BUILDING INFORMATION MODELLING (BIM) AND THE CDM REGULATIONS INTEROPERABILITY FRAMEWORK

Purpose

Building Information Modelling (BIM) has received wide coverage within the research, academic and industry communities over the last decade. Yet, its degree of integration with various industry standards in the architecture, engineering and construction (AEC) sector varies extensively. An exploratory research approach explores the interoperability between the CDM Regulations and BIM.

Design/methodology/approach

The research design comprised: (1) a methodical '*state-of-the-art*' review of extant literature—exploring some 19 variables emerging from the literature review; (2) detailed content analyses of the current CDM regime (CDM 2015); and (3) conducting a '*test*' to map and determine the degree of interoperability between BIM and CDM. The study develops several meta-matrices, and a framework for BIM and CDM interoperability.

Findings

New insight reveals that BIM provides a systematic approach for the discharge of CDM obligations. The framework developed is easily transferable into BIM Common Data Environments (CDEs) and offers an expeditious discharge of CDM obligations.

Research limitations/implications (if applicable)

Some features of the developed BIM/CDM interoperability framework invite further tests to predicate the degree of discharge of CDM obligations. Duties related to provision of preconstruction information invite further research.

Originality/value

Little research provides insight into the interoperability of BIM and the Construction Design and Management (CDM) Regulations. Therefore, this study contributes to the knowledge relating to the degree of interoperability of BIM in construction systems, processes and standards.

Keywords: Building Information Modelling (BIM), CDM regulations, health and safety

1.0 INTRODUCTION

The sluggish adoption of new and advanced technologies in the construction industry is easily noticeable given the long-standing conventional methods of construction and its procurement. While it is common knowledge that the construction industry contributes considerably to the growth of the economy, it still faces several impediments which prevent a consistent positive outlook. Challenges such as: poor health, safety and well-being of construction workers; and project cost or time overruns remain commonplace. Moreover, often, it is considered that several layers of fragmentation in the construction industry for the most part lend themselves to slow progress in terms of modernisation, adoption and uptake of new advanced technologies and digitization. Whereas, in the United States (US), efforts towards improved uptake and attainment of digitization has gained significant momentum (see Becerik-Gerber and Rice, 2010).

Indeed, most AEC sectors still show signs of a slow uptake of new technologies towards improved project delivery. Even seminal reports published as far back as the 1990s revealed this trend. For example, the report by Sir Michael Latham (Latham, 1994) recommends improved cost reduction (p.80), while Sir John Egan’s report (Egan, 1998) recommends a reduction in capital costs and construction time (p.16). On the other hand, Wolstenholme (2009) identified four key blockers to progress, namely: business and economic models, capability, delivery model and industry structure (pp. 5-6). Wolstenholme’s report concludes that, there is need for joined-up thinking between government and industry stakeholders; and a cohesive manner of working attained through proper industry leadership and uptake of business models that encourage integrated teams and processes, and less subcontracting. However, increasingly, studies show that BIM can play a significant role in this regard. For example, adopting a BIM-enabled procurement approach yields improved inter-organisational and inter-dependent working and easier team and process integration as explained by Fox and Hietanen (2007).

Despite notable progress in some areas of construction project delivery, it is no surprise that the industry is still making slow progress and often has a poor image and reputation because of accidents, injuries, and illnesses (see Donaghy, 2009). Although it is outside the scope of this research to explore accident causation given that other researchers address this aspect thoroughly (e.g. Abdelhamid and Everett, 2000; Gibb *et al*., 2006; Hale *et al*., 2012), this study extends current knowledge and understanding by considering the degree of BIM and CDM interoperability underpinned by the theoretical principles of prevention. Fundamentally, the principles of prevention denote an assigned ‘duty of care’.

Given the poor reputation often associated with the construction industry because of the prevalence of accidents and injuries, which result in low productivity and increases the anticipated project cost and duration (HSE, 2015), consideration of modernisation and digital technologies in the broader view of H&S is critical. The foregoing observation resonates well with the International Labour Organisation’s (ILO) Occupational Health and Safety (OHS) agenda which advocates for improved workplace H&S. ILO (2015) explain the importance of government driven initiatives such as laws and regulations that address H&S during all phases of construction; and the redistribution of contractor’s responsibilities by inclusion of other project stakeholders such as the client.

In the UK, domestic laws and regulations such as the Construction (Design and Management) (CDM) regulations are well placed to address improved H&S in construction, however, the challenge often lies with implementation practices (e.g. Baxendale and Jones, 2000). The primary H&S legislation in the UK is known as the Health and Safety at Work etc.

Act (HSWA) of 1974; as such, secondary legislation such as the CDM regulations often stems from this primary H&S legislation.

Indeed, the CDM regulations are frequently considered as the most far-reaching and relevant legislation in terms of H&S in construction (Bomel, 2007). Despite this view, the shortcomings surrounding these regulations are widely reported (e.g. Beal, 2007; Bernard, 2007; Dalby, 2009), as noted in the literature review. Often, there are numerous efforts put in place to address these shortcomings, such as redrafting of the regulations to provide more clarity. While it is commendable that such changes often trigger a rethink in the typical execution of CDM obligations, several problems still reoccur such as misunderstanding of roles and responsibilities. In the current regime (CDM 2015), some notable changes include:

- replacement of the CDM coordinator (CDM-C) role with the new Principal Designer (PD) role;
- close alignment of the CDM regulations to the EU Directive 92/57/EEC; and
- placing significant responsibilities on commercial and domestic clients.

Besides these changes, it is considered advantageous to identify tools that complement the discharge of CDM obligations. For example, because of the shared responsibility ethos that underpins CDM, it is reasonable to envisage that BIM may significantly contribute to the operation and discharge of CDM obligations. Moreover, several studies reach a consensus which supports the view that BIM increases project stakeholder integration and collaboration across the supply chain (e.g. Barlish and Sullivan, 2012; Bryde *et al*., 2013; Eadie *et al*., 2013; Volk *et al*., 2014; Ghaffarianhoseini *et al*., 2017) which is a key requirement for effective CDM implementation. Shedding light on the interoperability of BIM and the CDM, provides researchers and CDM practitioners, new insight and understanding.

2.0 RESEARCH DESIGN

The research design adopted for this study was largely exploratory given that BIM research relating to health and safety (H&S) legislation has been rather limited. This exploratory approach took the form of document analysis, which according to Bowen (2009), is a systematic procedure for reviewing or evaluating documents for the purpose of eliciting meaning, gaining understanding, and developing empirical knowledge of a phenomenon. Although their role in social research is rarely highlighted, it has been observed that documents often serve as key sources of social scientific data (Given, 2008). Documents are one of the main ways of communicating at all levels of society and hence, can provide deep insights into many aspects of life at an organisational or societal level (Cardno *et al*., 2017).

The research design is largely informed by the guidance offered by Bowen (2009), O'Leary (2014) and Bryman (2016). A two-stage process was adopted comprising firstly, a thorough and systematic '*state of the art*' review of literature highlighting the health and safety (H&S) performance in the UK construction industry, and secondly, an analysis of critical documents relating to health and safety obligations and BIM. These stages are discussed in more detail below.

2.1 Systematic literature review

A systematic literature review was undertaken to provide a comprehensive understanding of key BIM implementation factors; particularly the role of information exchanges, and the potential impacts on h&s performance. Over 150 studies related to BIM were considered and subsequently carefully narrowed down to over 60 based on quality, proximity to BIM integration and uptake, and authority in the AEC industry. Selection of these studies involved a detailed search of several research databases such as '*Emerald Insight*', '*Science Direct*', '*Web of Science*', '*Zetoc*', and '*Elsevier*', using key words and phrases such as 'BIM', 'Building Information Modelling', 'Building Information Models', 'Information Modelling' and 'Automation in Construction'. To narrow the search results, the studies were categorised into six BIM-related topics as listed below.

- Category 1: BIM implementation and benefits process improvement
- Category 2: BIM improved H&S outcomes
- Category 3: BIM information exchange
- Category 4: BIM technologies
- Category 5: BIM facilitation and interoperability
- Category 6: BIM in a wider context and other information modelling studies.

Furthermore, the study employed matrices to develop understanding of the patterns in the literature. According to Miles *et al*. (2014), matrices provide defined rows and columns in which, information can be systematically arranged in a tabular format based on time and other variables as perceived fit, to permit detailed analysis, easy viewing and the ability to order information. From the matrices, it is then possible to make inferences, by noting patterns, themes, contrasts, comparisons, clustering and counting (*ibid*, p.117). Typically, the analysis involved, scanning through the matrix to determine the emerging patterns.

2.2 Document Analysis

Document analysis, like other analytical methods in qualitative research, requires that data is systematically examined and interpreted in order to construct new meanings or develop deeper insights into the subject matter (Bowen, 2009). Documents can be wide-ranging and can include *inter alia*: advertisements; agendas, attendance registers, and minutes of meetings; manuals; background papers; books and brochures; diaries and journals; event programmes; letters and memoranda; maps and charts; newspapers (clippings/articles); press releases; radio and television programme scripts; organisational or institutional reports; survey data; and various public records (*ibid*). For this study, the principal document analysed was the Construction (Design and

Management) Regulations 2015. Whilst Bowen (2009) suggests that the wider the array of documents analysed the more robust the results, it is also noted that the quality of the document analysed is more crucial than quantity (Bowen, 2009).

The analytical procedure adopted entailed finding, selecting, appraising (making sense of), and synthesising data contained in CDM 2015 relating to information production or exchange. Based on Bowen (2009) and O'Leary (2014), the data extracted from the Regulations, specifically through content analysis, was organised into major themes and categories.

Content analysis is a viable data analysis technique often employed in qualitative research design. Indeed, it is considered by a large body of research scholars as credible. It is therefore unsurprising that its use and application in the field of construction related research is wide. Bryman (2016), an authority in organisational and social science research, defines content analysis as:

> *[…] an approach to the analysis of documents and texts (which may consist of words and/or images and may be printed or online, written or spoken) that seeks to quantify content in terms of predetermined categories and in a systematic and replicable manner.*

Essentially, this involves researchers determining the key issues, then documenting and organising the occurrences of the issues within the document. Content analysis provides a means of drawing up inferences from text as demonstrated on numerous occasions. While content analysis is widely considered as transparent and transferrable (Bryman, 2016), there are a few drawbacks. For example, the content analysis is only as detailed as the assessed documents. Meaning, for this study, the insights presented are limited to the content of the CDM 2015. Arguably though, the authoritative nature of this piece of legislation in construction H&S management in the UK, provides a robust basis for mapping the information requirements within a BIM Common Data Environment (CDE). This is sufficient to address the aim of this study which is to test whether

BIM adoption offers a solution for the expeditious discharge of information production and exchange obligations under the CDM 2015 and develop a framework for CDM implementation within a CDE.

3.0 LITERATURE REVIEW

The literature review covers three main areas: (i) H&S performance; (ii) Building Information Modelling (BIM) implementation and uptake factors; and (iii) the Construction (Design and Management) (CDM) regulations. Doing so achieves two outputs. First, it reinforces the need to undertake this research; and second, it increases the level of understanding surrounding BIM implementation. To date, there is insufficient progress that provides a clear “roadmap” explaining the extent to which BIM complements the discharge of CDM obligations. At best, such efforts are mostly intermittent and provide limited guidance.

3.1 Health and Safety performance in the United Kingdom construction sector

The current state of the UK construction sector in terms of H&S reveals a steady decline in the number of accidents. This notwithstanding, up-to-date figures show that in 2017/18, 38 workers were fatally injured in the construction sector. This still paints a rather unpleasant image of the construction industry. Figures relating to non-fatal injuries and ill health because of construction related activities are similarly alarming. The average annual number of non-fatal injuries between 2013/14 to 2015/16 was 66,000 of which the majority (23%) accounted for slips, trips and falls (HSE, 2017). In comparison with other sectors, figures within the construction sector are striking (see HSE, 2015). In 2017, the HSE’s construction division found that of the 79,000-work-related illnesses reported, 64% were because of musculoskeletal disorder, while stress, anxiety and depression and other illnesses, accounted for 18% each (HSE, 2017). Without question, more action is required to improve the H&S performance of the industry.

Table 1: Fatal injuries to workers in the UK construction industry (HSE, 2016, 2018)

Year	Self-employed	Employees	Total number of fatal injuries
2011/12	23	25	48
2012/13	14	26	40
2013/14	14	30	44
2014/15	11	24	35
2015/16	16	31	47
2016/17	9	22	31
2017/18	13	25	38

3.2 Building Information Modelling (BIM) implementation factors

Building Information Modelling (BIM) has gained significant momentum since the mid-2000s. The implementation of BIM to date is wide-ranging and covers a number of important areas and features. For example, a study conducted by Fox and Hietanen (2007) considered the inter-organisational use of building information models in Finland. The research explored the uptake of BIM by 20 organisations comprising: three building owners, seven building design consultants, two building component producers, five building contractors and three software companies, of which the results revealed that BIM integration was popular across all the organisations despite the barriers experienced. Sebastian (2010) on the other hand considered the integration of BIM on a small-scale project of four independent houses in the Netherlands and reached a conclusion that BIM makes it possible to integrate solutions from various project participants. Khosrowshahi and Aryici (2012) developed a roadmap for BIM implementation based on secondary data. The main headline features of the BIM implementation roadmap included organisational culture, education and training, and information management. The study concludes that each area highlighted in the roadmap invites careful consideration for further research.

Eadie *et al*. (2013) conducted an online survey to determine the implementation of BIM throughout the UK and reported that BIM was widely used during the early stages of the project lifecycle and less as the project progressed. Unsurprisingly, Eadie *et al*. (2013) also conclude that there is lack of industry expertise. These insights suggest the need for more support for BIM implementation.

Indeed, even in other countries, BIM integration and uptake varies considerably. For example, in Australia, Gu and London (2010) conducted two focus group interviews in two major cities and revealed that there was lack of experience in BIM. Similar findings have been reported by Teo *et al*. (2016) in Singapore and Cao *et al*. (2015) in China (cf. Bryde *et al*., 2013). Although the challenges for the integration and uptake of BIM universally appear varied, the underlying and recurring concern is lack of expertise. Even recent studies reveal intermittent uptake of BIM. For example, Ghaffarianhoseini *et al*. (2017) conducted a literature review and concluded that the lack of BIM uptake was to a certain degree linked to the risks and challenges. While Alreshidi *et al*. (2017) corroborate this view and reveal that there were several barriers to BIM adoption (p.92). Similarly, Bradley *et al*. (2016) revealed barriers such as lack of effective governance of project information integration.

A study that explored information exchange through cloud BIM based on 11 semi-structured interviews revealed that cloud computing had the potential to contribute to BIM interoperability (Redmond *et al*., 2012). Demian and Walters (2014) considered the advantages of information management through BIM and measured the flow of information based on four case studies of an offsite precast concrete fabrication facility in the UK. The benefits observed because of BIM adoption, included:

(i) improved information exchange,

(ii) timely information exchange, and

(iii) promotion of early stakeholder integration.

Additionally, Maki and Kerosuo (2015) considered the site manager’s daily work and use of BIM. Conducting an ethnographic method, by shadowing the site manager, the study revealed that despite the benefits, there was still a lack of competence in the use of BIM software tools and that the models lacked the desired information content. Overall, the study revealed that the site managers had no guidelines or protocols of how to utilise BIM, as such, the onus was on the project stakeholder to implement BIM. Because of the varied nature of what might obtain on sites in relation to BIM implementation, development of BIM adoption frameworks is crucial. Where BIM is successfully deployed (see Davies and Hardy, 2013a), there is a real sense of ownership amongst the project team.

Occasionally, studies have demonstrated the capability of BIM, highlighting its varying dimensions. According to Harrison and Thurnell (2015) and Abanda *et al*. (2017), BIM is multi-dimensional integrating varying dimensions of data from 3-dimensional (3D) to 6-dimensional (6D) and beyond (*n*D) (see Table 2). *n*D implies that the integration of project information may significantly vary in degree. However this also offers the scope for integration of H&S data.

Table 2: BIM: widely accepted dimensions

Dimension	Commonly accepted data integration dimensions	Example of citations
3D	Geometric Model	Davies and Harty (2013a); Abanda *et al*. (2017)
4D	Construction programme scheduling	Volk *et al*. (2014); Abanda *et al*. (2017)
5D	Cost estimation and cash flow modelling	Volk *et al*. (2014); Lu *et al*. (2016)
6D	Sustainability/facilities management	Redmond *et al*. (2012)
*n*D	Various	Fox and Hietanen (2007); Abanda *et al*. (2017)

Barlish and Sullivan (2012) on the other hand developed a more comprehensive methodology to analyse the benefits of BIM. Using a variety of metrics such as duration improvement, change orders, requests for information (referred to as return) and design and cost information (referred to as investment), tested against three case studies, the findings revealed a high potential for the realisation of BIM benefits, although it was acknowledged that the returns and investments will vary across projects. While BIM uptake has increased over the recent past, numerous studies still reveal varied BIM implementation and uptake as demonstrated in Table 3.

In terms of research that addresses the association between BIM and CDM, it conceivable to note that it is far from comprehensive. For example, Mordue and Finch (2014) identifies a number of benefits of adopting BIM to improve H&S outcomes in the construction industry. Although there is some consideration for improved H&S, through a BIM process, there is need to extend this idea. Most importantly, it is established that effective information exchange in a BIM environment requires: (i) openness and accessibility; (ii) a standardised structure; and (iii) a consistent format using appropriate standards such as PAS 1192-2: 2013, which sets out specifications for information management using BIM (BSI, 2013).

Table 3: BIM implementation and operation in the AEC industry

BIM implementation factors / Arranged in chronological order by year of publication	C1. Collaboration	C2. Integration	C3. Technology	C4. Automation	C5. Visualisation	C6. Interoperability capability	C7. Information capturing	C8. Information management	C9. Information distribution/reuse	C10. Information exchange	C11. Information integration	C12. Information accessibility	C13. Information	C14. Information control	C15. Information contribution	C16. Information retrieval/extraction	C17. Information redundancy	C18. Clash detection	C19. Point of reference
	The BIM implementation and operation matrix																		
Fox and Heitenen (2007)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓			✓
Anumba *et al*. (2008)			✓	✓	✓		✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓
Baldwin *et al*. (2009)						✓	✓	✓					✓	✓		✓			✓
Succar (2009)				✓	✓	✓	✓						✓			✓			
Froese (2010)	✓	✓	✓				✓	✓			✓			✓		✓			
Grilo and Jardim-Goncalves (2010)						✓	✓		✓	✓			✓			✓			
Gu and London (2010)	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Matipa *et al*. (2010)		✓	✓	✓	✓	✓	✓				✓		✓			✓			✓
Sebastian (2010)	✓	✓		✓	✓		✓				✓					✓	✓	✓	✓
Peterson *et al*. (2011)		✓					✓	✓			✓			✓		✓			
Sebastian (2011)	✓	✓					✓		✓	✓	✓					✓			✓
Becerik-Gerber *et al*. (2012)		✓				✓	✓				✓		✓			✓			✓
Cheung *et al*. (2012)			✓	✓	✓	✓	✓						✓			✓			✓

Arranged in chronological order by year of publication / **BIM implementation factors**	C1. Collaboration	C2. Integration	C3. Technology	C4. Automation	C5. Visualisation	C6. Interoperability capability	C7. Information capturing	C8. Information management	C9. Information distribution/reuse	C10. Information exchange	C11. Information integration	C12. Information accessibility	C13. Information storage/repository	C14. Information control	C15. Information contribution	C16. Information	C17. Information redundancy	C18. Clash detection	C19. Point of reference
Arranged in chronological order by year of publication	**The BIM implementation and operation matrix**																		
Chi *et al*. (2012)		✓	✓			✓	✓				✓		✓			✓			✓
Khosrowshahi and Arayici (2012)		✓				✓	✓	✓			✓		✓	✓		✓			
Li *et al*. (2012)			✓	✓	✓		✓									✓			
Redmond *et al*. (2012)			✓			✓	✓		✓	✓			✓			✓			✓
Bryde *et al*. (2013)							✓	✓						✓		✓			
Bynum *et al*. (2013)		✓		✓	✓	✓	✓				✓		✓			✓			
Davies and Harty (2013a)	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓			✓		✓			✓
Davies and Harty (2013b)	✓	✓				✓	✓				✓		✓			✓			✓
Eadie *et al*. (2013)		✓	✓			✓	✓				✓		✓			✓			
Porwal and Hewage (2013)	✓	✓				✓	✓	✓			✓		✓	✓		✓			✓
Zhang *et al*. (2013)			✓	✓	✓		✓									✓			
Arslan *et al*. (2014)		✓	✓	✓	✓	✓	✓				✓		✓			✓			✓
Chien *et al*. (2014)		✓				✓	✓				✓		✓			✓			
Demian and Walters (2014)		✓				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓
Elmualim and Gilder (2014)	✓	✓	✓			✓	✓	✓			✓		✓	✓		✓			
Murphy (2014)		✓				✓	✓				✓		✓			✓			

The BIM implementation and operation matrix

BIM implementation factors / Arranged in chronological order by year of publication	C1. Collaboration	C2. Integration	C3. Technology	C4. Automation	C5. Visualisation	C6. Interoperability capability	C7. Information capturing	C8. Information management	C9. Information distribution/reuse	C10. Information exchange	C11. Information integration	C12. Information accessibility	C13. Information storage/repository	C14. Information control	C15. Information contribution	C16. Information	C17. Information redundancy	C18. Clash detection	C19. Point of reference
Olatunji (2014)	✓	✓					✓		✓	✓	✓				✓	✓			✓
Volk *et al*. (2014)		✓				✓	✓				✓		✓			✓			
Zhou *et al*. (2014)		✓	✓			✓	✓				✓		✓			✓			✓
Cao *et al*. (2015)		✓				✓	✓	✓			✓		✓	✓		✓			✓
Eadie *et al*. (2015)	✓	✓					✓	✓			✓			✓		✓			
Ganah and John (2015)		✓				✓	✓				✓		✓			✓			✓
Harrison and Thurnell (2015)				✓	✓	✓	✓	✓					✓	✓		✓			✓
Kassem *et al*. (2015)		✓				✓	✓	✓			✓	✓	✓	✓		✓			
Lu *et al*. (2015)	✓	✓				✓	✓				✓		✓			✓			
Li *et al*. (2015)			✓	✓	✓		✓									✓			
Maki and Kerosuo (2015)	✓	✓		✓	✓		✓	✓	✓	✓	✓			✓		✓			✓
Malsane *et al*. (2015)				✓	✓	✓	✓						✓			✓			
Wetzel and Thabet (2015)		✓				✓	✓				✓		✓			✓			✓
Zhang *et al*. (2015)	✓	✓	✓	✓	✓		✓	✓			✓			✓		✓			

BIM implementation factors / **Arranged in chronological order by year of publication**	C1. Collaboration	C2. Integration	C3. Technology	C4. Automation	C5. Visualisation	C6. Interoperability capability	C7. Information capturing	C8. Information management	C9. Information distribution/reuse	C10. Information exchange	C11. Information integration	C12. Information accessibility	C13. Information storage/repository	C14. Information control	C15. Information contribution	C16. Information	C17. Information redundancy	C18. Clash detection	C19. Point of reference
	The BIM implementation and operation matrix																		
Bradley *et al*. (2016)		✓				✓	✓	✓			✓		✓	✓		✓			✓
Brathen and Moum (2016)	✓	✓	✓	✓	✓		✓				✓					✓			✓
Ciribini *et al*. (2016)		✓	✓	✓	✓	✓	✓				✓		✓			✓			✓
Hallowell *et al*. (2016)		✓	✓	✓	✓	✓	✓	✓			✓		✓	✓		✓	✓		✓
Hoeber and Alsem (2016)							✓	✓						✓		✓			✓
Kim *et al*. (2016)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓
Lu *et al*. (2016)				✓	✓	✓	✓						✓			✓			
Teo *et al*. (2016)		✓		✓	✓	✓	✓				✓		✓			✓			
Zou *et al*. (2016)						✓	✓						✓			✓			✓
Abanda *et al*. (2017)		✓	✓	✓	✓	✓	✓				✓		✓			✓			✓
Alreshidi *et al*. (2017)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓
Ganah and John (2017)		✓				✓	✓				✓		✓			✓			✓
Gerrish *et al*. (2017)		✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
Ghaffarianhoseini *et al*. (2017)	✓			✓	✓	✓	✓	✓	✓	✓			✓	✓		✓			✓
Rowlinson (2017)	✓	✓					✓				✓					✓			
Liu *et al*. (2017)	✓	✓		✓	✓		✓	✓	✓	✓	✓			✓		✓			✓
Won and Cheng (2017)		✓				✓	✓				✓		✓			✓			
Score	*20*	*44*	*22*	*27*	*27*	*42*	*60*	*26*	*15*	*15*	*44*	*6*	*42*	*26*	*5*	*60*	*5*	*4*	*36*

Table 3 reveals 19 factors which emerge from the literature review. The initial step in the literature review involved pairing the factors in the most logical manner, largely underpinned by the theoretical background of BIM. From the 19 factors, 12 factors were considered as compatible given their close proximity in terms of operation, occurrence and sequencing, thus forming six pairs as listed below:

- integration and information integration (C2, C11)
- interoperability capability and information storage/repository (C6, C13)
- information management and information control (C8, C14)
- information exchange and information distribution (C9, C10)
- automation and visualisation (C4,C5)
- information capturing and information retrieval/extraction (C6, C16).

While the factors listed above are in no particular order of importance, it is imperative to mention that the last pair is central to BIM implementation as confirmed by all the studies reviewed. Besides, BIM largely hinges on information capturing and information retrieval.

The results show that the top four factors for BIM implementation and operation in descending order are:

(1) information capturing and retrieval (C6, C16);
(2) integration and information integration (C2, C11);
(3) interoperability capability and information storage/repository (C6, C13); and
(4) information point of reference (C19).

The factors with the least point-scores in terms of BIM implementation and operation based on the literature review, include:

(1) clash detection (C18);
(2) information contribution and information redundancy (C15, C17);
(3) information accessibility (C12); and
(4) information distribution/reuse and information exchange (C9, C10).

Considering the remaining five factors as ‘close to average’ is reasonable, although technology (C3, 22-point score) is short by over five points. Factors such as automation (C4), visualisation (C5), and information control (C14) were within a reasonable reach. It is surprising to note that clash detection (C18) returned the lowest score (4-point score), and that factors such as information contribution (C15) and information redundancy (C17), information accessibility (C12), information distribution (C9) and information exchange (C10) appeared in the bottom six. Information exchange and accessibility are critical for collaboration. Information redundancy is the ability to ensure that there is limited repetition and overly complex data repositories which usually block information distribution.

3.3 The operational impact of BIM

The literature review shows that BIM offers a range of notable benefits that enhance project management processes. Increasingly, BIM integrates data at various points of the project. While it is also clear that BIM enhances the degree to which project information is retrievable, there are concerns that the degree of exchange and accessibility of such data is questionable. Indeed, even the degree of accessibility of project data by various stakeholders invites further scrutiny in terms of the role of BIM, given the often underestimated complexity of sharing information (see *Trant*

Engineering v Mott MacDonald [2017] EWHC 2061 (TCC)).

Arguably, of critical importance, is the need for timely and optimal sharing of project information. Having an implementation framework can therefore assist achievement of best practice. Because of the different types of tools for BIM implementation, there is often need for both bespoke and generic frameworks. Whatever framework is deployed, Grilo and Jardim-Goncalves (2010) explain that there are five factors, i.e. communication, coordination, cooperation, collaboration and channel that create a conducive environment for BIM interoperability and must therefore be reflected in any framework.

While BIM has the ability to offer more beyond information exchange (see Charef *et al*., 2018), in the context of CDM, it is reasonable to argue that DHs may significantly benefit from the operational impact of BIM technologies, particularly when it comes to information exchange. Based on this understanding, it is vital to highlight that this research only refers to the CDM obligations that usually trigger information exchange.

In terms of the interoperability aspect, this research takes the view of governance in the generic sense, rather than the technical or sophisticated software interoperability. To illustrate this BIM governance aspect, Alreshidi *et al*. (2017) developed a framework for BIM governance known as G-BIM, and highlights three overarching components, i.e.: actors and teams (A&T); data management and ICT (DM&ITC); and process and contracts (P&Cs). Within the first component of the framework, the reasoning is that A&T constitutes the roles and responsibilities of the actors and the team, requiring a clear set of defined obligations. Indeed, the idea behind BIM governance is consistent with the underlying ethos that largely informs CDM implementation, whereby specific duty holders are mandated with specific obligations. Which means that in the G-BIM framework, reference to the actors and teams (A&T) as duty holders

(DHs) because of their role to discharge specific obligations within the context of CDM is feasible. The foregoing discussion reinforces the context within which the research is theoretically underpinned. An analysis of the statutory instrument—S.I. 2015/51 relevant to this study is considered in the next section.

4.0 THE CONSTRUCTION DESIGN AND MANAGEMENT (CDM) REGULATIONS

The CDM regulations have been in existence since the mid-1990s. The first regulations, widely referred to as CDM 1994, came into force in 1995 in response to the European Union (EU) Directive 92/57/EEC, referred to as the 'Temporary or Mobile Construction Sites' (TMCS) directive. Since then, major changes have taken place, manifesting in the introduction of the CDM 2007 and later the CDM 2015. While there are a number of notable changes in the content and wording of the CDM regulations (hereafter referred to as 'CDM') since inception, in its current state (CDM 2015), the principles generally remain the same as those established in the first regime. Theoretically, the ethos underlying the TMCS directive is the 'principles of prevention' (see Article 4), a subject addressed in scholarly articles such as Gambatese *et al*. (2005).

In terms of the content, the CDM outlines obligations for five DHs, two of which are non-traditional roles i.e. Principal Designers (PDs) and Principal Contractors (PCs), and workers. This has generally been the underlying structure of the CDM since the first regime. However, the lack of understanding, overly bureaucratic processes, too much paperwork and unclear CDM provisions (e.g. Baxendale and Jones, 2000; Bomel Ltd, 2007), triggered the changes in CDM 2007. CDM 2007 was also criticised for being misaligned with the TMCS directive and being widely misunderstood (see e.g. Dalby, 2007; Beal, 2007), leading to the CDM 2015.

The implementation of the CDM typically involves provision of a range of documents and information. The criticality of accuracy and adequacy of information such as pre-construction information (e.g. Regulations. 4(4), 9(2), 9(3)(b),9(4), 11(6)(a), 11(6)(b)) and information needed in preparation of the construction phase plan (e.g. Regulations 12(1), 12(4)) and the H&S file (e.g. Regulations 12(5), 12(6), 12(8), 12(10)) cannot be overemphasised. Table 4 provides a full list of duties that typically trigger information exchange.

4.1 Mapping of the CDM Obligations to BIM

In Table 4, a number of words or phrases are underlined to identify the obligations that trigger information exchange. The process of identification of such duties involved an extensive and carefully executed content analysis. Some of the keywords or phrases considered included: ‘information exchange’, ‘pre-construction information’, ‘construction phase plan’, and ‘health and safety file’.

Table 4: Duties that trigger information exchange under the CDM 2015

CDM 2015	**DH and description of duties**
	Client
Reg. 4(4)	*A client must provide adequate pre-construction information as soon as practicable, without risks to the health or safety of any person affected by the project* [...].
	Designer
Reg. 9(2)	*When preparing or modifying a design the designer must take into account the general principles of prevention and any pre-construction information* [...].
Reg. 9(3)(b)	*If not possible to eliminate these risks, the designer must, so far as is reasonably practicable provide information about these risks* [...].
Reg. 9(3)(c)	*If not possible to eliminate these risks, the designer must, so far as is reasonably practicable ensure appropriate information is included in the health and safety file.*
Reg. 9(4)	*A designer must take reasonable steps to provide, with the design, sufficient information about the design, construction or maintenance of the structure* [...].
	Principal Designer (PD)
Reg. 11(6)(a)	*The principal designer must assist the client in the provision of the pre-construction information* [...].
Reg. 11(6)(b)	*The principal designer must so far as it is within the principal designer's control, provide pre-construction information, promptly* [...].
Reg. 11(7)	*The principal designer must liaise with the principal contractor for the duration of the principal designer's appointment and share with the principal contractor information relevant to planning, management and monitoring of the construction phase* [...].
Reg. 12(3)(a)	*The principal designer must assist the principal contractor in preparing the construction phase plan by providing to the principal contractor all information the principal designer holds that is relevant to the construction phase plan, including pre-construction information* [...].
Reg. 12(3)(b)	*The principal designer must assist the principal contractor in preparing the construction phase plan by providing to the principal contractor all information the principal designer holds that is relevant to the construction phase plan, including any information obtained from designers* [...].
Reg. 12(5)	*During the construction phase, the principal designer must prepare the health and safety file* [...].
Reg. 12(6)	*The principal designer must ensure that the health and safety file is appropriately reviewed, updated and revised from time to time* [...].
Reg. 12(8)	*If the principal designer's appointment concludes before the end of the project, the principal designer must pass on the health and safety file to the principal contractor.*
Reg. 12(10)	*At the end of the project, the principal designer or where there is no principal designer, the principal contractor must pass the health and safety file to the client.*

CDM 2015	DH and description of duties
	Principal Contractor (PC)
Reg. 12(1)	*During the pre-construction phase, and before setting up the construction site, the principal contractor must draw up a construction phase plan* [...].
Reg. 12(4)	[...] *the principal contractor must ensure that the construction phase plan is appropriately reviewed, updated and revised from time to time* [...].
Reg. 12(7)	*During the project, the principal contractor must provide the principal designer with any information in the possession of the principal contractor* [...].
Reg. 12(9)	[...] *the principal contractor must ensure that the health and safety file is appropriately reviewed, updated and revised from time to time* [...].
Reg. 12(10)	*At the end of the project, the principal designer or where there is no principal designer, the principal contractor must pass the health and safety file to the client.*
Reg. 14(c)	*The principal contractor must ensure that those workers or their representatives can inspect and take copies of any information* [...].
	Contractor
Reg. 15(5)	*If there is only one contractor working on the project, the contractor must draw up the construction phase plan* [...].
Reg. 15(8)	*A contractor must provide each worker under their control appropriate supervisions, instructions and information* [...].

4.2 Analysis and Implications of Findings

Introduction of CDM 2015 coincides with the fourth industrial revolution (Industry 4.0), which has given impetus to move away from the traditional ways of executing projects and embracing the digital age/innovation agenda across various sectors. In the construction sector, this revolution has manifested in the adoption of BIM to enable project delivery. The evidence from the research undertaken so far reveals a broad consensus that BIM plays a significant role towards attainment of enhanced project information capture and exchange; and integrated project delivery, among other operational impact factors. BIM operates within a CDE. The CDE is typically defined as a database management system (DBMS) where there are opportunities for multiple data access, known as data points (see Mordue and Finch, 2014; Sacks *et al*., 2018).

To conduct the degree of interoperability ‘*test*’, initially, a critical review of the literature revealed 19 factors that improve the construction process, practice and procedure because of the integration of BIM-enabled technologies. Based on the 19 factors, three recurring themes emerged, i.e.: —(i) information capture/exchange; (ii) integration/collaboration; and (iii) interoperability. To demonstrate the operational impact of BIM, mapping of the three factors considered topmost in terms of BIM and CDM interoperability was undertaken. For example, duties in relation to provision of pre-construction information (i.e. Regulations 4(4), 9(2), 11(6)(a), 11(6)(b) and 12(3)(a)) demonstrate that there is an opportunity to deploy BIM for the exchange of such information, thus making such information readily accessible.

In the main, at least 22 duties were identified under the CDM 2015 that align well with information exchange. The ‘*test*’ reveals that out of 22 duties, majority of these obligations are those placed on PDs (i.e. 9 of 22), while six of those duties are placed on PCs. These duties align well with BIM integration, showing that PDs and PCs will benefit significantly from a BIM-enabled approach. Other DHs also stand to benefit from such an approach, provided they have the right skillset. It is to facilitate this and optimise the potential of BIM in H&S management that a new framework is offered in the next section.

Table 5: Duties performed in relation to exchange of information

Duty holder	**Number of duties (%)**
Client	1 of 22 (5%)
Designer	4 of 22 (18%)
Principal Designer (PD)	9 of 22 (41%)
Principal Contractor (PC)	6 of 22 (27%)
Contractor	2 of 22 (9%)
Total number of duties	22 of 22 (100%)

5.0 THE PROPOSED FRAMEWORK: BIM AND CDM INTEROPERABILITY

A summary of the findings is captured in the overarching framework developed in Figure 1, which shows the operational impact of BIM on the CDM. In Figure 1, the ribbon reflects the point at which information relevant for the discharge of a particular duty is imported, stored and retrieved, while the arrow represents the actual discharge of the specific duty. The framework retains the shared responsibility ethos of the CDM and conveys the message of information exchange in a simple manner without utilising extensive BIM jargon.

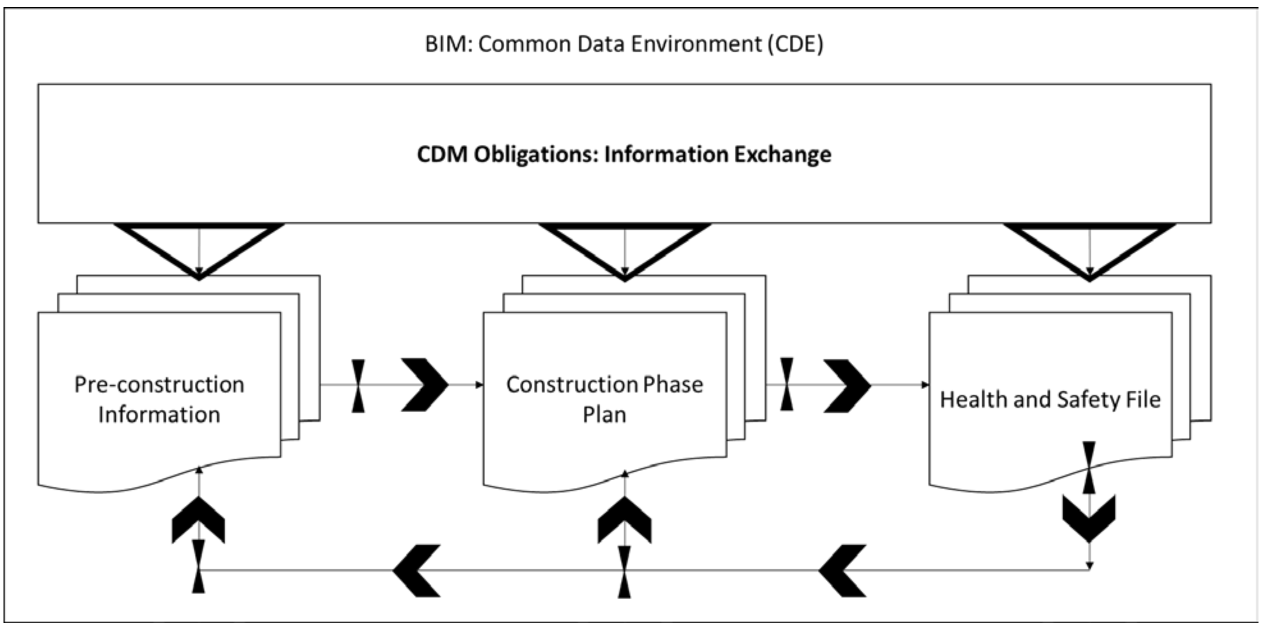

Figure 1: Overarching framework for the operational impact of BIM on CDM regulations

5.1 Mapping of CDM obligations that trigger information sharing and exchange

Preconstruction information (PCI)

During the early stages of the project, it is expected that majority of the relevant PCI is provided by the client and PDs. In the context of CDM, provision of PCI is a duty typically discharged by

PDs (Reg. 11(6)(a)). Besides assisting the client to provide PCI, PDs collate information from other DHs and ensure it is readily accessible. For a more detailed and concise representation of the duties discharged during this stage, the study develops a CDM information model-1 as illustrated in Figure 2 and summarised in Table 6, similar to a stem and leaf-plot diagram used in statistics to illustrate the distribution of the data. Based on this model, it is clear that PDs play a central role in the provision of PCI.

Table 6: List of duty holders and duties for preconstruction information

Duty holders (DHs)	**Duties**
DH1	Reg. 4(4)
DH2	Reg. 9(2), 9(3)(b), 9(4)
DH3	Reg. 11(4), 11(6)(a), 11(6)(b), 11(7)
DH4	Reg. 14(c)
DH5	Reg. 15(8), 15(9)

Key: DH1-Client, DH2-Designer, DH3-Principal Designer, DH4-Principal Contractor, DH5-Contractor

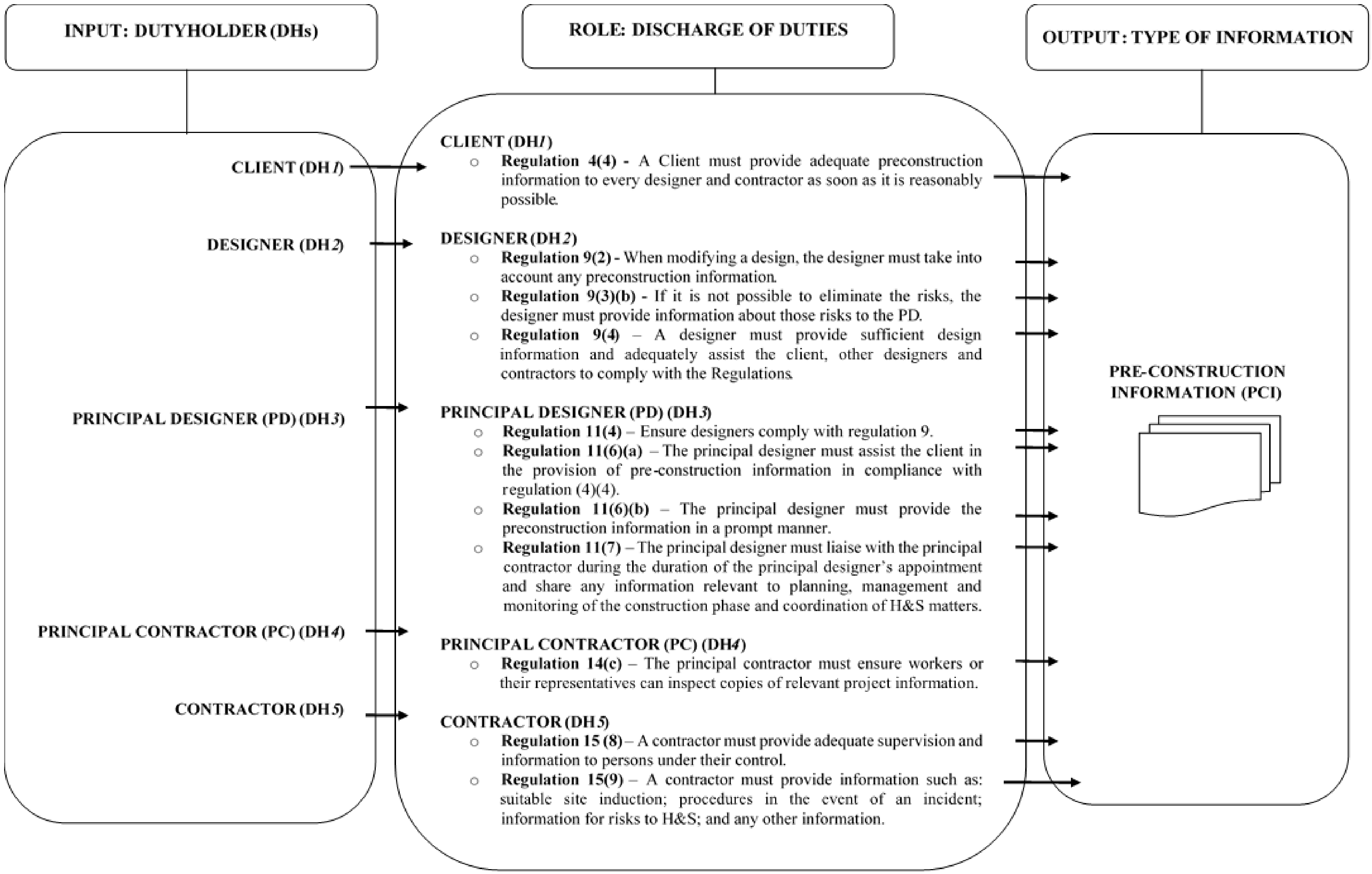

Figure 2: CDM Information model 1 (Preconstruction Information)

Construction Phase Plan (CPP)

The role played by PCs during the construction phase is instrumental. Not only is it crucial for PCs to collate and collect sufficient and detailed information from various project stakeholders for the preparation of the CPP, often, timely exchange of this information will ensure adequate management of the construction phase. The second information model as illustrated by Figure 3, depicts the exchange of information and discharge of duties to develop the construction phase plan in compliance with the CDM 2015. Table 7 on the other hand, reveals that both the PD and the contractor have an equal number of duties to perform during the construction phase. Arguably, the level and perceived degree of difficulty and importance of the duties will vary (see Mzyece, 2015).

Table 7: List of duty holders and duties performed to prepare the construction phase plan

Duty holders (DHs)	Duties
DH3	Reg. 11(7), 12(3)(a), 12(3)(b)
DH4	Reg. 12(1), 12(4)
DH5	Reg. 15(3)(b), 15(5), 12(6)

Key: DH3-Principal Designer, DH4-Principal Contractor, DH5-Contractor

Health and Safety File (H&S File)

The H&S file is typically prepared by the PD (Reg. 12(5)). While the sequence of the duty to prepare the H&S file typically comes after the construction phase, it is reasonable to assume that preparation of the H&S file occurs throughout the construction phase. Although preparation of the H&S file typically occurs during the latter part of a project, it would be unreasonable to consider this duty as least important, given the sequencing observed in the regulations. Table 8 lists the duties performed to prepare the H&S file.

Table 8: List of duty holders and duties performed to prepare the H&S File

Duty holders (DHs)	Duties
DH2	Reg. 9(3)(c)
DH3	Reg. 11(4), 12(5), 12(6), 12(8), 12(10)
DH4	Reg. 12(7), 12(9), 12(10)

Key: DH2-Designer, DH3-Principal Designer, DH4-Principal Contractor

By developing the CDM information model relating to the production of the H&S file (Figure 4), a clear link is established, which combined with the other models, then informs the developed BIM and CDM interoperability framework shown in Figure 5.

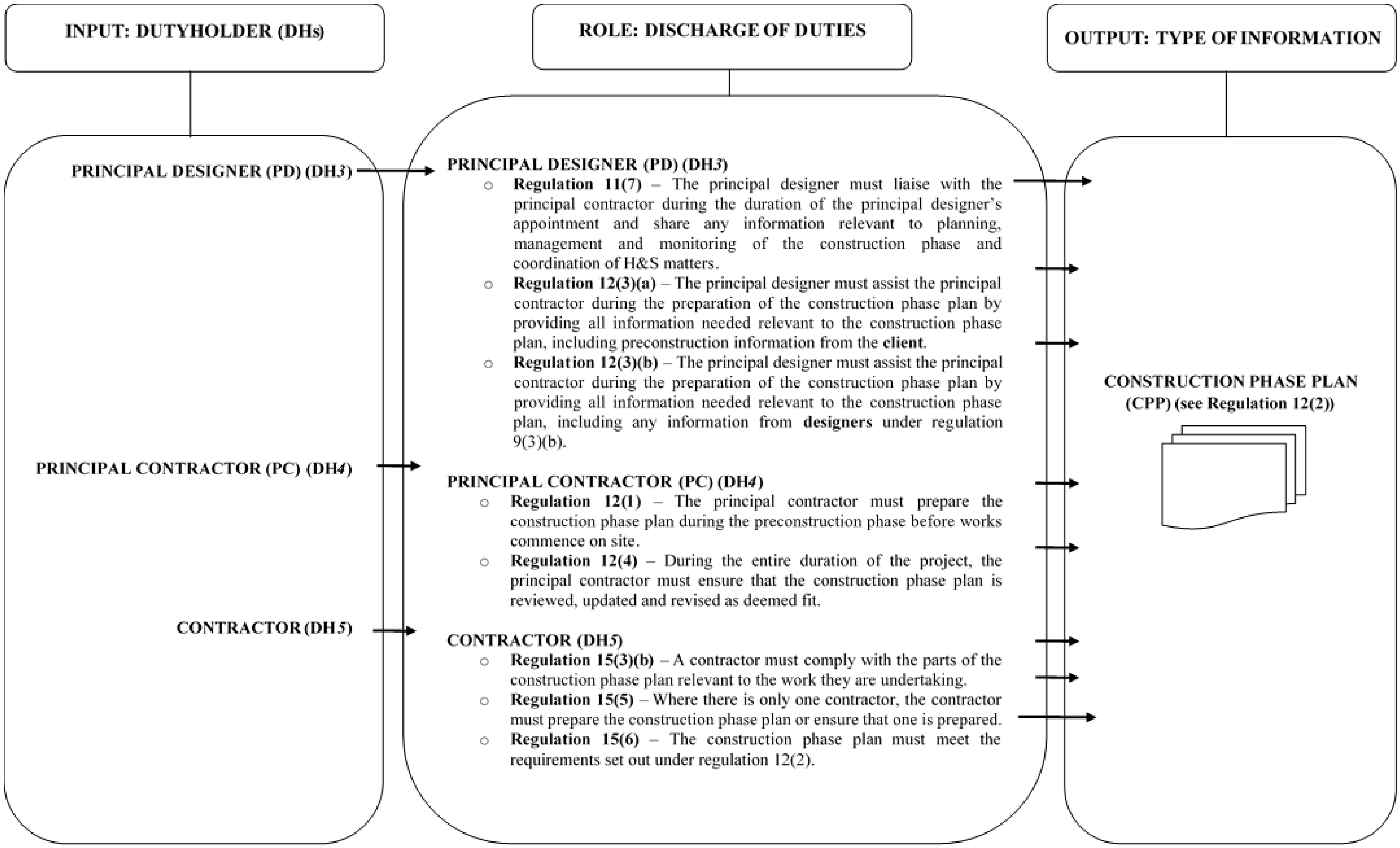

Figure 3: CDM information model 2 (Construction Phase Plan)

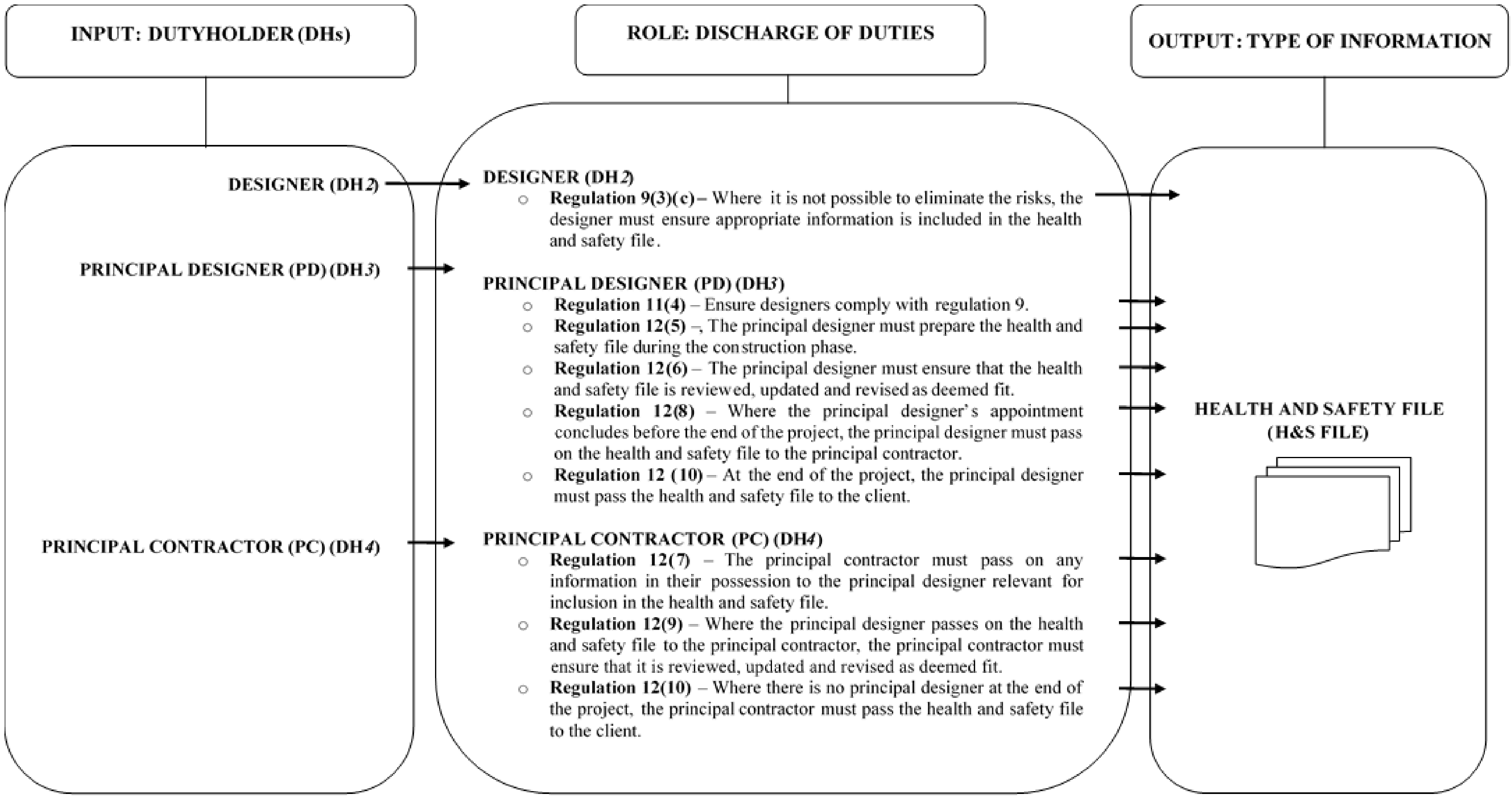

Figure 4: CDM information model 3 (Health and Safety File)

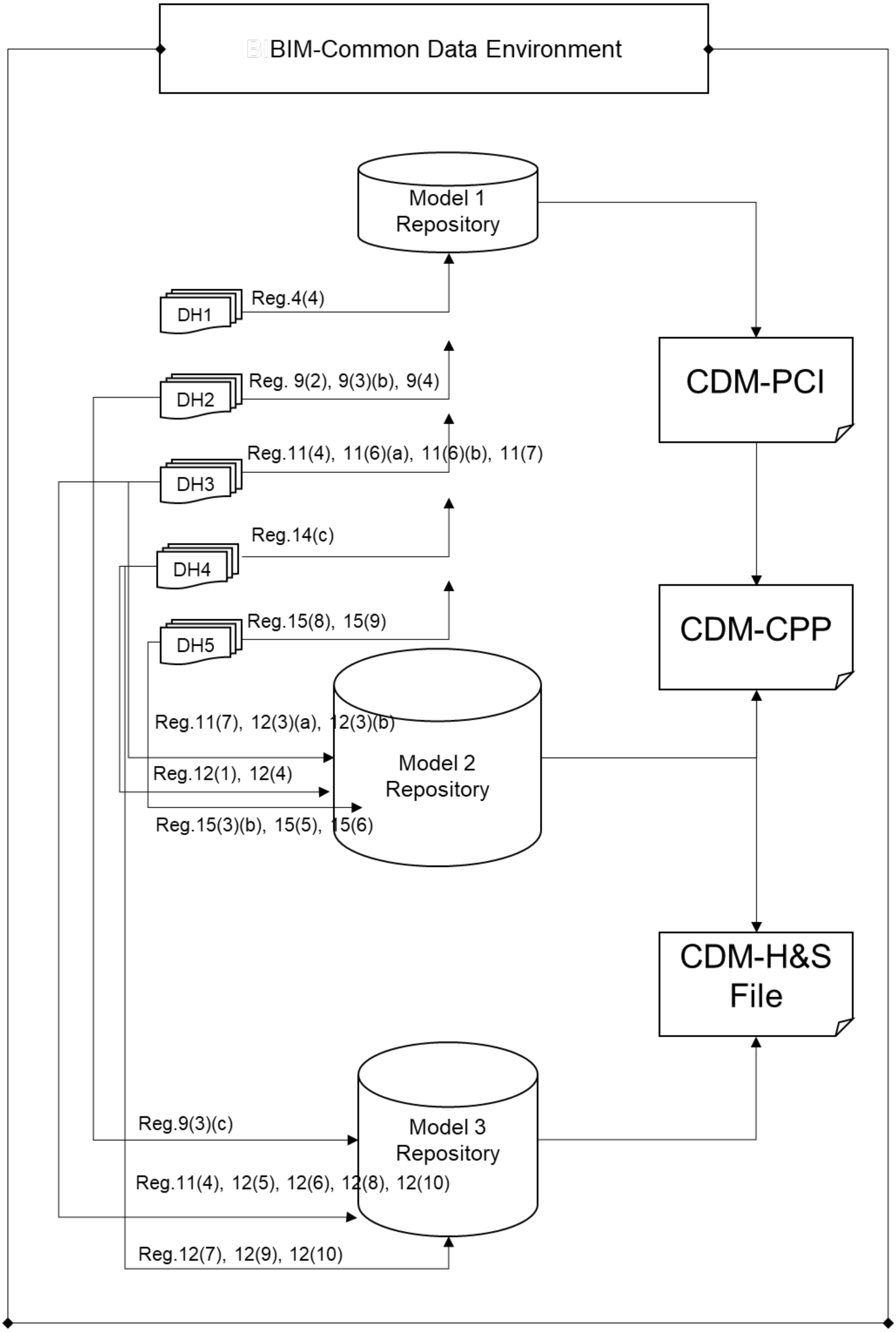

Figure 5: BIM and CDM interoperability framework

5.2 The way forward

Development of standards and frameworks that allow the AEC industry to adopt and move towards BIM level 3 is essential. BIM level 3 considers integrating new technologies and systems beyond level 2 (see HMG, 2015, p.26-31; Health and Safety Lab, 2018). It is therefore critical for legislation not to lag behind, when it comes to BIM adoption. Furthermore, while PAS 1192-6 considers collaborative sharing of risk and argues that risk can be identified earlier using information models (BSI, 2018), the developed framework provides realisation of the above objectives. Details of actionable insights on practical aspects that industry stakeholders can implement straightaway are provided in the subsequent section.

5.2.1 *Actionable insights*

At organisational level, DHs with CDM obligations must: (i) invest in BIM software (*typically user-defined*); (ii) undertake training in the area of BIM; and (iii) disseminate knowledge through various industry partnerships.

To illustrate and operationalise the framework, Figures 6, 7 and 8 provide practical insight DHs must consider. The abbreviation 'IEX', in the context of this study, refers to information exchange and retrieval drop points.

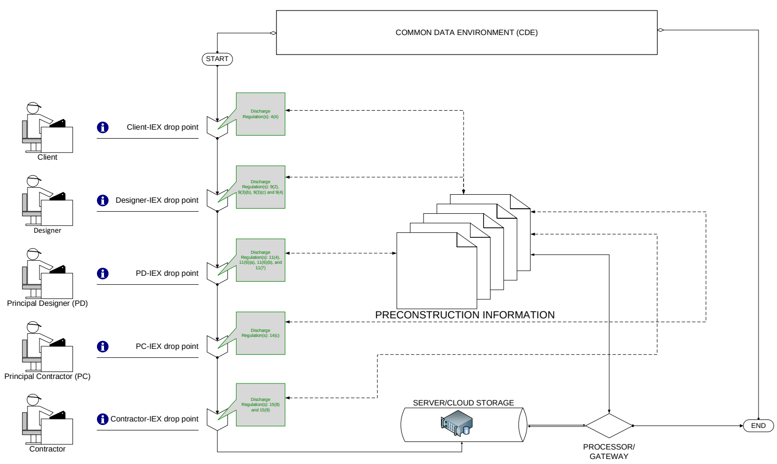

Figure 6: Provision of Preconstruction Information in a CDE

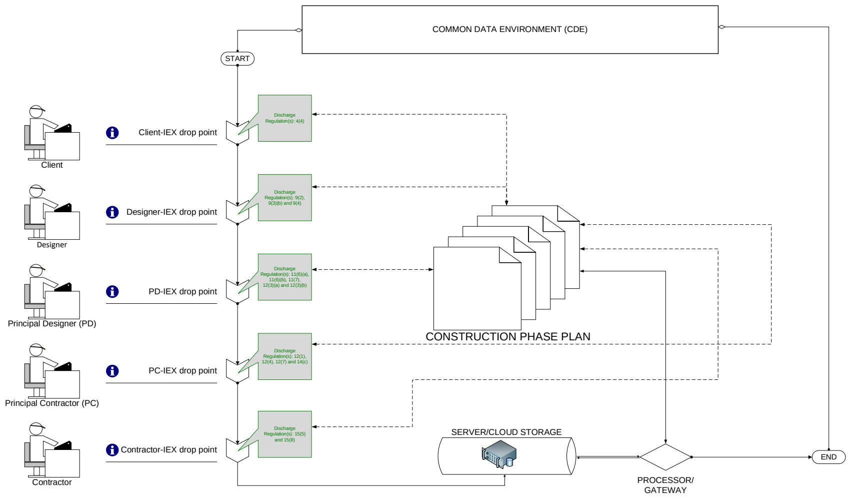

Figure 7: Preparation of the Construction Phase Plan in a CDE

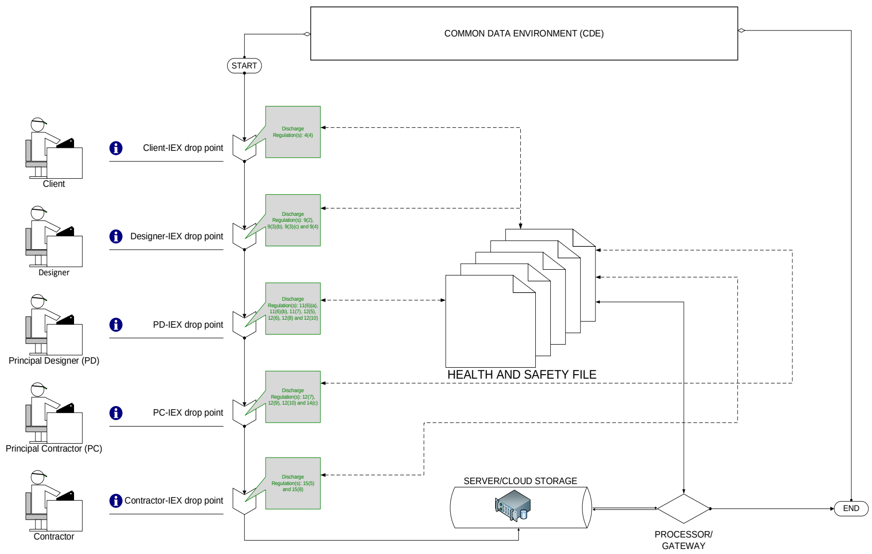

Figure 8: Preparation of the H&S File in a CDE

While the BIM and CDM interoperability framework provides deeper understanding and new insight, several factors invite further consideration. For example it is assumed that the level of knowledge of the DHs is sufficient to discharge CDM obligations in a CDE. Moreover, the client may see adoption of this framework through the lens of 'value for money', as such the onus is on DHs to demonstrate the importance of a BIM-enabled approach. Further, classification and checking the degree of: accuracy, adequacy and completeness of such information is central, beyond the call of duty. However, the authors are conscious to point out that the findings from this study are not entirely generalizable, rather, they widen the debate surrounding BIM interoperability and offer DHs an alternative mechanism to trigger improved CDM implementation, compliance and action.

6.0 CONCLUSION

This study reveals that CDM DHs have an opportunity to discharge their duties in a CDE with BIM at the fore. While PDs and PCs play critical roles in the discharge of CDM obligations related to information production, provision and exchange, the implications are broader and require that DHs attain the necessary skills, knowledge and experience (SKE) related to BIM integration. The study unlocks the key features related to CDM implementation, supported by a BIM-enabled approach.

The CDM DHs can no longer spectate and remain on the periphery of BIM adoption. Rather, there is need for more concerted effort and proactive approaches towards BIM adoption and facilitation based on the framework offered. Having said that, it is worth noting the limitations of this research. There is need to test the developed framework in terms of industry readiness, capability and compatibility with procurement procedures. A ‘test-run’, would provide greater understanding of the feasibility of BIM and CDM interoperability and offer more concise recommendations to practitioners. Further, given the subjective nature of the research design, there is need to consider a study based on empirical evidence.

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