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A state-of-the-art review of built environment information modelling (BeIM)

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Abstract: Elements that constitute the built environment are vast and so are the independent systems developed to model its various aspects. Many of these systems have been developed under various assumptions and approaches to execute functions that are distinct, complementary or sometimes similar. Furthermore, these systems are ever increasing in number and often assume similar nomenclatures and acronyms, thereby exacerbating the challenges of understanding their peculiar functions, definitions and differences. The current societal demand to improve sustainability performance through collaboration as well as whole-system and through-life thinking is driving the need to integrate independent systems associated with different aspects and scales of the built environment to deliver smart solutions and services that improve the well-being of citizens. The contemporary object-oriented digitization of real-world elements appears to provide a leeway for amalgamating the modelling systems of various domains in the built environment which we termed as built environment information modelling (BeIM). These domains include architecture, engineering, construction as well as urban planning and design. Applications such as building information modelling, geographic information systems and 3D city modelling systems are now being integrated for city modelling purposes. The various works directed at integrating these systems are examined, revealing that current research efforts on integration fall into three categories: (1) data/file conversion systems, (2) semantic mapping systems and (3) the hybrid of both. The review outcome suggests that good knowledge of these domains and how their respective systems operate is vital to pursuing holistic systems integration in the built environment.

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1 Introduction

The built environment, as opposed to natural, can be described as constituting the surroundings and the existing elements created by humans. It is defined, from a social perspective, as the human-made space in which people live, work and recreate on a day-to-day basis (Roof 2008). By extension, this draws on disciplines such as the visual arts, architecture, engineering, urban planning, real estate, history, interior design, industrial design, geography, environmental studies, law and sociology. Thus, parks, roads, walkways, urban reserved areas, building structures, infrastructures and cities, as well as how they are occupied or used, all come under the built environment. The built environment therefore encompasses associated interdisciplinary aspects of design, construction, management and operation of these created surroundings and artefacts. The key industry sectors directly concerned with these interdisciplinary aspects include the architecture, engineering and construction (AEC) industry as well as the geography and urban planning industry sectors. Although interwoven in certain aspects, these sectors rely on different systems in the synthesis and management of information associated with the built environment. In recent times, building information modelling (BIM) has been used in the AEC industry sector to manage information on building processes and structures. Offering a parametric object-based representation of elements, BIM is expected to contribute to increasing project efficiencies and reducing project delivery cost and time. As such, efforts are being directed towards extending BIM working approaches to other infrastructures such as bridges, tunnels, roads, waterways and water supply. On the other hand, the geography and urban planning sectors have seen the extensive use of geographic information systems (GISs) and, more recently, applications in virtual

3D city modelling in the design and visualization of urban forms. We termed these systems as built environment information modelling (BeIM). With GIS being capable of providing reference for >80% of information required in the AEC industry (Kim et al. 2012), the need to integrate the two information modelling systems, BIM and GIS/3D city modelling, in the built environment has been suggested to become increasingly important (Deng et al. 2016). This could engender holistic decision-making in the built environment through the enhancement of more efficient systems for information management and sharing.

While advantages may exist for systems integration in the built environment, the challenge lies with identifying what systems to integrate and how to actually implement such integrations. Considering BIM, for instance, there exist currently >122 identifiable BIM software systems (Abanda et al. 2015), different application areas (e.g. bridges, tunnels, and city) – with their peculiar emerging terminologies – and the extensions of applications to Cloud and Web technology, as well as *n*-dimensional (2D and 3D) performance assessments such as those for sustainability. A key driver for this direction of development is the urgent need to foster more efficient ways to collaboration in the built environment. The result is the proliferation of overwhelming concepts, nomenclatures and acronyms about systems that sometimes turn out to be identical and thereby confusing to stakeholders. This review therefore aims to examine existing systems and categorize them based on their functions and domain of application and analyze current integration efforts in the built environment. We link existing systems to related integration works inherent in BIM and GIS/virtual 3D city modelling applications. Furthermore, discussions are extended to outlooks and directions of integration, as well as suggestions for future improvement.

This article is therefore organized as follows. An insight into related works is provided in Section 2, before presenting the research method in Section 3. This sets the stage for Section 4, which discusses the overview of information modelling systems in the built environment and provides the opportunity to streamline existing terms and terminologies. In Section 5, fundamental aspects of the process of systems integration as it relates to the built environment are dissected. The practicalities of existing integration works in the built environment are analyzed in Section 6, with a further discussion in Section 7. Section 8 concludes the article.

2 Related works

BIM and GIS have featured a lot in scientific information and communications technology (ICT) literature in the built environment. One driver of such level of research activity is the industry's quest to intelligently digitize all aspects of the built environment. BIM and GIS/virtual 3D city modelling are tools through which aspects of digitization could be achieved, although with quite distinct application levels. Efforts have also been directed towards the integration of these domains for better collaboration in the modelling and designing of systems in the built environment. Integration, here, refers to configuring two or more systems to execute tasks jointly and to seamlessly communicate/exchange data with one another. To integrate BIM and GIS/3D city modelling domains, Stoter et al. (2011) suggested that the difference between both types of data should be acknowledged because their specifications at various levels of detail (LoDs) – visualizing the interior parts, e.g. floors, rooms and staircases of buildings – differ significantly. BIM deals with the micro real-world details of buildings' indoor/envelop data using a local object/building coordinate system, whereas GIS uses geographic coordinate systems to model outdoor real-world elements at the macro level at varying scales. Traditional GIS is characterized by pairing 2D points to create lines/polygons of geographic elements, whereas BIM technology is about building intelligent objects represented by 3D solids and surfaces (Zhang et al. 2009). However, opportunities to synchronize BIM and GIS are being explored by researchers in order to make the digitization of the built environment more robust. In alignment with the scope of this study, the related works discussed here focus on similar review-related works carried out on BIM, GIS and 3D city models, particularly aspects of their integration. As such, discussions here do not dwell much on isolated research works on implementation developments on BIM alone or GIS alone, which in themselves constitute a vast area of research.

2.1 BIM and City Information Modelling (CIM) file formats for information mapping

Integration efforts for BIM and 3D city modelling have been mostly focussed on mappings between the Industry Foundation Classes (IFC) and City Geography Markup Language (CityGML). The organization buildingSMART International is responsible for developing and maintaining the IFC specification, which is based on the express G modelling language. Currently, about 150 software applications in the construction sector are acknowledged to be IFC compliant. IFC is a neutral BIM data exchange standard, with the current version as IFC4 accepted as ISO 16739. IFC4 is incorporated with more enhanced definitions for building engineering.

This includes aspects of Coordination View (CV V2.0) aimed at facilitating the seamless sharing of building information models between the major disciplines of architecture, structural engineering and building services (mechanical). In this respect, IFC4 is divided into two definitions – Reference View and Design Transfer View – for a more effective data exchange process. While Reference View is targeted at supporting the coordination of disciplines based on building geometry, Design Transfer View focusses on the use of model data to aid further discipline-specific design and analysis. Future expansion of this current version will cover other infrastructure (IFC Infra), such as roads, rails, bridges and tunnels, with more emphasis on the Semantic Web and linked open data applications (buildingSMART 2016) that link up with city scale modelling.

CityGML, on the other hand, was initiated in 2002 and is attributed to the Special Interest Group 3D (SIG 3D) chaired by Thomas H. Kolbe (Gröger and Plümer 2012). The current version is CityGML 3.1.1, incorporated with the latest revisions of contemporary modelling requirements. CityGML was standardized in 2008, and it is now the international standard for the representation of 3D city models under the auspices of the Open Geospatial Consortium (OGC). Based on the GML, the capabilities of CityGML include definition of 3D geometry, topology, semantics and the appearance of geographic objects at varying LoDs. Moreover, CityGML is an extensible markup language (XML)-based format and so provides opportunity for Web service integration in terms of supporting operations involving semantics, objects, attributes and geo-referencing of data (Stoter et al. 2011). This broadens the interoperability capability entrenched in CityGML coding and therefore provides great opportunities for integration of other modelling systems, such as BIM, for building and infrastructure design. Considering that the research community is now looking at opportunities to integrate BIM and GIS/3D city models for holistic information modelling in the built environment, a more comprehensive study to analyze the progress and propose further directions in this area is much needed. This study therefore focusses on BIM–3D city (with GIS) information integration and related applications.

2.2 The state of BIM and CIM integration

The early developments in city modelling were clouded with a combination of diverse independent modelling techniques and lack of coherent approaches (Batty 2000; Shiode 2000). Typically, 3D city models were generated by combining data collected at different times from varying sources and LoDs (Döllner et al. 2006). The challenges posed by such approaches are now being resolved with the advent of CityGML in 2008 (Gröger and Plümer 2012) and other concerted research efforts Billen et al. (2014). Shiode (2000) suggested that 3D modelling methods reflect two different groups of approach. The first group includes the ad hoc combination of in-house components constructed from different software packages (such as computer-aided design [CAD] tools, image rendering, database and interface authoring tools). This is suitable for small-scale modelling in terms of area. The integration of GIS software with 3D visualization constitutes the second group and is characterized by the extrusion of vertical elements from digital map data occasionally combined with image mapping techniques. It is the most appropriate application for covering large areas, spatial analysis and simulations.

Döllner et al. (2006) stated that the creation and maintenance of virtual 3D city models is dependent on the systematic and pragmatic integration of geo-data from a number of sources, including cadastral data, digital terrain models, aerial photographs, 3D building models and architectural models. Although there are no widely accepted encoding standards, the commonly used ones are as follows: CityGML for building models; 3D-Studio Max object and virtual reality modelling language (VRML) files; Environmental Systems Research Institute (ESRI) Shapefiles with 2D footprint polygons and height values for buildings; and ESRI Shapefiles containing explicit geometric description in the form of boundary polygons. Among these encoding systems, CityGML appears to be more researched on in the context of integration with BIM. CityGML is an XML-based data model developed from GML 3.1.1 (GML3) under the OGC. It is used to capture and represent the shape and graphical appearance of city models including object semantics, thematic properties, taxonomies and aggregations (Kolbe 2009). On BIM and GIS/CIM integration research, there have been some previous works on transforming CityGML to IFC and vice versa (Du and Zlatanova 2006; Hijazi et al. 2009; Isikdag and Zlatanova 2009). A more recent work on the extension of CityGML, called GeoBIM, which incorporates IFC data into GIS and is implemented in open source BIMserver, was carried out by de Laat and van Berlo (2011). This work suggested that it is technically possible to add semantic information from IFC to CityGML aided by central model servers.

3 Method

We undertook a literature review to explore the recent developments in information modelling integration in the built environment. While there is a myriad of literature on these subjects within this broad domain, a number of terms now exist either as descriptions of standards in the concerned subjects or as acronyms coined to describe developed systems. The key most occurring terms are identified, classified and discussed. The primary sources of information in the study are publications from journals, conferences and workshops. Websites, discussion forums and blogs of organizations also served as information sources for analysis.

This review cuts across commonly used systems in modelling the geographic environment and cascades down to civil engineering infrastructure and thereafter to building structures. These systems include 3D city modelling applications, GISs, infrastructure modelling systems, CAD applications and systems for modelling building information, among others. We discuss these applications in the various domains to provide a background for analyzing progress in their integration.

Consequently, for the purposes of system integration in the built environments, key applications that fall within the radar of this work include virtual 3D city modelling, GIS, CAD and BIM. While many recent research efforts tend to dwell on exploring 3D city models and BIM, they appear to be built on the foundations of GIS and CAD integration. On the one hand, GIS applications form an integral part of 3D city modelling, which has struggled with attaining a standard definition, as noted in Döllner et al. (2006) and Biljecki et al. (2015). On the other hand, CAD capabilities, or at least information exchange utilities for CAD file formats, are embedded in BIM applications. As such, the research areas covered in this review include GIS/CAD/virtual 3D city model/BIM integration.

4 An overview of built environment information modelling (BeIM) systems

Advances in information technology (IT), particularly object-oriented computer programming, have given rise to great improvements in the representation of real-life physical elements with their digitized counterpart. It is now possible to incorporate rules and attach attributes to digitized objects in order to bring their behaviour much closer to that of their physical counterparts. Transcending the CAD era of line-and-vector representation in the built environment, BIM software applications are now being used to aid the planning, design, construction, operation, retrofitting, reuse and demolition of buildings. Although still undergoing improvements and expansion in scope of application, these applications are poised to be the latest approach for project delivery and management in the built environment. Thus, the envisaged successes in the BIM approach have triggered similar developments in other built environment domains. We now have information modelling applications extended to bridges (Shirole et al. 2009; Marzouk and Hisham 2012), known as bridge information modelling (BrIM). Closely related to this is civil information modelling, termed civil engineering information modelling (CEIM), for the modelling of civil engineering structures (Cheng et al. 2016). Similarly, at the urban and regional scales of modelling in the built environment, the applications of GIS have metamorphosed into the modelling of 3D virtual cities or 3D city modelling, herein termed as city information modelling (CIM). We suggest a general term, BeIM, as illustrated in Figure 1, to encompass information modelling of all such systems used in the built environment to design buildings, infrastructure as well as geospatial and built facilities.

5 The integration of BeIM systems

Systems can be integrated within an organization or between two or more organizations to achieve better performance outputs or upgrades. For the wider construction industry, reasons for integration can extend to include improvements on efficiency and productivity. Similarly, in this respect, integration can occur between systems associated with a particular domain or across different domains. In any of these cases, the goals are similar – seamless communication and exchange of data between systems and joint execution of tasks or fusing of functions where applicable. The main objective is to achieve holistic and robust systems that can engender improved stakeholder collaboration and, as such, enhance the efficiency/positive impacts of projects (Toroghi Bidabadi et al. 2016). To meet the desired objectives, it is important to identify key elements that can facilitate the achievement of the necessary aspects of integration. For BeIM, interoperability and LoD have been identified to be important. Moreover, the concentration of the literature has been on the integration of BIM and CIM systems based on the interactions of IFC and CityGML information representation systems, respectively.

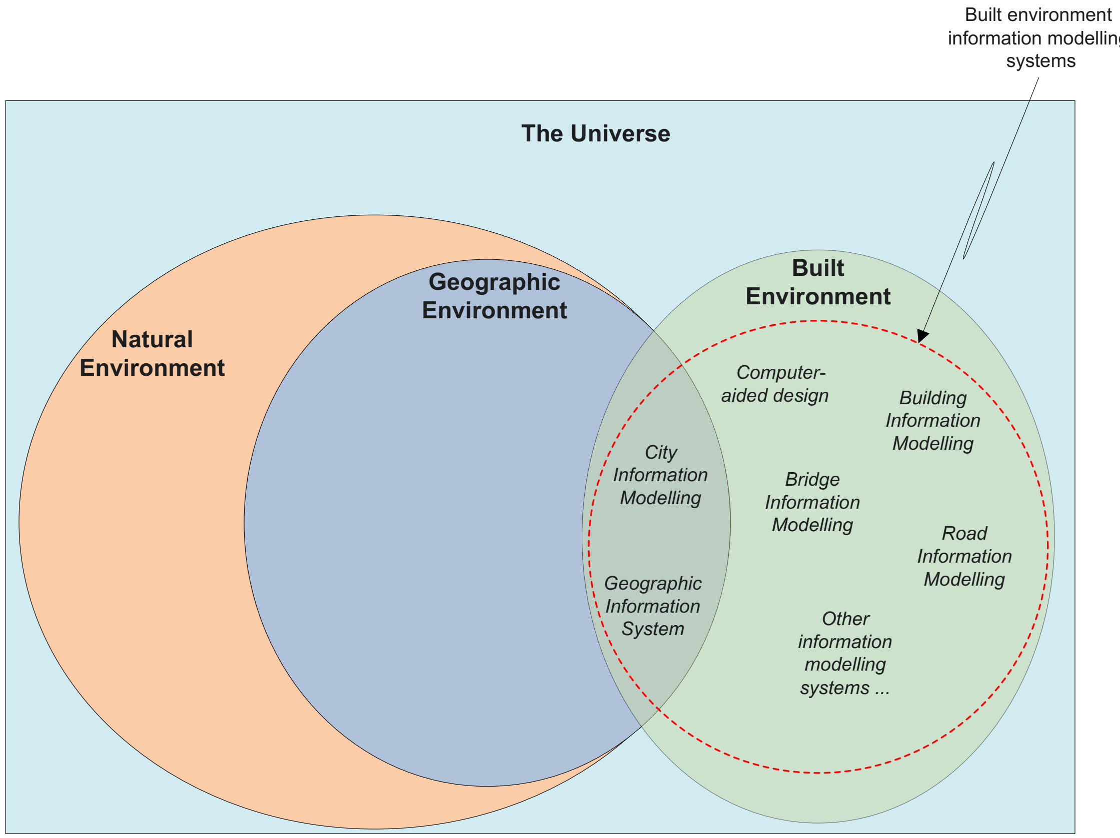

Fig. 1: BeIM systems and the geographic environment.

5.1 Elements facilitating integration of BeIM systems

The integration of systems is not without challenges. Challenges usually result from the difficulties in reconciling the different information representation approaches and structures adopted by various systems (Visser et al. 2002b). In most cases, the degree of integration achieved between any two or more systems can be defined in terms of the levels of interoperability attained. For better results, Gröger and Plümer (2012) suggest that integration efforts should be directed at features represented in similar LoDs as this is likely to be more successful than those for different LoDs. As such, data interoperability and LoDs are important factors for integration, which can be said to be technical, syntactic, structural or semantic (Visser et al. 2002b).

5.1.1 Levels of interoperability

The fragmented nature of the industry makes working in teams inevitable in the built environment. Closely linked to a project team's success is the demonstrated level of collaboration, which has been described as a durable and persuasive relationship requiring greater commitment to common goals (Mattessich and Monsey 1992; Kvan 2000). As such, one of the top priorities of the construction sector has been to continuously improve the level of collaboration in projects for the purposes of achieving effectiveness and excellence in the industry (Egan 1998). One factor that promotes project collaboration is the ease with which information is exchanged among the project parties, otherwise known as interoperability. It is the ability of a system, or components of a system, to provide information portability across other systems or components. Interoperability is characterized by systems intelligence that enhances the cooperation between component information systems (Bishr 1998) and has been described to be in order of levels in the literature (Charalabidis et al. 2004; Charalabidis et al. 2008; Veer and Wiles 2008; Bahar et al. 2013; Rezaei et al. 2014a). The interoperability between GIS systems has been broken down to six different levels (Figure 2). In the ascending order of advancement, these levels include (i) network protocols, (ii) hardware and operating systems, (iii) spatial data files, (iv) database

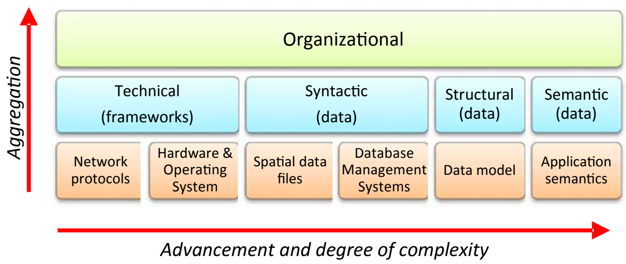

Fig. 2: Relationship of levels of interoperability.

management systems, (v) data models and (vi) application semantics. Each of these levels at which interoperability can occur constitutes a wide field of technology with room for improvements/advancement. The most advanced levels (data model and application semantics), characterized by transparent and homogeneous representation systems, are more difficult to achieve.

It is worth mentioning here that other broader views of levels of interoperability exist. For example, in the quest to define ontologies for GIS, Visser et al. (2002b) reduced the interoperability of information sources to four levels of integration: technical, syntactic, structural and semantic. Furthermore, a more recent study resolved interoperability into four types (technical, syntactic, semantic and organizational), which are not exactly similar to the previous ones. Figure 2 provides the synchronized concept of fusing these views of interoperability levels and corroborates the assertion by Bishr (1998) that interoperability is scalable and can be improved in scope.

5.1.2 LoD and level of development (LOD)

LoD specification is an important subject in the built environment for information representation and exchange. It varies from one domain to another in accordance with the peculiar requirements and accepted practices defined within such domains. Such variations have been acknowledged by Deng et al. (2016) between the GIS and BIM domains. While GIS LoD specification dwells on geometric details for supporting different applications, LoD in BIM applications is concerned with information requirements at the different stages of the building process's life cycle. This difference arises as a result of the concepts that are considered important in these two domains. For building models developed in BIM, the decomposition of objects and their relationships are key details for definition, whereas server-focussed GIS uses geolocation (real-world coordinates) to describe geospatial objects (van Berlo and de Laat 2011). In the GIS and CIM domains, five LoDs have been consistently discussed in literature (Chen 2011; van Berlo and de Laat 2011; Cheng et al. 2013; Deng et al. 2016). These are LoD0, LoD1, LoD2, LoD3 and LoD4. LoD4 is the most advanced and includes interior details, such as rooms, staircases and furnishing of structures. This is followed by LoD3 with vivid details of wall, roof, windows, doors and balconies of structures, as well as transport objects. These features are not as vivid in LoD2, tending more towards block models, with angular roof extrusions that disappear into rectangular blocks in LoD1. LoD0 is characterized by the greatest level of coarseness among all the LoDs and essentially constitutes a 2.5D representation of digital terrain models as obtainable in aerial imagery.

For BIM, LoD refers to the amount of detail added (input) to the model at the various stages of development, and it is subtly different from the degree to which information in the model can be reliably extracted (output), known as the level of development (LOD)(BIM Forum 2015). According to Publicly Available Specification (PAS) 1192-2:2013 (British Standard Institution [BSI] 2013), levels of model detail relating to the graphical contents of elements that align and can be associated with the non-graphical contents are called levels of model information (LOI). Leite et al. (2011) noted five LoDs from the efforts of Vico Software Inc. by Trimble as follows: conceptual, approximate geometry (criteria design), precise geometry (detailed design), fabrication and as-built. In terms of LOD, these have been respectively referred to as LOD 100, LOD 200, LOD 300, LOD 400 and LOD 500 (American Institute of Architects [AIA] 2013; BIM Forum 2015). LODs 100 – 400 pertain to model elements that have not been verified in the field, while elements in LOD 500 are as-built and field verified. A BIM project milestone that has achieved a record model consists of model elements in LODs 100–500 (AIA 2013). The preceding premises briefly acknowledge the concerted efforts on LoDs in both CIM and BIM domains. However, the challenge is in figuring how these two schools of LoDs, namely, GIS/CIM and BIM, map into one another and how they can be synchronized for the purposes of integration. Thus, to make progress in integration efforts, the differences between the data structures in both CIM and BIM domains need to be understood as their various LoD specifications differ significantly (Figure 3). The successful export of the IFC BIM file format to CityGML in LoD4 has been reported by van Berlo and de Laat (2011). However, Stoter et al. (2011) cautions that LoD4, which includes internal details in the CIM domain, differs significantly from the corresponding LoD specification in BIM. For BIM, the internal details of structures get developed right from LOD 200 and become approved by the project team in LOD 300.

	Virtual 3D City model (CityGML)	BIM (Revit/IFC)
Graphical illustration		
Information details	▪ Surfaces (wall, floor, roof) ▪ Installed objects (windows, doors) ▪ Edges and object demarcation lines ▪ Visible internal details (e.g. floor slabs)	▪ Surfaces (wall, floor, roof) ▪ Installed objects (window, doors) ▪ Edges and object demarcation lines ▪ Visible internal details (e.g. floor slabs) ▪ Detailed outline for edges of objects (e.g. frame around windows) ▪ Partition lines for surfaces of an object (e.g. double doorpanels, window panes) ▪ Can be used for constructionpurposes as dimensions are accurate

Fig. 3: Differences between LoD 4 for CityGML and the BIM counterpart.

6 Works on the practicalities of BIM and CIM integration

Focussing on the asset management domain, the review carried out by Zhang et al. (2009) examined the performance of four cases allegedly harnessing BIM and GIS integration in the management of their assets. These cases include the integration of GIS into the space management system of the University of Minnesota, USA; the National Aeronautics and Space Administration (NASA) implementation of GIS-based spatial data management and decision support system; The Shore Facility Capital Asset Management Roadmap programme of the United States Coast Guard; and the New South Wales Department of Housing (DoH) in Australia. DoH explored the capacity of IFC-based BIM in facilitating a spatial decision support system to solve the challenge of locating individual tenancies within large unconsolidated cadastral units (Barton and Plume 2006). The Australian project reportedly achieved a visualization system that zooms from an urban scale to individual buildings and then to tenancies. Such utility is an advancement of the functional asset management system, which is expected to furnish decision-makers with adequate and reliable data for making informed asset deployment decisions (Lemer 1998).

To provide the asset manager with a complete existing portfolio, a functional asset management system should typically be rich in information regarding general project and contract information, design data, change orders, contract correspondence, maintenance records, repair data and renewal information (Kyle 2001). Before the advent of BIM, CAD systems were believed to be adequate to generate such data to assist in facility/asset management (Vanier 2001). To this end, Zhang et al. (2009) argue that BIM is more than capable to replace CAD because of its associated data structure and the level of interoperability achievable with BIM systems. The literature reveals that areas currently being explored to associate BIM data structure with that of GIS and 3D modelling are becoming vast. Areas identified in this study have common grounds with the six key application areas of climate adaptation/energy analysis, view quality and shadow adaptation, utility visualization, facility management, spatial querying/location and space navigation, planning and emergency situations/natural disaster damage analysis, earlier discussed by Fosu et al. (2015). However, the generally noticeable integration approaches used by studies to achieve BIM, GIS and 3D city integration are (i) data/file conversion (DFC) systems, (ii) semantic mapping (SM) systems or (iii) a hybrid of both, as given in Table 1. We consider integration approaches that are based on DFC to be synonymous with syntactic interoperability and coding/SM-based approaches to be associated with semantic interoperability. These are discussed separately in Sections 6.1 and 6.2. It agrees with the proposal of Visser et al. (2002a), who argued that GIS integration challenges are of three levels: syntactic, semantic and structural. Structural integration entails the re-formatting of data structures and is discussed as synonymous with the hybrid approach in Section 6.3.

Tab. 1: Recent developments on the integration of 3D city modelling and BIM.

Source	Study origin	Area of application	Integration elements considered	Features
Integration approaches using DFC				
Saygi et al. 2013	Turkey Italy	Historic buildings and heritage site	GIS AutoCAD BIM (Revit)	• Explored workflows with BIM and GIS integration capabilities in 3D modelling for historic buildings • Proposed enhancement of heritage information management and digital archiving of historic buildings
Dore and Murphy 2012	Ireland	Historic buildings and heritage site	CityGML BIM (ArchiCAD)	• Use of geometric descriptive language to create Historic BIM • Documentation and analysis of cultural heritage sites
Thompson et al. 2011	UK	Integration of cities	GIS	• Creation of 3D computer model of two adjacent cities • Explored the convergence of GIS, BIM and 3D city modelling
Irizarry and Karan 2012	USA	Construction site management	GIS Revit Architecture	• Location optimization of tower cranes at construction sites • Integrating BIM with GIS at application level through BIM implementation in the geospatial environment
Integration approaches using the SM approach				
El-Mekawy et al. 2012	Sweden	Building elements and features	CityGML IFC	• Development of a unified building model • Merging of overlapping concepts in CityGML and IFC • Redefinition of spatial relationship between objects
Irizarry et al. 2013	USA Canada	Construction supply chain management	GIS IFC	• Visual monitoring of construction supply chain events • Mapping the flow of materials and resources in supply chain
Cheng et al. 2013	China	Levels of detail	IFC CityGML	• Development of reference ontology to exchange semantic information between IFC models and CityGML models • Harmonization of LoDs in CityGML models and IFC models
Akinci et al. 2010	USA	Semantic Web	CAD GIS	• Interoperability of CAD and GIS • Use of web ontologies to resolve potential semantic challenges
Isikdag and Zlatanova 2009	The Netherlands	Level of detail	IFC CityGML	• Proposed a framework for SM between models in IFC and CityGML formats
Hijazi et al. 2011	Germany	Interior utilities	IFC CityGML	• Integration of 3D BIM network data into 3D city models/GIS • Used SM of building's interior utility elements to the corresponding utility network in CityGML
Borrmann 2010	Germany	Spatial analysis	Spatial query language (SQL) IFC CityGML	• Use of spatial operators in SQL to query 3D building data and 3D city models • Creating SQL for building information models
Borrmann et al. 2015	Germany	Shield tunnels	IFC GIS	• Proposed a multi-scale representation of shield tunnel models (as obtained in GIS) in BIM • Suggested extension of IFC data model to include multi-scale representation of shield tunnels
Karan and Irizarry 2015	USA	Semantic Web on preconstruction operations	GIS BIM XML	• Translation of BIM and GIS data to Semantic Web format • Generation of database query to access Semantic Web data

(*Continued*)

Tab. 1: Recent developments on the integration of 3D city modelling and BIM (*Continued*).

Source	Study origin	Area of application	Integration elements considered	Features
Integration approaches using the SM approach				
Karan et al. 2015				
Döllner and Hagedorn 2007	Germany	Semantic Web	CAD GIS BIM	• Integration of CAD, GIS and BIM through a service-based system • Web service-based integrated visualization of semantic-enhanced information
Benner et al. 2005	Germany	Building elements and features	IFC CityGML	• Developed a Quartierdaten-Management system (QUASY) model, which is a hybrid of IFC and CityGML standard • The model represents semantic objects geometrically described by surfaces visible to the user
Clemen and Gründig 2006	Germany	Land survey	IFC GIS	• Modelling of topology and geometry in IFC • Proposed considerations of geodetic measurements and coordinate frames in IFC
de Laat and van Berlo 2011	Netherlands	Semantic Web	CityGML IFC BIMServer	• Development of CityGML extension known as GeoBIM • The use of the Web (BIMServer) to implement output
Peachavanish et al. 2006	Thailand USA	Data exchange	CAD GIS	• The use of query-based ontological engineering methodology to enable semantic interoperability between CAD and GIS
Isikdag et al. 2008	Turkey UK	Site selection and safety management	IFC GIS	• Implementation of IFC in a geospatial environment for GIS-related investigations • Demonstration of BIM providing sufficient level of information for GIS-based site selection and fire response
Stadler and Kolbe 2007	Germany	Spatial analysis	CityGML IFC	• Proposed reducing the challenges with spatio-semantic coherence of 3D models in data integration
Elbeltagi and Dawood 2011	Egypt	Project management	GIS BIM (Revit) MS Project	• Visualization of project progress at distributed sites using GIS • Development of mathematical model for time control of repetitive construction tasks • BIM-compliant dynamic integration of project progress
Integration approaches combining DFC and SM				
Hijazi et al. 2009	Germany/ The Netherlands/ Turkey	Water utility network	CAD BIM GIS	• Integrating 3D BIM utilities network into GIS • Development of software component to convert IFC to CityGML
Rafiee et al. 2014	The Netherlands	View coverage and shadow analysis	IFC GIS	• Integration of IFC BIM model in GIS environment • Use of extract, transform, load process to convert IFC data to geographic format and geo-referencing of such data

6.1 Integration approaches using DFC systems

Syntactic interoperability refers to the ability of systems to exchange data in formats characterized by well-defined syntax and encoding structure (Veer and Wiles 2008). It is associated with system application level, which allows the communication of multiple software components, such as implementation languages, interfaces and execution platforms (Ram and Ramesh 1999). Here, problems related to different data types can be solved (e.g. short int vs. int and/or long) using tools such as wrappers to restructure information sources to achieve uniformity (Visser et al. 2002a). Among the reviewed literature, presentations in four studies (Thompson et al. 2011; Dore and Murphy 2012; Irizarry and Karan 2012; Saygi et al. 2013) appear to have pursued GIS, 3D city and BIM integration at a syntactic level. Saygi et al. (2013) explored the roles, potentials and distinction between BIM and GIS in the systematic conceptualization, structuring and representation of architectural heritage data. The research claims to extend beyond integration of BIM with historic digital data into information systems, as explored in some studies (Fai et al. 2011; Apollonio et al. 2012; Apollonio et al. 2013; Murphy et al. 2013), to the management phase of historic buildings. The management process involves generation of 2D and 3D visualizations, definition of parameters and relations among the data for the purposes of restructuring and eventual integrated visualization. Thereafter, 3D models were created in Autodesk 3ds or Trimble SketchUp and imported into the GIS environment by means of plug-ins. The authors caution that loss of information could result from the conversion process due to structural differences between both environments and compatibility issues. Some of the information loss challenges posed by such file conversion seem to have been overcome by the work of Dore and Murphy (2012) in recording and managing cultural heritage sites. Dore and Murphy (2012) used a novel prototype library (IFC-based plug-in) of objects with historic data, known as historic building information modelling (HBIM), to convert models to CityGML. This was initially tested through exporting an HBIM model to Google SketchUp free of any interoperability setback before opening in a GIS environment. The plug-in helps to convert objects into CityGML semantic classes based on associated layer names. Thus, the interoperability challenges faced by associating BIM-compliant historic building data with GIS appear to be momentary. Considering that there has been ample progress in digitizing architectural cultural heritage data, the mapping of associated semantic attributes using contradistinctions between heritage data and modern architectural forms offers a promising approach for BIM–GIS integrated management of historical buildings according to Dore and Murphy (2012).

Currently, one solution towards enhancing better collaborative practices in the built environment is the integration of models and applications associated with different domains. This is recognized by researchers, such as Breunig and Zlatanova (2011) and Bansal (2010), who are requesting for the harmonization of domain-specific models and modelling methods. They suggest that such harmonization will resolve the complexities of natural and man-made objects inherent in geographic regions. The harmonization of two cities in the UK as representation of different geographic regions was explored at the syntactic level by Thomas (2011). Model information of the two regions in CAD format was converted to the IFC file and then to ESRI Shapefiles before being merged in ArcGIS to achieve a rich digital city model. Moreover, at a syntactic level, Irizarry and Karan (2012) demonstrated that ArcGIS is a useful tool for determining the geometric intersection points to optimally locate cranes on site for subsequent integration into BIM. The research relied on the extent of semantic compatibility entrenched in the IFC format of BIM with GIS data. Since IFC and GIS are not yet fully interoperable, researchers have consistently mentioned loss of data as the resulting limitations. However, Irizarry and Karan (2012) suggest that good knowledge about BIM and GIS functionalities can provide some advantage in getting around certain integration limitations. Such possibilities are offered by extending the integration processes to the semantic level (Karan and Irizarry 2015).

6.2 Integration approaches using SM

The ability to bridge semantics conflicts between entities is associated with knowledge-level interoperability. This entails resolving differences in implicit meanings, perspectives and assumptions between systems (Park and Ram 2004; Maarof and Yahya 2009). Sen et al. (2007) suggested two requirements to achieving semantic interoperability, which have both proved difficult to fully fulfil because of variations with respect to time. The first involves the quantification of existing interoperability (existence or absence of semantic conflicts) between two systems and the second is ensuring that there is a translationary mechanism for cases that lack semantic equivalence. However, the use of ontologies has been alleged to provide the opportunity to meet these requirements and achieve an appreciable level of semantic interoperability (Chandrasekaran et al. 1999). Against this backdrop, Kuhn (2005) rather asserts that techniques more powerful than ontology and reasoning are required to achieve full semantic interoperability.

Interoperability, in the context of the Semantic Web, requires the aggregation of expressions built from symbols used in service description languages, such as Web Services Description Language (WSDL) and Web Ontology Language for Service (OWL-S) (Kuhn 2005). The goal of the Semantic Web as a Web of data is to develop systems that can support trusted interactions over the network, thereby allowing computers to perform more useful works (World Wide Web Consortium [W3C] 2015). Such works include using Semantic Web technologies to create data stores in the Web, build vocabularies and develop rules in the form of queries for handling data. In this context, Akinci et al. (2010) adopted the approach of using CAD/GIS domain ontologies defining specific concepts to resolve potential issues on the semantic searching and matching of Web services. As an explicit specification of conceptualization (Gruber 1993), ontologies represent concepts and their relationships within a particular domain. Ontologies can therefore be used to establish formal semantic agreements within and across domains for the purposes of processing and matching of Web service requests and registered Web services, as explored by Akinci et al. (2010). The authors envisioned semantic CAD/GIS Web services as a means to reconciling both CAD and GIS data/operations through the development of algorithms for their interpretation, as well as the matching of service requests and service composition.

Similarly, considering the Semantic Web as a common framework for providing semantic interoperability between BIM and GIS operations, Karan and Irizarry (2015) have developed a standard method to describe information interpretable by both domains. Building elements in IFC BIM formats and GIS data were first translated into a Semantic Web data format, namely, resource description framework (RDF). This was followed by developing a set of standardized ontologies for pre-construction operations to integrate and query the heterogeneous spatial and temporal RDF data, before accessing and acquiring the data with a query language (simple protocol and RDF query language [SPARQL]). The work was able to obtain publishing data in forms that machines can naturally understand, which is important for the automation of data integration. Consequently, this provides the opportunity to tackle issues of data consistency in collaborative environments. Thus, challenges relating to the drawback of users having to manually ensure the consistency of geospatial data being integrated from multiple sources, highlighted by Stadler and Kolbe (2007), can now be handled. Stadler and Kolbe (2007) assert that CityGML can capture objects that potentially have both spatial and semantic attributes and is therefore a good tool for addressing challenges with data exchange in collaborative heterogeneous environments. CityGML is an open XML-based data model for the storing and exchanging of virtual 3D city models, which are usually acquired and refined. As such, the coherence of spatio-semantic data within virtual 3D city models cannot be assumed, as insisted by Stadler and Kolbe (2007). In this context, they propose the harmonization of fragmented CityGML data from distributed sources to establish geometrically, topologically and semantically consistent 3D scenes. However, a major drawback with CityGML representation that has been constantly highlighted in the literature is lack of adequate metadata or semantic information (Benner et al. 2005; Benner et al. 2013; Cheng et al. 2013).

Although modelling with CityGML is alleged to be limited to building exteriors and to not cover building activities (Karan and Irizarry 2015), it has been widely explored in the quest by researchers (Döllner and Hagedorn 2007; Nagel and Kolbe 2007; Hijazi et al. 2009; Isikdag and Zlatanova 2009; van Berlo and de Laat 2011; Benner et al. 2013) to integrate the information modelling of cities and buildings. The work of Döllner and Hagedorn (2007) to integrate urban data as a service-based virtual 3D city model (fundamental to the early developments of LandXplorer system) is a remarkable example. This CityGML-based 3D viewer allows the client access, import and integration of semantic-enhanced information models from CAD, GIS and BIM domains provided within a service-based geo-data infrastructure. The CAD/GIS/BIM thread, adapted after Cote

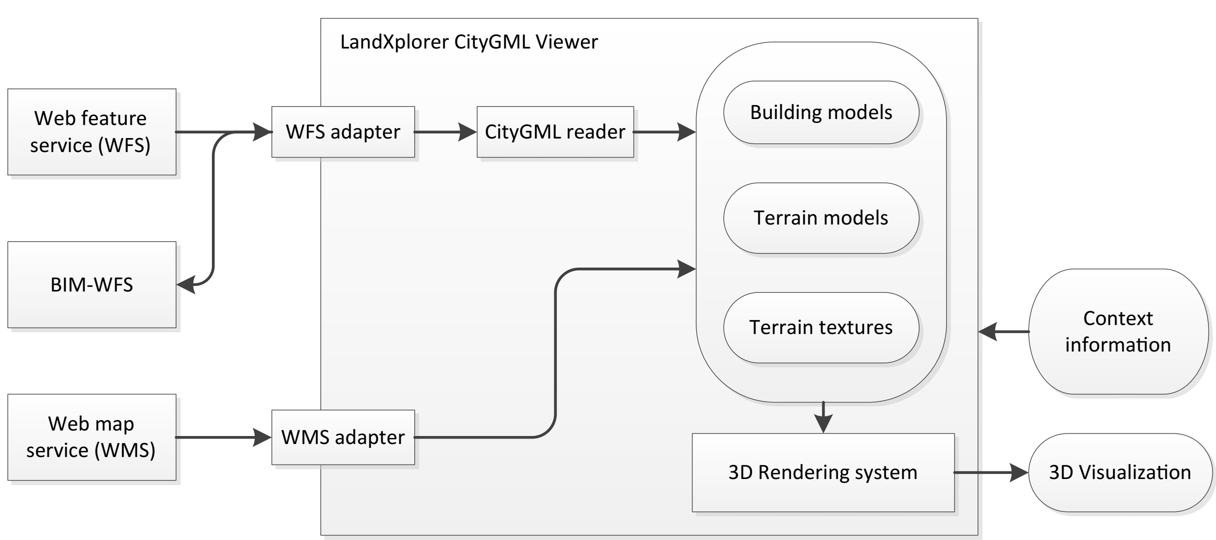

Fig. 4: System Architecture for 3D viewer for CAD/GIS/BIM integration (Döllner and Hagedorn 2007).

(2007), yielded the system architecture (Figure 4) of the 3D viewer within the LandXplorer technology framework extended to support CityGML and adaptors for OGC-compliant Web services. Another work of interest is that by van Berlo and de Laat (2011), who developed the GeoBIM CityGML extension to store window dimensions, calculate indoor routes for responders, locate building structural elements in cases of disaster and simulate evacuation scenarios during incidents in the building. Suggesting that about 17 IFC classes map directly to corresponding CityGML types (e.g. IfcBuilding, IfcWindow and IfcColumn to Building, Window and Column, respectively, in CityGML), the authors stated that the GeoBIM extension is able to create new objects, such as *stairs* characterized by properties and semantics, in CityGML at LoD 4. They aspire to expand the conversion of IFC to CityGML from LoD 4 to cover LoDs 3–1 in future research.

Regarding the representation of models in the form of objects or cities at varying scales, as may be obtainable in virtual 3D city, the concept of LoD is a very important factor. As Benner et al. (2013) suggested, it is indispensable in supporting the partitioning of a complete model into alternative models of different complexities, qualities and the provision of metadata to address various information requirements. On the grounds that CityGML is deficient in metadata to complement LoD information and to distinguish between building exteriors and interiors, Benner et al. proposed an enhanced LoD concept. The concept differentiates between geometric level of detail (GLoD) and semantic level of detail (SLoD) to describe both the interior and the exterior of buildings. These LoDs are combined to produce better visualization of details, as illustrated in Figure 5. This means an increase in CityGML capability to model the interiors and exteriors of building, with the possibility of extension to similar city objects.

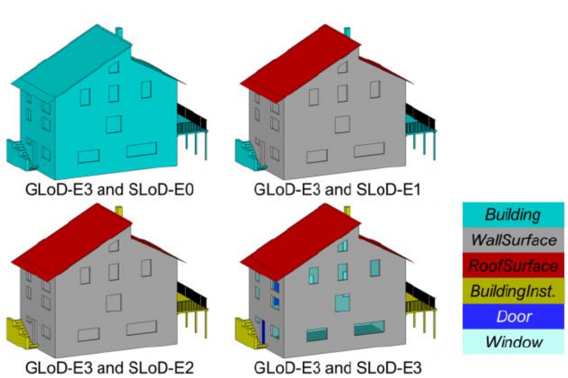

Fig. 5: Combining geometric LoD and semantic LoD in CityGML (Benner et al. 2013).

6.3 Integration approaches combining DFC and SM

To fully resolve the interoperability challenges between GIS and BIM, processes may need to be combined and subsequently improved. In addition to synthetic and semantic integration, Visser et al. (2000) argued that aspects of data re-formatting to achieve homogeneous data structures, known as structural integration, cannot be skipped to make GIS interoperable. The re-formatting of data structures may be executed by middleware (mediator) at a low level, such as Common Object Request Broker Architecture (CORBA) (Object Management Group [OMG] 2015), or at a high level (Wiederhold 1992). Basically, the function of the mediator is to map or convert source information, such as from DBMS, GIS, Internet, etc., into an integrated view (Chawathe et al. 1994; Visser et al. 2002b; Visser et al. 2002a). Rafiee et al. (2014) took advantage of this data conversion facility to transform the geometric and semantic information of BIM to a geo-referenced model to achieve view coverage and shadow analysis to enhance spatial planning. The initial process involves using extract, transform, load (ETL) to convert the BIM IFC format to a homogeneous vector geographic format. This is followed by assigning semantic information from the IFC model to the spatial information model and the use of transformation mechanism to geo-reference the resulting local coordinate system associated with the IFC model. Another application of intermediary transformation of information is in the integration analysis of interior utility networks for geo-analysis (Hijazi et al. 2009; Hijazi et al. 2012). The intention is to manage the analysis of 3D interior utilities in an integrated GIS environment, such as CityGML-based 3D city models. The approach involves obtaining interior utility objects from a BIM and storing them up in a Network for Interior Building Utilities (NIBU) model, with the capability to hold semantic information as well as explore network connectivity. NIBU is a data model intended to provide 3D building interior utilities networks that can be used for electricity, gas and water. It consists of the true 3D geometry of network objects, the logical graph structure for analysis and the thematics/semantics associated with network objects presented in the IFC format. The transformation process from the IFC to the NIBU model includes the following steps: parsing and storing IFC data as a temporal schema that can be converted into NIBU; extracting and transforming the geometry of objects obtained from the IFC model; and using PostgreSQL/PostGIS to create corresponding polyhedrons to finally achieve the shapes of the desired network objects.

7 Discussion

As the world is increasingly migrating towards integration, the need to combine independent systems associated with different aspects and scales of the built environment is now becoming pertinent. The contemporary object-oriented digitization of real-world elements appears to provide a leeway for amalgamating two major aspects of BeIM systems, as explored in this review. BIM, which involves the designing of building structures within local coordinate systems at a richer LoD, is on one side, and 3D city modelling, used for urban-level design based on the earth's coordinate system, is at the other end. These two different groups of applications are respectively closely related, or even embedded with, the earlier-developed CAD and GIS functionalities. While efforts are on gear to combine BIM and CIM, these systems have their own individual implementation challenges, which may transform as disadvantages to the integration quest. For example, the terminologies and encoding systems of 3D virtual city are yet to be fully standardized (Shiode 2000; Döllner et al. 2006; Biljecki et al. 2015), which implies a state of yet-to-reach maturity. On the other hand, the scope of BIM is still largely undefined, growing larger every now and then. However, it is recommended that BIM should never be "complete" to make room for bolting on new construction practices. The question then is to what extent is the scope of BIM expected to grow, which – in some sense – encompasses aspects of integration, as investigated in this review. As widely discussed in the literature, the technology is great and has earned appreciable progress as well as commendations. This is evident from the level of interest and ongoing research around the world, including the continuous increase in the number of BIM tools and new areas of applications giving rise to various acronyms. However, a slower level of progress seems to be made in other aspects of BIM, such as the people and process elements embedded in the holistic definition of BIM. Considering that there are a series of ongoing training and re-training sessions for personnel to become BIM competent, the structures in processes wherein BIM is to be implemented are largely still being experimented, with challenges yet unresolved. Among these are contractual issues, such as obligations and liabilities of parties, ownership and intellectual property rights of the developed models. Thus, expanding the scope of BIM to integrate with CIM may further exacerbate such challenges.

Notwithstanding these hurdles, the strides made in the three BIM–CIM integration aspects (Figure 6) of DFC systems, SM systems and the hybrid of both are commendable. We take these three aspects as respectively synonymous with integration at the syntactic, semantic and structural levels, which are needed to be achieved if interoperability challenges are to be fully resolved in the modelling of

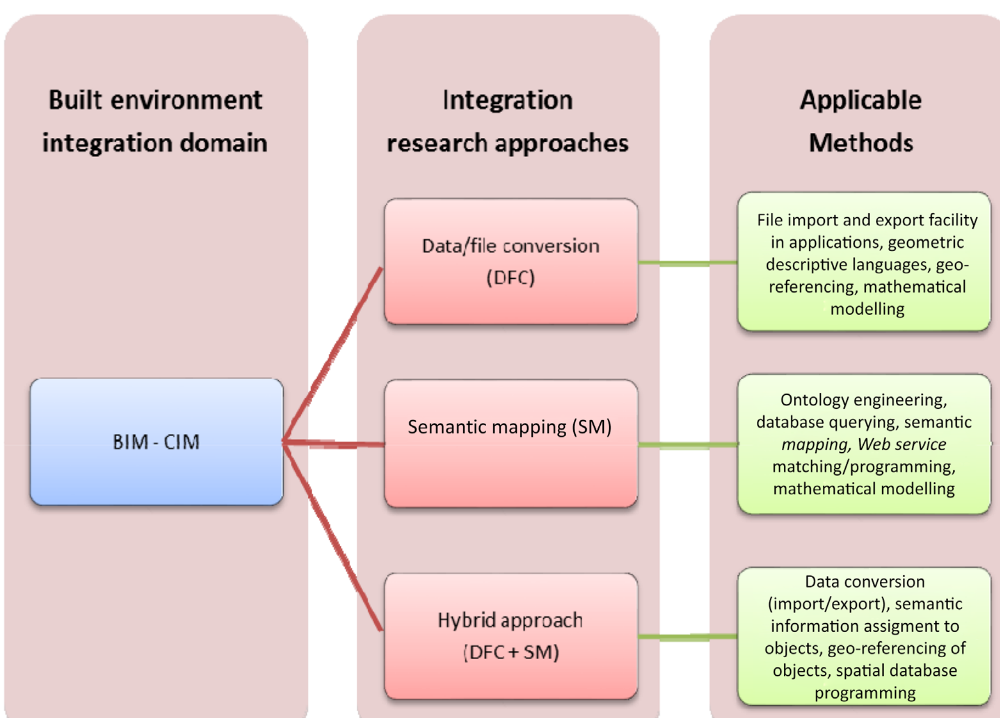

Fig. 6: BIM–3D city modelling integration approaches and applied methods.

urban systems (Visser et al. 2002a,b). In addition to the use of tools such as ontology engineering, Semantic Web applications and structural transformation methodical approaches may all be required to tackle integration challenges. In this context, the plausible relationships between IFC and CityGML, the respective representation file formats for BIM and CIM, have been explored by researchers. While IFC, an Express-based language, can be used to represent semantic information, CityGML – which is XML-based format – has its limitations in terms of inability to capture metadata/semantics information (Benner et al. 2005; Benner et al. 2013; Cheng et al. 2013). Researchers (van Berlo and de Laat 2011) advise to take advantage of the strong points of both systems to explore integration possibilities. However, as Irizarry and Karan (2012) suggest, this requires very good knowledge of how both systems operate. Such knowledge appears to have been adequately demonstrated in the developed HBIM applications (Dore and Murphy 2012) and GeoBIM extension (van Berlo and de Laat 2011). This premise sparks up some food for thought. It means that for the integration of BIM and 3D city modelling to achieve a high success rate, there must be some higher level of collaboration between urban designers and building designers/system developers alike, or a middle-ground profession combining the cores of urban design and building design/systems development may be required in the built environment.

In the authors' opinion, CIM systems that can cover large areas and perform spatial analysis/simulations will do better in the integration with BIM than those that model a limited small area. Such systems are more sophisticated as they are embedded with GIS applications that can allow transformation from the local building system used in BIM. Thus, 3D city models generated using the modern point cloud scanning methods can benefit from progress already made in associating point cloud images with BIM. Point cloud scanning of historic buildings has been explored as a means to creating and updating digital models of As-built BIM, a representation of the building as-is at the state of survey (Hichri et al. 2013). This will be of great value to the GIS-based management of the digitization of architectural heritage data from sites and buildings.

8 Conclusion

The integration of BIM and CIM is becoming much needed in the built environment to achieve more robust and interoperable BeIM systems. This aligns with contemporary globalization trends looking towards the integration of systems associated with different domains. The advances in IT that now allow the increasingly close representation of real-life physical elements with their digitized counterpart (in the form of objects governed by rules) provides some advantage in this direction. BIM is concerned with the designing of building structures based on a local coordinate system, and CIM systems use the earth's coordinate system to capture urban forms. These two systems have their strengths, which can be harnessed in integration. Existing applications of CIM vary in the size of the spatial area that they can accommodate and in their functionalities. Thus, 3D city systems embedded with GIS applications that can cover large areas and perform spatial analysis/simulations will do better for integration with BIM than those that model a limited small area. Furthermore, there is the possibility of generating models in CIM using modern point cloud scanning methods to benefit from progress already made in associating point cloud images with BIM.

The activities on current integration research efforts fall into three categories: (1) integration aspects of DFC systems, (2) SM systems and (3) the hybrid of both. At the moment, a number of research efforts rely on the hybrid approach to achieve the desired result. In other words, some form of file conversion process that may entail re-formatting (manual or machine aided) of data structure is still needed even in the SM approach. The various methods adopted in the literature include aspects of ontology engineering, Semantic Web applications and database query manipulations. For better application of these methods to achieve BIM–CIM integration, good knowledge of both domains and their system functionalities is important. On the one hand, this generates a demand for higher levels of collaboration between urban designers and building designers/system developers alike. On the other, the birth of a middle-ground profession combining the cores of urban and building design/systems development may be required in the built environment to encourage such integration. In any case, it is clear that BIM–CIM integration has begun, and challenges are gradually being surmounted at various levels and scales.

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