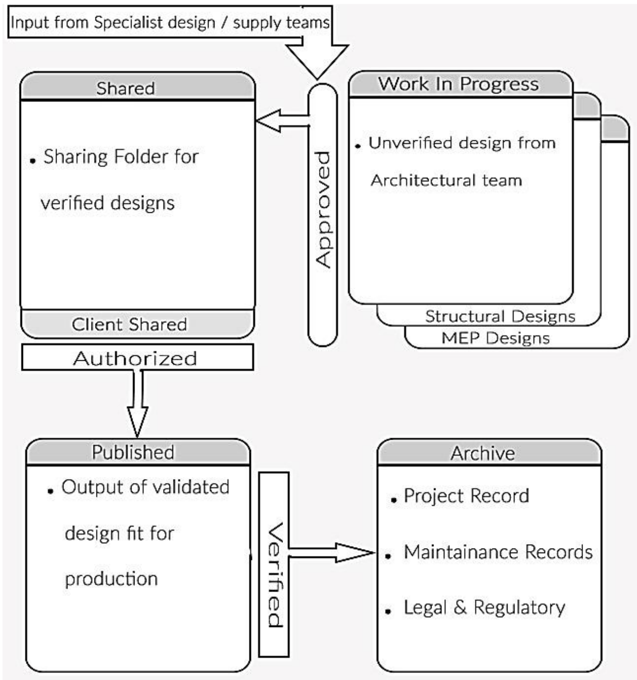

Figure 1. Schematics of a common data environment based on PAS 1192-2 (Source: [2]).

3.4. The Work-In-Progress Stage of a Common Data Environment

The WIP section is used to store the "unverified designs" of the individual disciplines. An MEP designer for instance, would access the architectural model in the SHARED folder to position his ductwork volume; but at this stage, the architectural and then the structural zones have already been defined (in the WIP stage). This implies that the MEP sub-systems and other specialty contractors and designers are designed to suit the architectural and structural volumes. The MEP designers (e.g., HVAC engineers) would therefore coordinate their models around an architectural volume to check for clashes in what has been described as after-the-fact and wasteful [52] since it digitally replicates the sequential comparison overlay process (SCOP) pre-BIM process. This raises doubts as to the capacity of a WIP-based workflow process to support common solutions that involves all players of the design chain. Currently, the process does not permit other designers to know what the architect and structural designers are conceiving in the early design phase where the most important decisions are often made. Although making fixed design decisions—i.e., "design fixity" [66–68]—as early as possible helps minimize costly changes downstream, wherever those fixed decisions are incompatible with additional system designs, clashes would be inevitable.

The need for designers to perceive other systems or other designers is therefore crucial for interdisciplinary coordination. Studies like Benning et al. [21] which although support an open and flexible framework for collaboration still favored a "shared" folder where results of individual work (as developed in their novel "Open Information Environment" (OIE) approach) can be exchanged. However, multidisciplinary collaborations do not provide automatic benefits if critical success factors facilitating information exchange are ignored. For instance, MacFarlane and Leigh [69] assert that an information framework which promotes taking decisions and actions before ascertaining the desired outcome is purposeless and that critical information needs to be coordinated by every team participant in the interdisciplinary team especially where complex systems are involved. Also, design clashes can result from vagueness and lack of lucidity about other systems [21], and secluded working can cause social boundaries and personal territories, which hinder collaborative participation by interdisciplinary team players [25]. Similarly, Kalay [36] emphasized that true collaboration should promote "shared super-objectives" and joint decision-making and should not prolong the cycle of design iterations [70].

Some aspects of CDE's and model collaboration servers represent a digitization of "over-the-wall" process due to the absence of on-line co-creation capabilities which limit the benefits they could provide to remote teams [49]; this is in addition to the threat posed by "over-the-wall" collaboration on design quality [36]. However, one possible obstacle to free sharing of information in BIM processes is linked to security and intellectual property (IP) around shared data/models.

3.5. Information Security and Concurrent Co-Design

Information hoarding is common practice among design practitioners. Information is not made available when needed and this is inimical to the principles of shared situational awareness [61] with negative consequences on concurrent working. Unsupervised or uncontrolled access to information could compromise the integrity of the asset model. Accordingly, MacFarlane and Leigh [69] emphasized that only those details necessary to enable full optimization of the collaborative effort need to be shared while maintaining that both shared situational awareness and team situational awareness are cognitive constructs that require inter-personal and interdisciplinary collaboration. Therefore, some controlled access will be required if design practitioners are to share and coordinate information in a concurrent platform implying that concerns about data security must be addressed. Shafiq et al. [39] report that as part of system administration requirements, collaboration portals need to implement access controls, data backups and data security most of which already exist in popular collaboration CDE's. Furthermore, Boyes [71] acknowledged that issues bordering on intellectual property as well as external, internal and business threats may undermine collaboration in a CDE, but organizations need to strengthen aspects of collaboration through established best practices.

The controls currently implemented in CDE's include role-based access rights especially to sensitive data, configuration control procedures, interoperability issues and back-up policies. Herewith, a Built Asset Security Manager role has been recommended in PAS 1192:5 [72] specification in which the asset owner is required to assess the sensitivity of the built asset or the proposed built asset and then evaluate the extent of security measures required. Interestingly, the PAS 1192-5 [72], which is currently the most sophisticated specification for BIM data security encourages real-time multi-disciplinary collaboration and transparent open communication among an interdisciplinary project team. Thus, there is no justification for hoarding information in the design phase of interdisciplinary BIM process. Nevertheless, it is mandatory that any CDE platform set up for interdisciplinary coordination facilitate co-design but prevent data breach and this calls for organizations to urgently review their concurrent working practices.

Apparently from the review; isolated working, lack of experts leading to more design errors and the absence of a CDE which both permit unhindered information exchange and ensure data security have been exposed as key ingredients inhibiting clash avoidance but are not validated. This study fills the identified gaps in literature and seeks to validate these findings through a mixed method study exploring how early phase multidisciplinary collaboration might contribute to clash avoidance. This was addressed through three objectives which are: (i) to investigate and establish the differences in the extent of occurrences and causes of hard clashes in 3D BIM; (ii) to investigate the predominant causes of clashes related to training of design practitioners; and (iii) to assess the extent to which the CDE facilitates interdisciplinary coordination and clash avoidance among design teams.

3.6. Variables Relationship between Clash Detection and Clash Avoidance

Based on the elements of clash reactive tools (clash detective) and clash proactive platforms (clash avoidance) identified in the literature review, a variables relationship between the two is presented in Table 3 below.

Table 3. Summary of variables relationship between clash detection and clash avoidance.

Clash Detection	Clash Avoidance
Key Differences	
It is a **reactive** process (after-the-fact) and checks for collisions and coordination only after design decisions have been taken	It is a **proactive** process and ensures that design decisions and outcomes are agreed to collaboratively through joint design
Mainly a pre-construction activity	Runs throughout all phases of the project
Focus is on the clash detective tool and improving the clash-rule sets	Focus extends beyond the tools. Emphasis is paid on the nature of collaboration between the MEP discipline and others
Requires basic level coordination skills	Requires more rigorous management and coordination skills
Does not require shared situational awareness	Requires shared situational awareness and how each player's design affects the others
Encourages silo-based working and hoarding of design information	Promotes information sharing and co-creation
May or may not be done by an experienced designer. A thorough understanding of the clash detective software by a newbie is deemed sufficient	Requires more experienced designers with a broader view of the design process
Longer design iteration time. Designers may keep going back and forth to get things right because of over-the-wall collaboration	Reduces design iteration time since decisions are taken jointly and information is shared freely as needed
Key Similarities	
The major objective is to issue clash-free models	The objective is similar
It identifies and fixes issues at the design phase which can lead to time and cost overruns at the construction phase	In many respects, similar
Aims to improve design quality	Similar

The implications for the literature review covered within the scope of this paper is summarized in Figure 2 below highlighting critical parameters from identification of the causes of clashes to their minimization or elimination via a CDE.

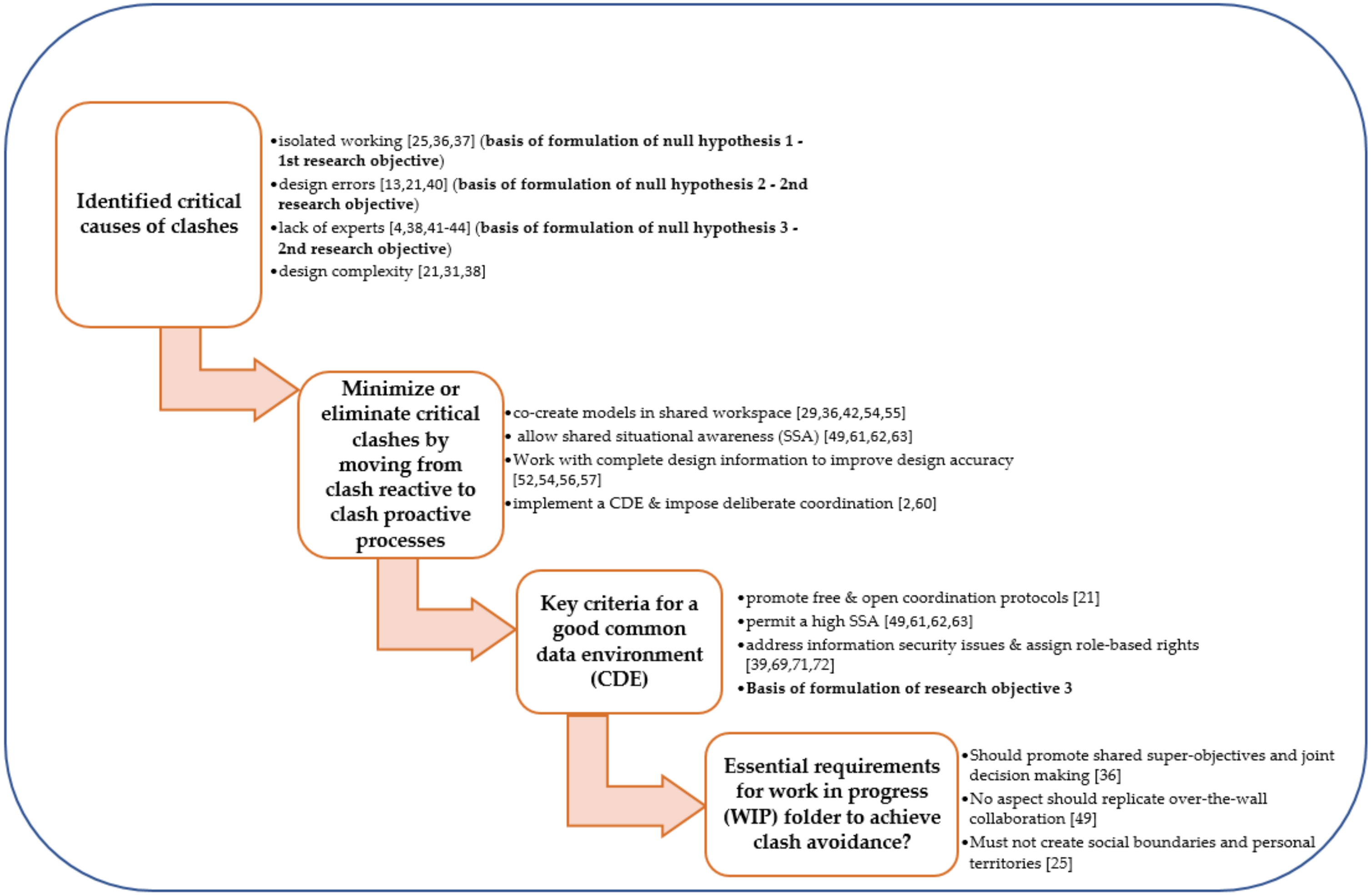

Figure 2. Summary of implications from literature review showing key relationships.

4. Methodology and Methods

This study adopts two different data collection methods with the initial phase involving the collection of quantitative data using a web-based questionnaire survey. The numeric data was subjected to descriptive and inferential analysis in the statistical package for the social sciences (SPSS). The goal of the quantitative phase of this study was to explore respondents' views on the issues emerging from the literature review to address the research questions raised. In the second phase, a qualitative data was collected through individual semi-structured telephone interviews. The basis for this approach is that it would help refine and explain the statistical results by exploring participants' views in depth. The sampling frame that was from the quantitative phase, consisted of design professionals who are regularly involved in clash detection practice. Based on literature reviewed, three hypotheses were developed and tested through the quantitative data from this phase. These are:

- H01: High incidence of MEP-related clashes in 3D BIM is not significantly related to isolated-working
- H02: Professional errors by designers are not related to their non-BIM specific training
- H03: The high incidence of Structural and HVAC clashes in 3D BIM is not related to the years of experience of designers

Using the same sample frame for the second phase of the study would increase accuracy and limit the introduction of errors [73]. Therefore, purposive sampling was employed in phase two to pre-select 20 out of the 43 Phase one respondents that indicated willingness to be interviewed, out of which six were eventually selected. These interviewees were selected because of their diverse backgrounds and years of experience in the field of design coordination and clash detection.

Figure 3 below presents the methodology roadmap showing how the research methodology derived from the framework and literature review and how it points to the research findings.

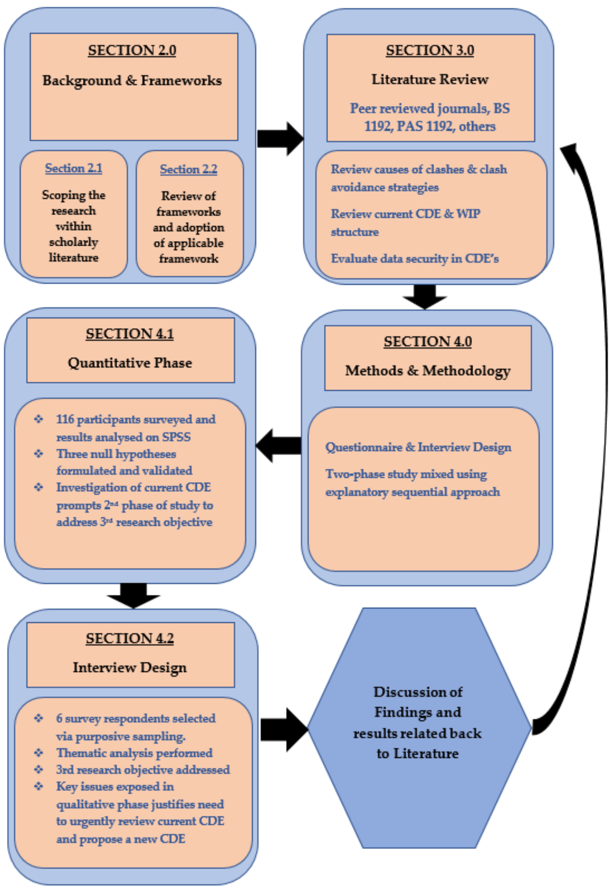

Figure 3. Methodology Roadmap for the study.

4.1. Phase 1: Quantitative Phase (Data Collection and Analysis)

To evaluate the critical causes of clashes and measure against important operationalized variables connected with multidisciplinary design clashes, respondents were asked to "select 5 most important reasons why you think 'hard/soft' clashes occur between components of 3D BIM models". The data was coded in SPSS and a descriptive analysis was done to identify the sub-variables of importance (Table 4).

Table 4. Absolute and mean number of causes of clashes according to respondents.

Causes of Clashes	N	Mean
Use of Placeholder objects	38	0.32
Complexity of buildings or their sub-systems	51	0.43
Inadequate time from design to construction	65	0.55
Professional error by designers	64	0.54
Working in isolation from each other	84	0.72
Use of wrong or low level of detail (LOD)	34	0.29
Use of 2D design instead of 3D BIM models	41	0.35
Use of Placeholders due to IPR	10	0.09
Designers working with different file formats	11	0.09
3D model objects exceeding allowable clearance	25	0.22
Inconsistency between design and actual fabrication	59	0.51
Others	12	0.1

From the data collected, "Working in isolation" (with a mean score of 0.72) stood out as the most important cause of clashes according to respondents. "Professional errors" and "inadequate design time" were also significant causes of clashes. In addition to these reasons and other reasons such as "complexity of buildings" (with mean of 0.43), or "use of placeholders" (with mean of 0.32), the catch-all "Other" reasons revealed that traditional procurement route (8%), late architectural changes (8%), lack of clash avoidance (17%) and poor knowledge of BIM systems (17%) were identified by respondents. Nevertheless, the prime reasons that will be used in subsequent analysis are: "working in isolation from each other" and professional errors by designers. Knowing that clients will continue to place a tight schedule deadline on their projects, the cause "inadequate time from design to construction" was considered a general requirement and will not be examined further in this research.

The three research hypotheses tested in this study would address the first two research objectives. The summarized results are presented in Tables 5 and 6 below.

Table 5. Results of the Null hypotheses tested and their correlations.

	Hypotheses		Struct/HVAC	Working in Isolation
Spearman's rho	Clashes between Structural and HVAC	Correlation Coefficient	1.000	0.210 *
		Sig. (2-tailed)		0.024
		N	116	116
	Working in isolation from each other	Correlation coefficient	0.210 *	1.000
		Sig. (2-tailed)	0.024	
		N	116	116
	* Correlation is significant at the 0.05 level (2-tailed)			
	Hypotheses		**BIM Qualification**	**Errors by Designers**
Spearman's rho	BIM specific qualification	Correlation Coefficient	1.000	−0.190 *
		Sig. (2-tailed)		0.035
		N	116	116
	Professional errors by designers	Correlation coefficient	−0.190 *	1.000
		Sig. (2-tailed)	0.035	
		N	116	116
	* Correlation is significant at the 0.05 level (2-tailed)			

Table 5. *Cont.*

	Hypotheses		Clash Detection Years	Structural and HVAC
Spearman's rho	Years of professional clash detection	Correlation Coefficient	1.000	0.171 *
		Sig. (1-tailed)		0.034
		N	116	116
	Clashes between Structural and HVAC	Correlation Coefficient	0.171 *	1.000
		Sig. (1-tailed)	0.034	
		N	116	116
	* Correlation is significant at the 0.05 level (1-tailed)			

Table 5 is a summary presentation of the results of the analysis using SPSS statistical tool indicating the results that were found to be statistically significant at $\alpha = 95\%$. The results from statistical tests (summarized in Table 6 above) led to all null hypotheses being rejected. However, an unexpected relationship was found for the third research hypothesis and will be treated in the discussion and conclusion section.

Results related to the third research objective (To what extent will the CDE facilitate interdisciplinary coordination and clash avoidance among design teams in the way they deal with clashes?) were examined and analyzed (see Figure 4a to Figure 4d). For example, respondents were asked to "Select two most important ways you think clashes can be minimized or avoided" (Figure 4a). This was a multiple-choice question permitting respondents to select what they considered to be the two most important ways to avoid clashes from a list of different clash avoidance strategies as found in the literature. Other related questions linked to this objective include:

- How can clashes be minimized? This question is fundamental to understanding whether practitioners are aware of (or use) any clash avoidance strategies.
- How do designers deal with identified clashes? This question was aimed at understanding the collaboration thought processes and behaviors of practitioners.
- How do designers communicate identified clashes? This question is important for appreciating the kinds of communication technologies used by practitioners for collaboratively discussing clashes. The technologies to be considered range from basic email to CDEs.
- Do designers use remote desktop to resolve clashes? This question would provide insights about whether any kind of real-time collaboration occurs during coordination/clash detection and subsequently to what extent such practices might help achieve clash avoidance.

With respect to "How can clashes be minimized?" Co-creation (29%) ranked highest among the clash avoidance strategies selected by respondents. Interestingly, reducing professional errors (27%) and providing more information (23%) for the use of the interdisciplinary project teams (23%) were also popular. Furthermore, shared situational awareness and clash avoidance approaches also emerged after analyzing the responses from those who selected "others". This indicates that design practitioners (survey respondents) may be willing to move from reactive approaches of resolving clashes to more proactive strategies. On the question of "How do designers deal with identified clashes? (Figure 4b)" there appeared to be variability in the way practitioners involved in clash detection dealt with clashes although the greater majority (37%) chose to resolve the clashes themselves. Further analysis showed that resolving clashes using the individual "silo" approach (40%) is still the prevalent tradition among those who took part in the survey.

Table 6. Summary and interpretations of the results of the tested hypotheses.

S/N	Research Questions	Null Hypotheses	Statistical Test	Results	Reject Null?	Interpretations
1	Are there differences in the extent of occurrences and causes of hard clashes in 3D BIM?	High incidence of MEP-related clashes in 3D BIM is not significantly related to isolated-working	Spearman's rho	Statistically significant at α = 95%. Correlation found to be positive	Yes	Positive correlation found suggesting that more isolated working leads to higher incidence of clashes.
						Based upon statistical analysis of the sample, accept alternative hypothesis
2	To what extent is the non-BIM specific training of designers related to design clashes?	Professional errors by designers are not related to their non-BIM specific training	Spearman's rho	Statistically significant at α = 95%. Correlation found to be negative	Yes	Inverse relationship found suggesting that more design errors are linked to designers with less BIM training.
						Based upon statistical analysis of the sample, accept alternative hypothesis
3	Are the high incidence of structural and HVAC clashes in 3D BIM related to the years of professional experience of designers?	The high incidence of Structural and HVAC clashes in 3D BIM is not related to the years of experience of designers	Spearman's rho	Statistically significant at α = 95%. Correlation found to be positive	Yes	Positive correlation found suggesting that practitioners with higher years of experience encounter more MEP-related clashes. *This direction of relationship was unexpected.*
						Based upon statistical analysis of the sample, accept alternative hypothesis

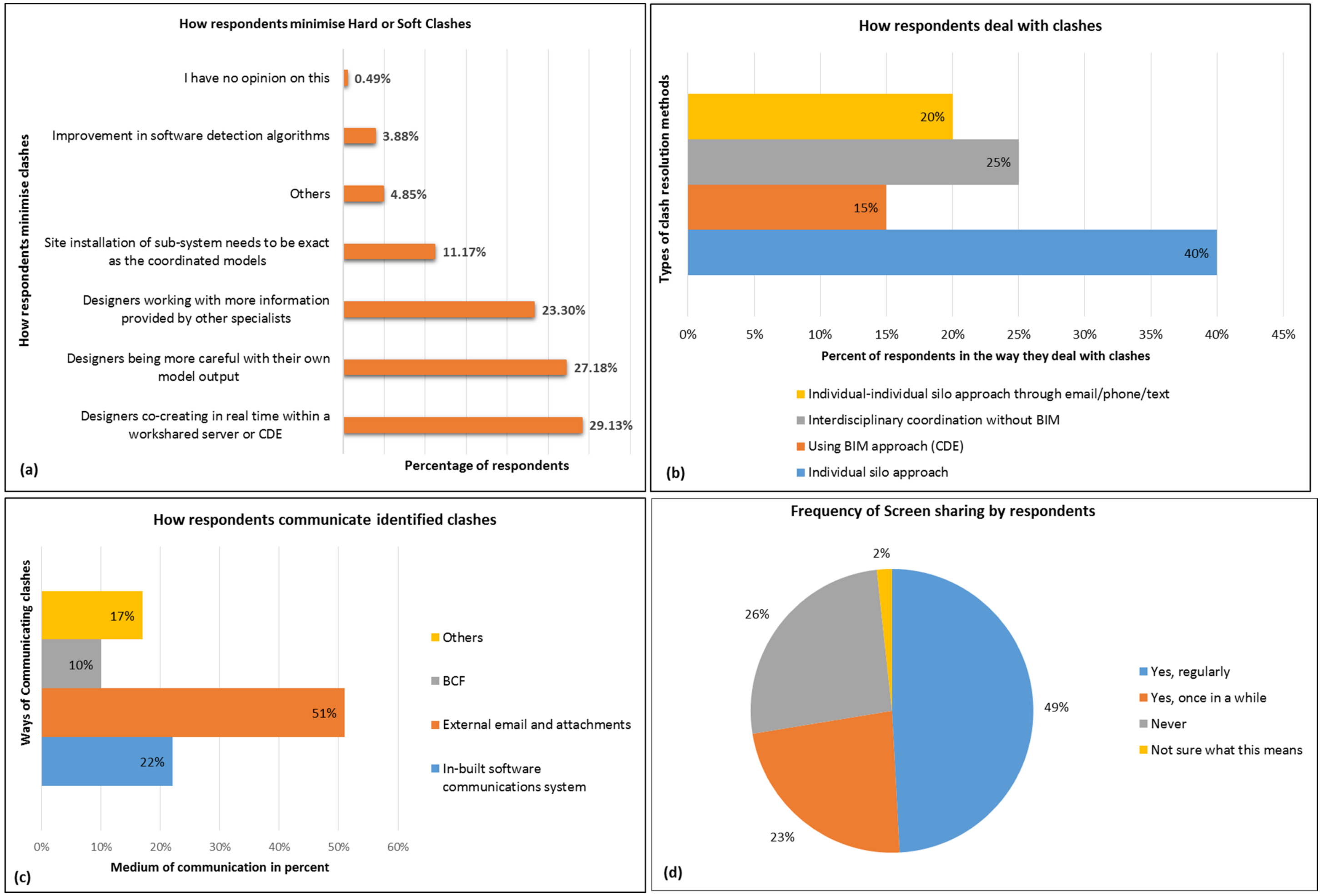

Figure 4. Respondents' views on how clashes are resolved.

However, resolving clashes by using a BIM approach (through a CDE) received the least mention. Concerning "how designers communicate identified clashes? (Figure 4c)" majority of respondents used email to communicate identified clashes. Evidently, the BIM collaboration format (BCF) has still not been embraced by practitioners based on this survey. Finally, with regards to whether "designers use remote desktop to resolve clashes?" (Figure 4d) up to 72% of respondents reported that they have been involved either occasionally or regularly in the use of remote desktop to share their clash detection screens. This implies that some sort of concurrent working (although this time in clash detecting) is evident among design practitioners involved in the survey. It was interesting to observe that while practitioners were not co-creating 3D models during the design process, they were readily sharing their clash detection screens. It might be that when faced with problems/challenges, they were willing to seek opinion or assistance in real-time but during the original creative design process, they were less inclined to get instant support. The extent to which the structure of CDEs either support or inhibit this practice will need to be considered.

Two important details emerged from the quantitative data analyzed in the first phase. First, designers employed different approaches in resolving clashes and second, the common data environment was still underexplored by designers, as evident from the popularity of email communication. This prompted the need to probe selected industry practitioners about how they dealt with clashes and how they collaborate via cloud-based platforms like CDEs during the design phase with focus on MEP coordination.

4.2. Phase 2: Qualitative Phase of the Study that Addressed the Research Questions

The first phase of this study examined and addressed two research questions; a third research question is: To what extent will the CDE facilitate interdisciplinary coordination and clash avoidance among design teams in the way they deal with clashes? The interviewees were selected based on (a) being specialists who had spent on average about fifteen years of professional design practice and (b) having at least two years of practicing clash detection. Both criteria were important because the insights provided would enhance the credibility of the data. From the six respondents who satisfied these criteria, two were based in the UK, three were from North America and one was from Singapore (Table 7).

Table 7. Profile of interviewees.

Interviewee	Location	Professional Role	Years Practicing Clash Detection
Interviewee 1	UK	BIM coordinator	2–3 years
Interviewee 2	UK	CAD/BIM Manager	2 years
Interviewee 3	South East Asia	Civil/structural Engineer	2 years
Interviewee 4	Canada	CAD/BIM Manager	2 years
Interviewee 5	USA	BIM coordinator	>7 years
Interviewee 6	USA	CAD/BIM Manager	>7 years

A total of four themes and eleven sub-themes that emerged from the interview are presented in Table 8. The interviewees' key comments presented verbatim highlighting the issues exposed are presented in Table 9. From the table, while it is apparent that the WIP of the CDE promotes some sort of collaboration among different design disciplines, it still suppresses design creativity among design participants and could hinder free exchange of information among design specialists.

In summary, the method section has validated the important results obtained from literature that falls within the scope of this study, namely; that working in isolation, inexperience of designers and design errors by practitioners are critical causes of clashes between the MEP discipline and other players. This is in addition to existing CDE's being isolated as not permitting co-creation. Following this, relationships between scope, framework, method and findings are presented in Figure 5.

Table 8. Thematic summary of the interview result.

Themes	Sub-Themes	Interviewee 1	Interviewee 2	Interviewee 3	Interviewee 4	Interviewee 5	Interviewee 6
Clash resolution platform	BIM	Use of WIP in BIM	Clashes saved as NWD files	Coordination meetings		Resolved outside BIM platform	Resolved outside BIM platform
	Email	Not used	Not used	Email communication	Emailing using snapshot	Email communication	Email communication
Clash resolution problems	People factors	Most designers only know how to use software		People still design conventionally	Poor coordination between disciplines	Lack of shared situational awareness	General contractors hinder coordination
	Process/policy	Change of designers due to contract type	MEP designs done last				Over-the-wall attitude of architects even in CDE's
	Time constraints	Not an issue	Short time for design and construction	Not an issue	Not an issue	Hurrying to meet deadlines	Not an issue
	Other constraints	Large MEP sizes	Design complexity		Inadequate MEP space		2D instead of 3D designs
Resolving clashes through coordination	MEP sequence blamed	Designers not speaking together affects MEP			Coordinate more with MEP	Work together	MEP given last priority
	Running clash tests	Too many irrelevant clashes	Poor clash reporting				
CDE and WIP	Structure of WIP in CDE	Still digitization of traditional practice	Cannot say	No response	Should allow switching btw life and snap shots	No response	Not aware of CDE
	Security concerns	Cannot say	Cannot say	Cannot say	Government projects has more security risks	Security in place hinders screen sharing	Cannot say
	Clash avoidance	Synchronous coordination will eliminate design errors	Proper use of BIM	Clear BIM process	Cannot say	Give MEP more space	No response

Table 9. Summary of key issues exposed in the qualitative research (interviewees' comments in verbatim).

Issues Exposed	Interviewee 1	Interviewee 2	Interviewee 3	Interviewee 4	Interviewee 5	Interviewee 6
There is a need to urgently change existing silo-based cultures. The CDE risks been treated as a digitized silo folder	*Inherently people like to work from a set point. Architects may not want to work with a model received from the MEP designer knowing it's WIP and waste time designing ceilings knowing full well that the design is very likely to change. People's natural tendency will be to create a file structure in theory within the WIP, Shared and Published folders. There shouldn't be any folders within them.*	*NWD file with clashes saved as viewpoints is simply issued to design team with an accompanying report.*	*At my work, we just conduct a coordination meeting. If we are using BIM in our projects, we will conduct 3D coordination among disciplines*	*Maybe we are old school... but we work with email communication using snapshots. Live models drive the MEP engineers in our company crazy*		
Existing practices which relegate the MEP discipline promote isolated working culture and adversely impacts design quality	*Isolated designers from each discipline will often work for a couple of weeks without speaking to the other design consultants and design changes can be made and go unnoticed by others*	*At present (and historically) we see that MEP designs follow*		*We receive designs from architects and try to fit our systems within those volumes . . . if the volumes are inadequate, we communicate with the architect to provide more volume . . .*	*It would be a lot more advantageous if the design teams work together rather than the MEP contractor just been handed over the work . . . we (MEP) end up redrawing the whole system*	*The architect has something and when they are done, it gets thrown down to the engineers to do their thing.* *Typically, the MEP contractors are at the end of the chain when it takes everybody to do the whole thing. So, we should all be talking together throughout the whole phase*
Clash detection tools are not enough. Coordination of designs and situational awareness needed	*Most technicians are taught how to use the software but not how to design*		*Designers still design in a conventional way (2D). They do not coordinate with other disciplines*	*Not enough coordination between the disciplines. Architects constantly change designs and do not highlight what has changed*	*The other thing...you don't know what is happening with other design disciplines*	
Information sharing not wholly embraced				*We have government projects. It's for security reasons*	*The security system in place is an issue*	

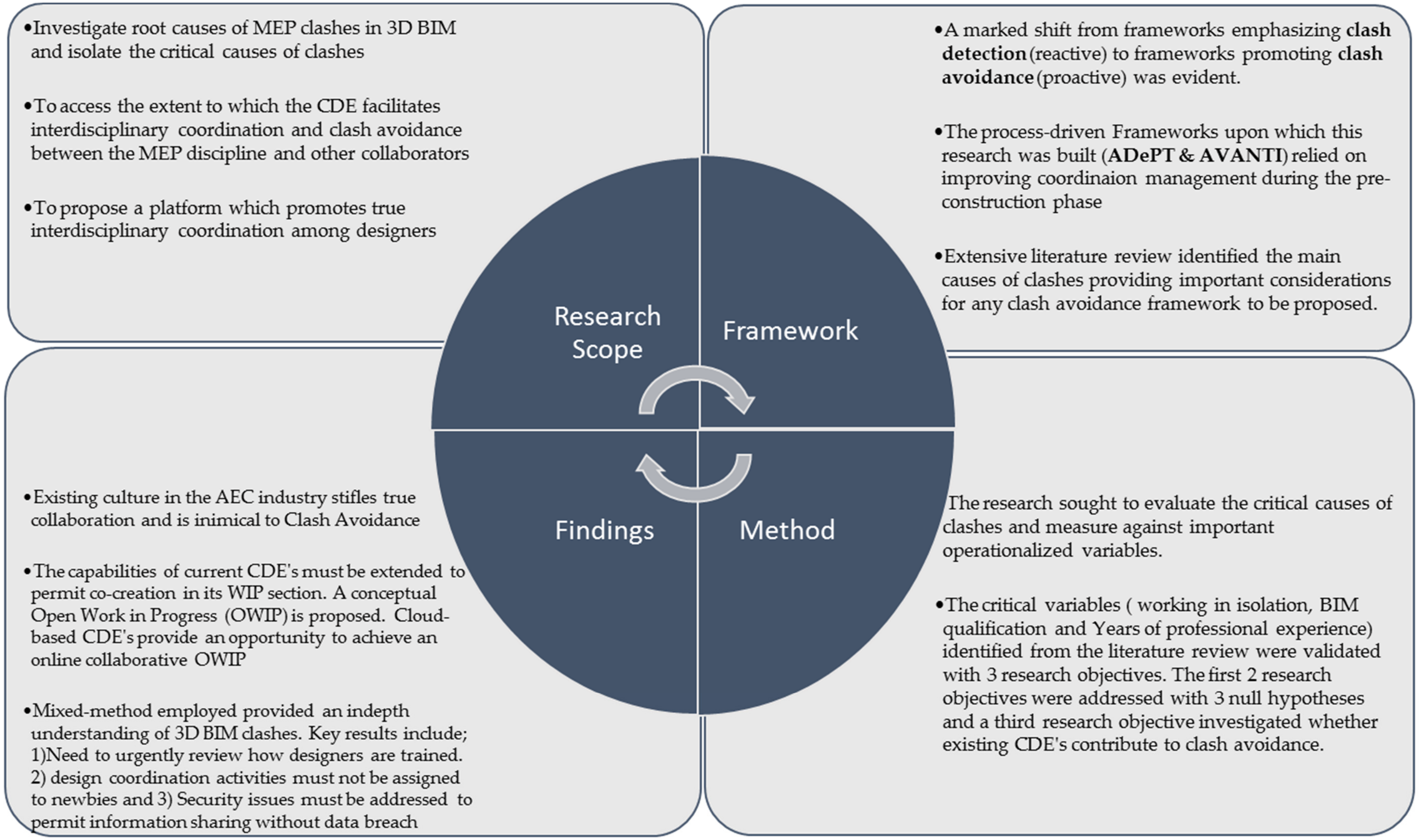

Figure 5. Relationships between scope, framework, method and findings.

5. Towards an Open Work in Progress (OWIP): A Proposal

The present practice of collaboration and coordination through emails and extranets is practical for document-centric information exchange, but the processes could improve by supporting a single concurrent version of design information. The data collected and analyzed suggests that because isolated working is a prime cause of clashes emerging, the "work in progress" (WIP) section of the CDE inadvertently encourages such practice at the crucial early phase of design. In fact, the WIP could be said to be a digitized version of the "over-the-wall" silo mentality based on the description of Froese [37], who argued that the breaking down of project work into discrete tasks assigned to specialist groups (e.g., architectural, MEP, structural, quantity surveyor (QS), etc.) creates design or construction tasks that are "far more independent" than they practically ought to be. Such practices have been characterized with litigations, costs and schedule overruns as well as breeding adversarial relationships and protectionism in multidisciplinary teams. While the findings of this study cannot be generalized, they can be accepted as evidence that the current structure of the CDE is already being critiqued by designers as to its capability to deliver a product which involves the collective design decisions of all stakeholders in the chain of design project delivery. This study therefore proposes an Open work in progress (OWIP) stage (see Figure 6 below) that eliminates the need for a "SHARED" folder in the CDE (Figure 1).

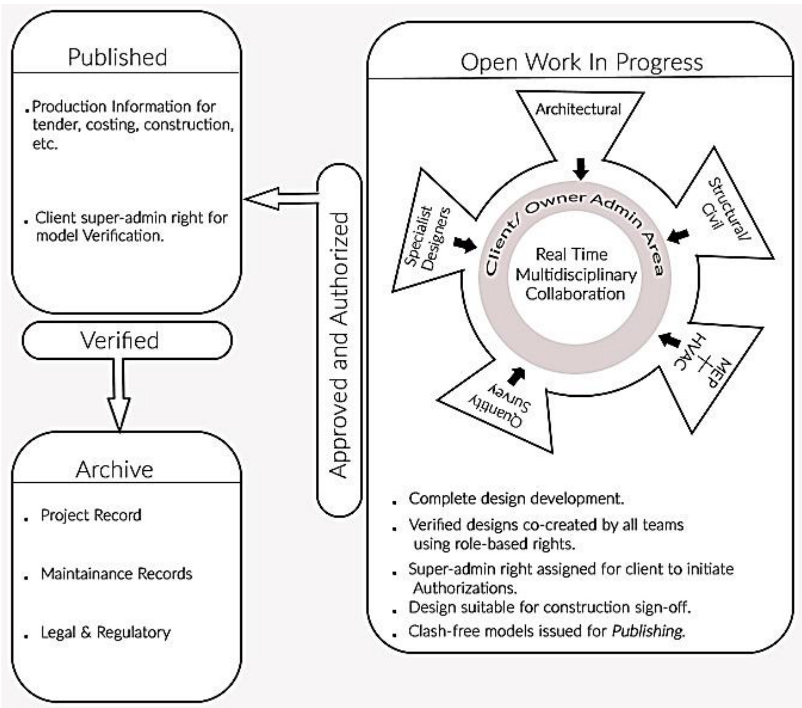

Figure 6. Proposed common data environment (CDE) with an open work in progress (OWIP).

By merging the "WIP" and "SHARED" containers into an "Open" stage, greater transparency and shared situation awareness can be encouraged. An adaption of the standard CDE as proposed in BS 1192 [60] and PAS 1192-2 [2] is illustrated in Figure 6 above showing the proposed OWIP. An admin area with a super-administrator access right is proposed for the client in the OWIP (Figure 6) to replace the client-shared area in the SHARED folder of the CDE proposed in PAS 1192-2 [2]. The proposed OWIP based CDE structure should facilitate concurrent working of inter and intra-disciplinary teams. Since OWIP would support the multiple iterations that typify the early design stage, it would ensure that project information during the critical early phase of the project's life cycle is co-created by (and accessible to) all project stakeholders. True collaboration cannot be divorced from shared situational awareness and through synchronous and concurrent design. This proposed structure eliminates after-the-fact sharing of information via the SHARED containers. The nature of information exchange among the principal parties involved in the typical design phase of a project according to the proposed OWIP is illustrated in Figure 7 below.

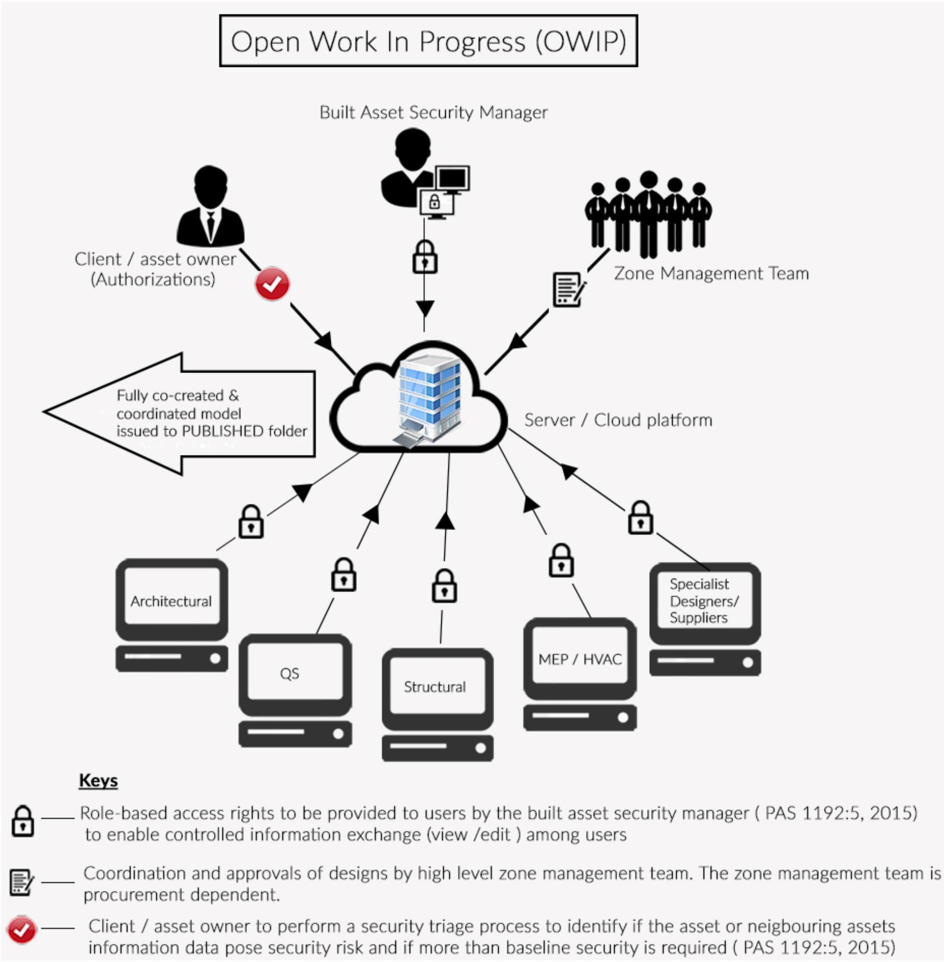

Figure 7. Information exchange and access control in OWIP.

This conceptual framework for an OWIP-based common data environment is grounded on theories like the Evolution-Sensitivity Framework [33] as discussed earlier. The fundamental principle involved in in the Evolution-Sensitivity Framework is that the design of an upstream and a downstream activity can be carried out under different overlapping scenarios. Similarly, the ADePT technique [32] also emphasizes concurrency in making crucial design decisions which involves minimizes lengthy iterations but encourages collaboration among a team who would assign "critical", "important" or "nice to have" statuses on design information to quickly identify areas of compromise. The proposed OWIP suggests the creation of project and asset information model as a collaborative design process that mimics actual construction process. If designers collaborated in the same way that contractors, sub-contractors and tradesmen were compelled to collaborate during construction as this study suggests, clash avoidance can be achieved. This is what informs the conceptualization of the OWIP which is underpinned by theoretical frameworks mentioned above, in addition to the principles of shared situational awareness [61,63] and supported by data collected and analyzed in this study. Models developed concurrently in an open platform where approved individuals can access will reduce or even eliminate the clashes linked to spatial coordination. The resulting clash-free models or data can then be approved and issued for publishing.

However, the OWIP as conceived does not specifically address issues bothering on security and intellectual property rights or professional liabilities. With the restriction of unauthorized access into the OWIP (see Figure 7), each discipline (e.g., the Architectural) will have user-controlled access rights permitting other disciplines to view, add comments, suggest changes or carry out controlled "editing" of parts of a model. At a minimum, viewing rights should be granted to all relevant design disciplines involved in the project on a need-to-know basis as suggested in PAS 1192:5 [72]. As the design and project develops, the access rights may need to be constantly reviewed and updated. It is also important to point out that determining the allocation of the status of user-controlled access rights is the responsibility of the asset owner or employer [72]. In this regard, the handling of approvals, coordination of the designs and managing of information flows in OWIP come within the purview of a zone management team (see Figure 7). It is appropriate that representatives of the zone management team need to possess a high level of shared situational awareness for them to indoctrinate it into other project participants. While this study is not intended to be prescriptive on the make-up of the zone management team, it is expected that the roles of lead designer, BIM coordinator and information manager would be represented in the team. This may also be influenced by the procurement strategy adopted for the project.

Finally, it is imperative to highlight that the success of a true cloud-based co-creation capability will largely depend on Internet availability, broadband speed and the extent of interoperability of the software solutions. This suggests therefore that open BIM solutions are most adaptable to an OWIP.

6. Discussion

Hard clashes typically involve MEP systems due to the density and sheer quantity of mechanical, electrical and plumbing components. This problem continues to affect the design process but clash detection has been favored more than clash avoidance due to cultural practices and lack of technologies that support the latter. Identifying the root causes of MEP related clashes will facilitate the development of digital systems and support tools that promote clash avoidance and may improve existing systems that stifle common design solutions.

In this study, we investigated the extent of occurrence and root causes of hard clashes in 3D coordination systems to identify while clash detection tools throw up a high number of clashes during clash detection. Using explanatory sequential mixed-methods, we identified Structural and HVAC components as the main building systems involved in hard clashes. It has been known that MEP or HVAC systems are regularly involved in clashes in 3D building coordination [21,31]. This has prompted studies on identifying the gains and problems associated with their coordination in building systems [12,46] as well as determining what needs to be modeled for MEP coordination to increase the effectiveness of clash detection tools [1]. Some studies that have explored the specific extent of MEP clashes in buildings [1,4] have viewed the problem from a clash detection perspective, which is a reactive process that encourages isolated working. Data collected from study supports these findings and has sought to investigate how the problem can be addressed proactively.

Traditional practices and culture have encouraged information hoarding and although practitioners are clear on the root causes of clashes [21,25,31,36,40] there appears to be ignorance about ways (or need) to achieve clash avoidance. This study found that working in isolation is the predominant cause of clashes in 3D BIM but there is no suggestion that the other causes of clashes are any less important. What this study can help establish (through the research question: Are the high incidence of MEP-related clashes significantly related to isolated working?) is that isolated working creates social boundaries which inhibit a sense of shared ownership and participation, thus leading to design conflicts and clashes. Empirical evidence from this study strongly linking MEP-related clashes in 3D BIM to isolated working among designers demonstrates the need for further reflection on how they work. Eliminating the opportunities for silo-based working in interdisciplinary collaboration would promote greater participation where MEP designers (whose models are crucial to coordination) are integrated early into critical design decision processes in project delivery.

There is a perceived link between clashes and unprofessionalism or incompetence in some design practices (as addressed through the research question; "Are professional errors by designers related to their non-BIM specific training?"). The findings from the quantitative phase of the study suggest that a significant number of designers have learnt clash detection "on the job" i.e., informally, while only 22% reported that they have over six years of experience doing clash detection. This corroborates Kensek and Noble [41] who bemoaned the lack of organizational training as well as Leite et al. [4] who attributed clash detection problems to the hiring of novices. The empirical data obtained for the null hypothesis of this research question establishes a link between clashes and the lack of specialized BIM training for designers. This implies that clash avoidance can be achieved when practitioners receive adequate industry and organization-led training on BIM practices which encourages transparency and collaboration and not just the use of (clash detection) software. This proactive approach (i.e., clash avoidance) will create a project environment where shared situational awareness thrives and where fewer design errors are made.

Nevertheless, evidence from the third null hypothesis (Are the high incidence of Structural and HVAC clashes in 3D BIM related to the years of experience of designers?) appears to conflict with previous literature. Although a significant correlation was found which suggests that Structural and HVAC clashes were related to the years of experience of the respondents (designers), the direction of the relationship was expected to be negative to be consistent with extant literature (e.g., [46]). This may indicate the emergence of new trends or perhaps some limitations due to the sampling (e.g., size, professional representation and geographic dispersal of respondents) used in the quantitative phase of this study. However, an interviewee's comment revealed that the older generation of MEP designers encounters more hard clashes because they are not familiar with the technologies/software. Admittedly, poor knowledge of clash detection software tools by older designers (who would be more familiar with traditional 2D-based coordination) may lead to wrong interpretations of false positive and false negatives [1] thus giving misleading results during MEP coordination. Still, the results are consistent with literature, that is, although non-BIM qualification increases design errors and clashes; unfamiliarity with the software also produces significant clashes when a clash detection test is run.

Lastly, investigation of the third research objective (To access the extent to which the CDE facilitates interdisciplinary coordination and clash avoidance among design teams) via the qualitative study revealed that MEP designers were less positive about the gains of working in the current WIP section of the CDE. The findings from this study agree with published studies on the problems of MEP coordination. For example, procurement concern [50], security controls [39,71] and the digitized nature of the CDE [49]. What this study has been able to establish is that any CDE that does not promote open sharing of information by its users can be counter-productive and in fact, the current WIP containers end up being "digital information silos". Therefore, true synchronous co-creation is by default difficult to achieve in the current structure of the CDE and hence cannot facilitate clash avoidance as desired in PAS 1192-2 [2].

7. Conclusions

This study was aimed at investigating the root causes of clashes in 3D BIM and the feasibility of implementing clash avoidance for minimizing such coordination problems. The study has found that a key ingredient necessary to achieving clash-free 3D BIM models is to discourage "isolated working". This could be achieved through platforms that enable real-time synchronous collaboration so that all participants possess the same level of (shared) situational awareness. Early engagement by relevant designers with the design model through an open work-in-progress (OWIP) will engender transparency and co-creation with designers able to review, modify or recommend design changes as the design progresses. In addition, it was found that the training and experience of designers is crucial to the effective use of BIM coordination (clash detection) technologies but the same could apply to any current or future technologies that support clash avoidance.

Some practitioners (designers) shared concerns about co-designing in a shared workspace to achieve clash avoidance. Commonly stated reasons bordered on proprietary rights, confidentiality and security concerns. While such fears about data security and intellectual property rights (IPR's) during co-design in a shared workspace are valid, these can be addressed by appropriate role-based access rights, configuration control procedures and back-up policies. Data from the study suggests that many practitioners are already familiar with technologies that empower them to (visually) share their work with remote stakeholders.

Moreover, the most recent publicly available specification (PAS) document on securing BIM data i.e., PAS 1192:5 [72] also contains detailed recommendations on how asset owners can assess the security requirements of the constructed model and this is expected to be a guide for design collaborators in the AEC industry in the UK. The language of the PAS 1192:5 guidance document suggests that it is the prerogative of asset owners to determine and grant data access to model collaborators on a need-to-know basis via a built asset security manager. This appear to place the security risks and costs involved in a virtually designed and constructed model on the employer who is to ensure due diligence. This may be easy to implement in huge government or global projects, but concerns about the additional security-related costs for private and small traditionally procured projects remain, including to what extent such costs will inhibit interdisciplinary cloud-based information exchange if a client does not address such concerns. Thus, a bottom-up approach by the different key players in the AEC industry is necessary while urgent administrative and policy review by construction organizations is essential to swiftly address current silo-based working cultures.

In addition, the findings suggest that to achieve clash avoidance, the CDE should be unsegregated and be able to adequately support interdisciplinary and remote collaboration. Without this, the CDE structure may end up re-creating the traditional over-the-wall coordination at the early design phase. To address this problem, OWIP has been suggested as a transparent process that supports co-creation at the early design stages when crucial long-term decisions are made. This transparent and inclusive process might have implications on the way a new generation of AEC professionals are trained because it challenges the way designers are trained to focus on their own systems in addition to requiring them to be given dedicated training on coordination and co-creation.

8. Limitations

The first phase of this study involved the use of an online survey questionnaire administered via a dedicated professional social network group focused on coordination in BIM. The risk of a non-response bias may have increased if the respondents in the original sample population (3000) who did not respond to the questionnaire have different opinions from those who responded (116). It is also possible that some more experienced designers involved in clash detection could not be reached through the process employed for data collection. In addition, non-random sampling was employed for this research and it is often impossible under such circumstances to generalize the findings beyond the sample represented in the study. However, the results obtained are generally consistent with published studies.

9. Future Work

The open work-in-progress described in this paper is based on established clash avoidance strategies and existing technologies and is intended to replicate the collaboration practiced during practical building construction. Nevertheless, there is need for more studies and evidence to validate the expected benefits.

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Conflicts of Interest: The authors declare no conflict of interest.

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