Digital Interoperability for the Facilities Management Domain: a Review of Semantic Web-based Approaches

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Abstract

The use of Semantic Web-based Technologies (SWT) to support digital Facilities Management (FM) activities has been shown to address interoperability challenges between disciplinary stakeholders. By establishing shared understanding through ontologies, eliminating precarious file exchanges and democratising participation through non-proprietary technologies, SWTs are receiving growing interest from the research community. Despite this, no comprehensive review exists which analyses works with a specific focus on the FM domain. This paper reviews 35 academic works and provides a broad discussion around academic and industry initiatives in SWTs for the FM domain, identifying research gaps and future directions of interest. We find that SWTs are already being used by FM practitioners and that implementation is highly case-specific and thus, developments need to be flexible and user-oriented in their design. This work towards a comprehensive domain review provides a useful reference for others in the field as well as informing our own future research activities.

Keywords: facilities management, digitalisation, interoperability, semantic web technologies

1 Background

According to the International Energy Agency's *Global Status Report* (2017), the built environment accounts for around 40% of anthropogenic CO_2 emissions. These *greenhouse gases* are having a warming effect and causing the Earth's climate to change to the detriment of society (IPCC 2018). Until recently the focus has been on reducing environmental and financial costs primarily during design and construction (Krstić & Marenjak 2012), however, given that around 70% of these costs are incurred during the operation and maintenance (O&M) phase of a buildings life-cycle (Geekiyanage & Ramachandra 2018), the focus is broadly shifting towards a whole life view, or the *life-cycle cost* (Kale et al. 2016).

Barrett & Baldry (2003) define FM as a strategic outsourcing of an organisations non-core activities. This broad domain scope is described by Shaw et al. (2021) and is responsible, in part, for a lack of domain standardisation. FM practitioners are concerned with the operational phase of the building life cycle, however, they are typically not involved in building projects until the handover phase, and thus have little control over data specification (McAuley 2016). Furthermore, due to the inherently complex and fragmentary nature of construction projects, interoperability issues frequently occur during data exchange between stakeholders (Huahui & Deng 2018), hence it is the single greatest area of focus for technical development in academic FM research (Gao & Pishdad-Bozorgi 2019).

The International Organization for Standardization defines interoperability as the ability to unambiguously exchange data between applications (ISO/IEC 2382:2015) and though the literature is replete with partial solutions to exchange challenges, no satisfactory methodology has been broadly adopted. Such a solution could realise the true potential of the BIM methodology as envisaged by Sacks et al. (2020). Significant progress has been made in agreeing a common, open data format for use in the Architectural, Engineering, Construction and Operations (AECO) industry. The most prominent example is the Industry Foundation Class (IFC) format, recently included as the required exchange format in the ISO 19650 standard (UK BIM Alliance 2020). However, most authors agree that IFC remains limited as far as a mechanism for true interoperability between a wide variety of stakeholders, with limited potential for scalability, being complex and difficult to implement into software (Redmond et al. 2012, Belsky et al. 2016, Bonduel et al. 2018). This reflects observations by Boddy et al. (2007) that the majority of development (and resulting need for integration) in *computer integrated construction* has taken place on the monolithic application side; an endeavour which the authors describe as a "spent avenue for further research" when we consider the effort of implementation and rapidly changing data landscape.

In line with the recommendations of Boddy et al., in recent years semantic web-based technologies (SWT) have received significant interest in the research community for their potential to address interoperability issues (Pauwels et al. 2017). Suited to the decentralised nature of construction projects (Verborgh 2017), SWTs have been shown to facilitate communication between disparate domains through the use of the open Resource Description Framework (RDF) data format and by agreeing ontologies which formalise the meaning of terms (Niknam & Karshenas 2017). By aligning these meanings, different domain actors can establish common understanding around shared concepts without changing their original (or *source*) data. This is a very powerful concept and, as a result, research on the topic has expanded across many domains. These include the built environment and, specifically, the FM domain for whom open standards are especially important for data longevity, given the lengthy lifespan of built assets (Patacas et al. 2020). However, issues remain regarding the ability of SWTs to handle complexity (Pauwels et al. 2017) and until now there is no comprehensive overview of Semantic Web (SW)-based initiatives as they relate to the FM domain.

In light of this gap, the aim of this work is to present initial findings from a review of FM-related SWT initiatives. The remainder of this paper consists of four sections; Section 2 describes the research methodology, section 3 provides a review of literature under relevant sub-topics, section 4 discusses trends and gaps concerning SWT use for FM and finally, initial findings are drawn in section 5.

2 Research Method

The primary research method is a comparative archival study of academic literature. It follows a four step methodology, adapted from Xue et al. (2021); (1) develop a conceptual model, (2) data collection by parametric archival search, (3) decoding of main contributions (4) analysis and discussion of initial results and gaps in the research.

2.1 Developing a conceptual model

A conceptual model was developed around which the literature can be organised and discussed. Foundational works include early or visionary studies. Next, it is important to discuss schools of thought on dealing with the geometric aspect of BIM for the FM domain, as is selecting a suitable ontological

Table 1: classification of literature sources per the guiding conceptual model

relevant area	reviewed authors
foundational works	Noy & McGuinness (2001), Schevers et al. (2007), East (2007), Vanlande & Nicolle (2008), Ruikar et al. (2007), Törmä (2013), Beetz (2009), Redmond et al. (2012), Belsky et al. (2016), Pärn et al. (2017), Rasmussen, Hviid & Karlshøj (2017), Godager (2018), Patacas et al. (2020)
geometric approach	Pauwels & Roxin (2016), Rasmussen, Pauwels, Karlshøj & Hviid (2017), McArthur & Bortoluzzi (2018), Chen et al. (2018), Bonduel et al. (2018), Krämer & Besenyői (2018), Wagner et al. (2020), East et al. (2021), Jung (2021)
ontological approach	Rasmussen, Pauwels, Karlshøj & Hviid (2017), Niknam & Karshenas (2017), Bonino & De Russis (2018), Rasmussen et al. (2020), Luo et al. (2021)
SWT uses for FM	Kim et al. (2018), Chen et al. (2018), Yalcinkaya & Singh (2018), Hammar et al. (2019), Gouda Mohamed et al. (2020), Kumar & Teo (2021), Droog & Baayen (2021), Liu & Chou (2021)

approach; a key consideration in SWT initiatives. Finally we group works which have addressed FM use cases to date.

2.2 Data collection, decoding and analysis

The data collection process includes; collecting, screening, reducing and synthesising the literature following the PRISMA standard (Page et al. 2021). The first step identifies related publications by parametrically searching the query string *((“Facility Management" OR “Facilities Management" OR “FM" OR “O&M" OR “Operations and Maintenance") AND (“Semantic Web" OR “Linked Data"))* in the advanced search engines of both *Web of Science* and *Scopus* databases. These terms allow for abbreviated and synonymic variation in the literature. In both cases the query returned items which included the search terms in the abstract only. Furthermore, the data collection included works which did not result from the parametric search but which have been identified as part of ongoing Cloud-based BIM (CBIM) European Training Network (ETN) activities. This was necessary due to the inherent diversity of the FM scope. Next, a visual screening of the results was carried out which omitted unrelated search results, for example disregarding literature containing ’FM’ in the context of radio. Priority was given to journals in the AECO domain. Of the 67 papers resulting from the parametric search, 36 were disregarded. 4 relevant papers were added resulting in a final selection of 35 papers being analysed for this work. The selection of works were analysed and organised into themes according to the conceptual model (see Table 1). These groupings guide the structure of the remaining sections.

3 Review of SW Initiatives for FM

Kim et al. (2018) summarise developmental milestones in digital information management for the FM domain. Parallel developments in SWTs were shown to converge in 2012 with the proposal of ifcOWL, and with the first example of *integrated management* in 2016. The authors state that “BIM-based data management is not yet capable of supporting real-world FM practice, with the exception of some exemplary cases from academia". This is a generalised appraisal, but suffice to say that at the time of writing the field is still in its infancy.

Though significant integration may have been demonstrated only recently, foundational work by Schevers et al. (2007) and later Törmä (2013) established a theoretical framework and justification for O&M by FM professionals utilising the SW a decade before; the former demonstrating their innovations on the iconic Sydney Opera House.

In their 2007 paper, Schevers et al. describe a “network of ontologies" which facilitates data fusion between IFC data (which is extended to host FM specific properties), as prototypical OWL classes, and the FM databases at the Sydney Opera House. The paper provides a number of insights including a recommendation for SWTs and *Service Oriented Architectures* as being well suited to the scalability and flexibility needed in the FM domain as well as the importance of IFC as a non-proprietary exchange format, in order to avoid vendor lock-in. The work demonstrates a deep understanding of the complexities of digitalisation within the FM context, recognising the importance of “gradual introduction" and the inherent “evolving" nature of the business, which must be considered. In the same year Ruikar et al. (2007) suggest FM practitioners as a logical beneficiary of a SW-based approach given their particular requirement for efficient information retrieval. A year later Vanlande & Nicolle (2008) developed the *Context DataModel Framework*, another FM prototype utilising RDF and the SW. The following year, Beetz (2009) proposed ifcOWL as part of his PhD dissertation, laying the groundwork for representation of vendor neutral building information in a viable SW format.

Though not specifically intended for the FM domain, a 2013 paper by Törmä (2013) provides key insights into the suitability of SWTs as a means to hosting building information. The paper explains the motivation, challenges and steps required to establish a truly collaborative future BIM paradigm. Acknowledging the limitations of the IFC data model, as identified by Schevers et al. above, the author explains that an advantage of the *Linked* SW approach is that it “reduces the future needs to extend [the] IFC schema to cover new domains" as *meaning* may instead be inferred through domain-specific ontologies. Among the advantages of a SW approach to interoperability over IFC file exchanges are: the existence of a standardised query language, the possibility to enrich the building data model with parametric relationships (fundamental to proprietary BIM authoring functionality but for which the IFC data model falls short) and the move away from file-based processes.

So despite perhaps the greatest effort of industry-wide standardisation to date, concerns remain about the viability of the IFC format going forward. Due to its inability to represent sufficient parametric relationships, in addition to scalability limitations of the *model view definition* (MVD) sub-set selection methodology (Törmä 2013, Rasmussen 2019), various authors postulate a need for fundamnetal revision of the approach (Redmond et al. 2012, Belsky et al. 2016). Furthermore, due to its complex (legacy) STEP/EXPRESS structure, IFC is also considered ill-suited to graph-based representation which will be discussed in the following sections.

3.1 Geometric approach

The BIM paradigm has been, and remains, largely geometry-centric. Designer / constructor led BIM methodologies, where there has been greatest uptake to date (McAuley et al. 2017, Edirisinghe et al. 2017), make use of, in particular, digital prototyping and clash detection; these are both geometry-heavy processes. However, works in digitalisation of the FM space tend to consider non-geometric data as priority. McArthur & Bortoluzzi (2018) demonstrate a Lean-Agile BIM strategy for FM, adopting a “minimum viable geometry" approach for five specific FM use cases; the results validated through practitioner surveys. Though not focused on representation in a SW environment, this grounded methodology provides an early example of the importance for case-specific, tailored approaches in the FM context, as well as emphasising the need to cater to what practitioners really *need* from their building information. As reality capture techniques become increasingly economically viable, various researchers in the FM space have investigated point cloud data as the primary geometry representation (Krämer & Besenyői 2018, Jung 2021) though this can be computationally heavy.

It is widely understood that various geometrical representations are needed by different disciplines (Wagner et al. 2020). One of the fundamental advantages of a SW-based building information paradigm is the ability to provide multiple geometric and non-geometric representations of a concept on demand. However, one of the drawbacks for representing BIMs directly in a SW context is the inherent complexity of the data models. For example, several authors agree that IFC is overly complex for querying efficiently in a graph database context; it suffers from legacy complexity as it was built for another purpose. Various initiatives by the *World Wide Web Consortium Linked Building Data Community Group* (W3C LBD-CG) attempt to resolve this by focusing specifically on representing legacy BIMs in SWT formats. Converters between BIM authoring software (such as Autodesk Revit) and native IFC are now available to obtain ifcOWL standard and SW compatible data (Rasmussen et al. 2017), endorsed by buildingSMART International. Though there remains criticism about the complexity of such graph representations of building information, the latest developments in alternative approaches are achieving much greater efficiency (Bonduel et al. 2018).

Both the *simpleBIM* work (Pauwels & Roxin 2016) as well as the ongoing buildingSMART *Equipment Maintenance* MVD development (East et al. 2021) opt for omitting geometric representation altogether. This focus on non-geometric data as priority is also seen in most SW developments for smart building applications where ontologies like the BRICK schema are not suited to representing geometry but instead focus on concepts and systems (Balaji et al. 2016). In contrast, work by Yalcinkaya & Singh (2018) highlights the difficulty of managing extensive tabular data. Their work on *visualCOBie* uses SWT to link IFC graph representations to handover data sheets with the motivation of reducing cognitive strain and improving searchability and visualisation. This seems intuitive when we consider the widely cited Gallaher et al. (2004) study that two-thirds of wastage in the domain has been due to searching and manual inspections and retrievals.

3.2 Ontological approach

Ontologies are a fundamental component of SWT architectures which establish the semantics, or what we *mean* by our information, providing a "common understanding of the structure of information among people or software agents" (Noy & McGuinness 2001). The structure and logic established through ontologies can then facilitate automation within IT systems. Various approaches to ontology development exist. In their seminal work, Niknam & Karshenas (2017) describe these as;

- **monolithic** (all-encompassing ontology to cover entire industry)
- **domain independent** (requiring manual alignment between each domain)
- **domain specific extensions** (of a/various foundational *shared* ontology/ies)

The first is perceived to be impractical and is broadly written off (Niknam & Karshenas 2017). The second is also impractical as it requires significant manual alignment between domains. The third approach is that which authors see as most promising and scalable and which has lead to such developments as the Building Topology Ontology (Rasmussen et al. 2020). This comprises a foundational description of topological relationships between building components which are widely used in W3C LBD-CG developments. According to Wagner et al. (2020) "the goal should be to create concise ontologies" which are combined with others "for a modular and complete description". Bonino & De Russis (2018) agree, explaining that "monolithic approaches to modeling are clearly not feasible, a linked-open data approach emerging bottom-up from currently adopted models can provide a suitable, shared modeling basis for the [AECO/FM] domain". Their *DogOnt* development provides an extensible model focused on connecting IoT devices, and aligns with the foundational or *shared* ontology approach.

Most works in the domain prescribe a modular, bottom-up approach to ontology development. It is notable, however, that authors in the field recognise a need for some top-down standardisation (Bonduel 2021) evident in initiatives on classification/format alignment such as the activities of the ASHRAE BACnet committee, IBIPSA Building Data Exchange Committee and IEA Annexes 66 and 81, as described by Luo et al. (2021). Such work in standardisation will be beneficial for facilities managers and ongoing work in this space by buildingSMART International and ISO further reinforce this need.

3.3 Recent FM specific SWT developments

As with a number of earlier examples, various recent SWT initiatives focus specifically on the needs of FM professionals. One such industry driven development is the RealEstateCore Ontology (Hammar et al. 2019). Its main functionality is alignment of Building Automation Systems (BAS) throughout a real estate portfolio to facilitate energy optimisation. The development consortium provide a thorough and useful description of their *minimum viable product* process and *eXtreme Design* ontology engineering method. It is notable that the authors report significant uptake by industry and so we learn that a comprehensive domain review should not be restricted to the academic sources. Another example of industry uptake is found at the Schiphol Group who use linked data and modular ontologies to manage their FM supplier data; the open RDF format is used to avoid vendor lock-in and provides consistency throughout departmental databases at the airport (Droog & Baayen 2021).

In the majority of the studied cases, where FM practitioners were explicitly identified as the target group, the initiatives were focused on the use of *Construction Operations Building Information Exchange* (COBie) data which is "a vendor neutral, IFC-based data exchange specification that describes the information exchange between the construction and operations phases" (Chen et al. 2018). COBie data comprises a tabular spreadsheet format which is compiled during construction as a substitute for extensive handover maintenance manuals, product data, warranties etc. (East 2007) and has been an important contribution to standardising the handover phase. The authors provide various SWT approaches to integrate COBie data with, typically, BIM data (in the form of IFC) and FM databases.

Chen et al. (2018) develop a COBie ontology in Protégé to map IFC data and COBie tabular data into the ARCHBUS relational FM database system. The authors point out that BIM cannot provide complete data requirements of FM systems, thus data must be aligned (or *fused*) from multiple sources, which they demonstrate. Validated through FM practitioner trial studies, the authors find the manual effort of alignment a limitation of the methodology and recommend greater research effort towards BIM-FM integration based on ontologies. Though their demonstration does not employ a SW database layer, they lay the theoretical foundations for this next logical step. In a similar study Kim et al. (2018) propose the *FM Information Ontology* with the same function of merging COBie, IFC and FM data, but which uses Resource Description Framework (RDF) triples as the merged database which can then be queried using SPARQL as well as inferring and storing new knowledge via the BOSSAM reasoner. This grounded study then validates the development through five FM practitioner case studies. It is clear that addressing the *real* needs of practitioners is a priority for researchers in the FM space.

Yalcinkaya & Singh (2018) demonstrate the *visualCOBie* prototype which fuses data from IFC (using *BIMserver*) and COBie data (in a *neo4j* graph database) with live sensor information from a sample building, and validate this with three FM companies. Having grounded their approach in *Gestalt's principals of visual perception*, their work "makes the case for end-user development/programming (EUD/EUP) in COBie-related developments", allowing end-users to "perform complex queries without typing any code". Recent work by Kumar & Teo (2021) extends this work by concentrating on change verification in COBie *data drops*, providing a comparison function between exchanges. Clear recognition of the industrial process of compiling COBie information throughout a construction project ahead of handover; the authors, again, stress the importance of enabling the "non-BIM user" to effectively query information. This sentiment is echoed by Liu & Chou (2021) and again by Gouda Mohamed et al. (2020) who emphasise the need for "user-friendly query interfaces [...] to enable users to employ SPARQL without having to acknowledge the SPARQL ontology query language". Their "integrated knowledge-base" puts a focus on the importance of retroactively applying FM to existing assets through reality capture techniques. This is clearly an important focus, given the scale of the existing building stock which must be included in digitalisation efforts (UN Environment and International Energy Agency 2017).

Despite this focus on COBie data, it should likely not be seen as a panacea in and of itself, Pärn et al.

(2017) suggesting in their seminal review of digitalisation in the FM domain, that "this one shoe fits all approach is not well received by practitioners – indeed, the general consensus appears to suggest that there is little value in collecting data for the sake of such". Nevertheless, the proportion of FM initiatives which focus on this topic alone demonstrates its importance to the research community.

4 Discussion

This review sought to cover a broad range of topics, and given that there is no comprehensive domain review of SWT for FM, the authors propose this work as a useful contribution to the field. This paper describes a *work in progress* methodology which may be extended in future by further developing the classifications of literature, such as in the work of Ali et al. (2021), with a view to providing insight on future trends. Though it is common for domain reviews on emerging topics to limit the search to, for example, the last decade, in this case important foundational works would be missed. Furthermore, for a more comprehensive result, the search query should be extended to both title and keywords (or possibly full document body). Even still, given the broad scope of FM activities, it will be difficult to obtain all potentially relevant works from a search of this kind. It may be preferable to instead limit the review scope to certain use-cases so that sufficient depth may be achieved.

It is clear from the review that the FM domain can, and in some cases already does, benefit from the interoperabilty, automation and democratisation brought about by the use of SWTs. The authors were in agreement that greater user-oriented development is needed to abstract away from querying languages to allow access to information for a wider breadth of practitioners. Also that the use of modular ontologies and data architectures is essential to allow for flexibility of implementation and inevitable process changes, typical of the FM business. There is a clear theme of grounding developments in real industry needs and validating with practitioners. Perhaps as a result there is significant focus on COBie data in the literature, however seeing this as the panacea should be viewed with skepticism, with a *one size fits all* approach unlikely to suffice in such a diverse profession. Having said this, developments in top-down standardisation are viewed as desirable by the authors but, as we can imagine in light of the aforementioned findings, such standards would require flexibility in their implementation.

5 Conclusions

The FM domain remains the least digitalised within the built environment and since the O&M phase of a buildings' lifecycle, for which FM practitioners are responsible, is the longest and most consuming in terms of resources, efficiency gains such as improved data interoperability are seen as opportunistic. SWTs are viewed by the research community as providing a promising approach to address this. To date there exists no comprehensive review of works involving SWTs as they related to the FM domain specifically. Therefore, this paper provides a methodology and initial findings of such a work. A parametric search of both Web of Science and Scopus databases resulted in a literature collection, enhanced with works which are being studied as part of ongoing CBIM ETN activities. This body of works was grouped and analysed by following a guiding conceptual model, developed to facilitate understanding of advances in the field as they relate to the FM domain.

The paper finds that the use of SWTs for FM was first suggested in 2007, predating perhaps what is presumed, and thus a comprehensive review must extend over multiple decades. Also that a parametric search alone is unlikely to return an exhaustive data set and that perhaps a scoping exercise would result in better depth of analysis based on one or several use-cases. Another finding was that though many technical challenges remain, industry has already adopted the approaches in several cases. A number of technical gaps were identified including: the need for user-oriented design of querying tools and abstraction away from programming languages, the need for flexibility and modularity in approach to ontology development and use, and that the FM domain needs are highly case specific and developments require validation with practitioners. This paper proposes a comprehensive review which would be the first of its kind and could facilitate clearer understanding of this broad domain, informing both the research community and our own research direction.

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