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A Review of Interoperability in the AECO Sector compared with the Oil & Gas Sector

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Abstract

This research reveals insights that can improve the interoperability of transactions between domains, building lifecycles, software systems and the web in the architecture, engineering, construction and operations (AECO) sector. The research design centres on a comparative review of standards and systems which address interoperability in the AECO sector and the Oil & Gas sector. For both sectors, different data exchange standards and specifications, prevalent data exchange issues, and the available solutions that address these issues have been discussed. The review of literature in the AECO sector confirms that the reliability and scalability of digital and web-based transactions have become an imperative. Currently, these transactions are file-based, using the vendor neutral Industry Foundation Class (IFC), developed since 2005 by buildingSMART. A review of literature in the Oil & Gas sector confirms that object-based, rather than file-based, exchanges have been the primary method of data exchange. Alongside data exchange models and formats other components, including use case methodologies, collaboration mechanisms and the use of reference data, have contributed significantly towards achieving semantic interoperability across systems. For all these components, the existing standards and specifications implemented in both sectors have been discussed, revealing insights from the Oil & Gas Sector applicable to the AECO sector. The paper also examines OIIE (Open Industrial Interoperability Ecosystem) principles used in the Oil & Gas sector and their potential for implementation in the AECO sector. The results of the comparative analysis are presented as findings and recommendations that aim to advance interoperability in the AECO sector, across domains, building lifecycles, software systems and the web.

Keywords: Interoperability, Transactions, Data exchange, Object-based, Semantic connectivity

1 INTRODUCTION

This paper examines and compares the standards and systems that have either been proposed, or implemented to improve, interoperability in both the AECO and the Oil & Gas sectors. Interoperability has been defined in the AECO sector as,

> …the ability of two or more systems to exchange information and to use the information that has been exchanged. (Hub, 2020)

A definition of interoperability from the Oil & Gas sector sources systems engineering knowledge,

> …the capability of two or more entities to exchange items in accordance with a set of rules and mechanisms implemented by an interface in each entity, in order to perform their specified tasks. ((ISO), 2019)

These definitions address technological issues and hint at the profound complexity of broader interoperability issues that are common to all sectors of industry. This complexity causes challenges in facilitating collaboration across management and technological levels, implementations in domains across service and asset lifecycles, and compatible connections between proprietary software and web-based information exchanges. Improvements at the managerial level, which might include the more open and trusting contractual relationships fostered by partnering and integrated project delivery (IPD), are outside of the scope of this research. It is the reliability and scalability of data exchanges at the technological level in the AECO sector across all interoperability configurations, and the means to achieve improvements via standards and systems, that is the focus of this review paper.

1.1 Research Design

We began by refining the focus of our research question and asked firstly, how can interoperability in the AECO sector be improved by systems and standards that reinforce object-based data exchanges? Secondly, we also asked, what can be learnt from the Oil & Gas sector's implementation of interoperability measures that is applicable to the AECO sector? Our research design aims to answer these questions through a comparative review of standards and systems in the AECO, Oil & Gas sectors, an approach which addresses the broad nature of the subject matter and the diverse range of disciplines involved.

In Section 2, we provide an overview of the AECO and Oil & Gas sectors, including the major data exchange issues faced and the solutions they are implementing to address these issues in the respective sectors. Following this, in Section 3, we perform a more detailed comparison of standards and systems in the two sectors, identifying the relationships between them and how lessons learned in the Oil & Gas sector could be applied to the AECO sector. The key findings and recommendations from this comparison are summarised in Section 4, and we provide concluding remarks in Section 5.

2 BACKGROUND

2.1 AECO Sector

The AECO sector is fragmented, comprised mainly of small to medium sized enterprises (SME) which are project focused and supported by a wide variety of proprietary software systems (Owen *et al.*, 2010, p. 234). Consequently, as there is no single organisation with the financial strength or intellectual capability to control software development, the sector continues to resist the concept of a single proprietary software system that would provide a vendor with a monopoly (Sacks *et al.*, 2018, p. 88, 94). Responding to this status quo, from the late 1970s, Charles Eastman and colleagues at Carnegie-Mellon University, U.S. developed research which led to the concept of Building Information Modelling (BIM), the system which aims to foster interoperability in the AECO sector. Thus, BIM fostered the development of exchange standards defined by the end users of software applications, and a non-proprietary, open standard, file-based method of transaction, the IFC, currently agreed to be the best option available to achieve interoperability in the sector (Hub, 2020).

2.1.1 Data exchange issues

With the increasing complexity of projects and collaborations, the success of interoperability depends not only on the reliability of digital transactions implemented by proprietary software systems, but also on its scalability towards web-based connectivity. It has become clear that these aims cannot be delivered by IFC ((ISO), 2018) in its current format as it has proven to be unreliable in its ability to deliver timely and error free transactions. In the U.S. in 2004, the wider costs of poor interoperability caused by delay, avoidance and mitigation were estimated to be

$15.8BN USD (Gallaher et al., 2004). Meanwhile, defective interoperability continues to be a serious impediment to collaborative design, partly due to large file sizes and also to limited coverage of the data model or exchange format (Jeong et al., 2007, Taylor et al., 2009, p. 75, Lee, 2011, p. 6).

Though IFC does have an object-based data modelling format, issues occur partly because IFC file-based transactions store the entire model as a file in a database, which makes partial transactions challenging. Furthermore, to retrieve a single object of interest, the whole file needs to be analysed to resolve (mostly multiple) dependencies. By contrast, an object-based transaction parses and saves a model at the object level e.g. wall, material or dimension. Such a transaction does not usually require a full model exchange because it primarily comprises an incremental update of an object and its parameters, hence the amount of data involved in the transaction is small compared to an equivalent set of files (Sacks *et al.*, 2018, p. 376).

2.1.2 Data exchange solutions

In the AECO sector, authors have identified BIM servers' object-based transactions as a solution to ensuring interoperability in the exchange of data (Taylor *et al.*, 2009). Because of their object-based format, servers or repositories improve data management by facilitating querying, transfer, updating, and the partitioning and grouping of model data to support many software applications.

Graphisoft BIM Server was the first proprietary model server to use objects rather than files as a unit of management (Sacks *et al.*, 2018, p. 122). Updates were limited to objects actually modified, thus reducing the file transfer size and the time it takes to update. BIMserver incorporates a key-value database which facilitates querying, allows the versioning of data models at the object level, and also demonstrates a free, open source, model server based on IFC STEP EXPRESS modelling language (Beetz *et al.*, 2010, p. 3, van Berlo and Krijnen, 2014). IFC files created by software applications are shared in a cloud-based server at BIMserver.center to facilitate the collaborative development of projects (BIMserver, 2020). Google X's Flux IO project 2015-2017 was a cloud-based server which exchanged object-based data rather than files using plug-ins for a limited range of proprietary software applications. Flux IO included a 'data interchange hub' for sharing project design, analysis and schedules (Afsari, Eastman and Shelden, 2016, p. 950).

If they are to avoid the same interoperability challenges of desktop BIM, authors note that cloud-based servers require standards that define, 'network based data transmission' protocols (Afsari, Eastman and Shelden, 2017, p. 189). Elsewhere, it is noted that BIM servers and repositories do not address a fundamental interoperability requirement, which is the need to import and export data between proprietary software systems (Day, Gasparri and Aitchison, 2019, p. 5).

2.2 Oil & Gas Sector

Oil & Gas comprises three main sectors which are vertically integrated, and some of the larger companies are completely integrated across the three sectors (Herkenhoff, 2018),

- Upstream: exploration and production, seismic, drilling, service, supply, and manufacturing.
- Midstream: pipeline, storage, distribution, and processing.
- Downstream: refining and processing.

Retail activity ranges across the midstream and downstream sectors but, because its workflows are notably distinct, it has been excluded from this study.

Because of its similarities with the AECO sector, it is the downstream Oil & Gas sector which is addressed by this review. Accordingly, in this review, the term 'Oil & Gas' refers to the downstream sector which is characterised by vertically isolated data silos, despite the need for reliable exchanges and integration between the design, operations, and maintenance of large-scale equipment. Similar to the AECO sector, software and hardware is governed by different standards bodies which impact many vendor supply companies.

2.2.1 Data exchange issues

Challenges affecting data exchange in the Oil & Gas sector are similar to those faced by other industries, including the need for lossless and automated data exchange in order to mitigate the substantial costs caused by inefficient and error prone transactions. Many engineering workflows in the Oil & Gas sector are multi-disciplinary, requiring diverse and specialised software tools necessitating a dependency on the reliability of each other's outputs. Thus, prominent data exchange issues facing the Oil & Gas sector include the following (Fillinger *et al.*, 2019, p. 265),

- The need for lossless format conversions when exchanging data across diverse systems.
- The use of unstructured document-based data exchange formats e.g. PDF, Excel, and Word, as the primary means of data exchange.
- The lack of agreement on use and management of common reference data leading to inconsistencies across systems.
- The need for standardised specification and management of information exchanges.
- The lack of maturity in existing reference standards, no single standard provides the required breadth and depth.
- Lock-in to proprietary software systems leading to high switching costs due to lack of standardisation.

These issues have been a major hindrance to achieving interoperability across the ecosystem of the Oil & Gas sector.

2.2.2 Data exchange solutions

In the Oil & Gas sector, multiple data models and exchange protocols are implemented to achieve information exchange across systems. The most prominent are listed below, in alphabetical order,

- CCOM (Common Conceptual Object Model) is an information model for the exchange of asset lifecycle information, including engineering, asset, configuration, operation and condition, etc., required during the lifecycle of plants and complex facilities. It is maintained and published by MIMOSA as an open specification.
- IEC 62714 AutomationML (Automation Markup Language) is an open standard based on XML for storage and exchange of plant engineering information.
- IEC 62264 B2MML (Business to manufacturing Markup Language) and IEC 61512 Batch ML (Batch Markup Language) published by MESA International are XML-based models that define an exchange format for data stored in ANSI/ISA-95 and ANSI/ISA-88 information models respectively across enterprise and control systems.
- IEC 62424 CAEX (Computer Aided Engineering Exchange) is an object-oriented XML based exchange format for storing hierarchical structure of plants, documents, products etc. and is primarily used for exchanging data between process engineering and process control engineering tools.
- IEC 62541 OPC UA (Open Platform Communications, Unified Architecture), is an object-based machine-to-machine communication protocol for industrial automation devices and systems developed by OPC Foundation.
- ISO 15926 is a standard used for representation and exchange of data supporting the life cycle of industrial plants which includes the engineering, construction, and maintenance phases. MTConnect is a manufacturing standard providing XML based exchange format for exchanging data between shop-floor and software applications.
- PRODML is a set of XML based standards and a data exchange format used in the upstream Oil & Gas sector for supporting workflows in production operations, published by Energistics.

Additionally, other initiatives include CFIHOS (Capital Facilities Information Handover) which provides specifications for information handover in process industries, and DEXPI (Data Exchange in Process Industry) which defines the exchange format (Proteus XML) for Process & Instrumentation Diagrams (P&IDs).

The exchange formats and information models listed above are all object-based and hence do not share the majority of problems associated with file-based exchanges as discussed in Section

2.1.1. This list is evidence of many attempts to standardise the exchange of data for specific purposes with relevance to particular sets of stakeholders.

3 STANDARDS & SYSTEMS

The following review examines standards and systems that address the interoperability of data exchange transactions in the AECO and the Oil & Gas sectors. Though many national and organisational standards bodies influence these sectors, we have focused on the principal generic and international standards and specifications published by buildingSMART, COBie and MIMOSA, as described in more detail in the sub-sections below.

3.1 Standards Bodies

3.1.1 buildingSMART

In the AECO sector the governance of standards and guidelines is the responsibility of buildingSMART, a not-for-profit, open, neutral organisation dependent on global collaboration between discipline and industry experts (2021b). As noted previously, with the development of BIM, the AECO sector acknowledged that the reliability of transactions should be determined primarily by user-defined exchange standards and use cases. Based on this approach, in 2005 buildingSMART began to address construction industry concerns by developing 'smart model-based collaboration tools', some also defined by other international standards, including:

- IFC (Industry Foundation Class, ISO 16739-1:2018), a non-proprietary, open standard, file-based method of transaction.
- IDM (Information Delivery Manual, ISO 29481-1:2016), the standard for defining use cases and workflow processes, plus ISO 19650 series for organising BIM workflows.
- MVD (Model View Definition). Though IFC is the basis for full interoperability each use case needs precise definition with the IDM, which is mapped to the MVD by information technology experts. buildingSMART release the MVD to the software vendor, with testing and certification of implementations following.
- BCF (Building information modelling Collaboration Format), enables the sending of model mark-ups, clash reports and general comments between team members.
- bSDD (buildingSMART DATA Dictionary), is an online service that hosts classifications and their properties, allowed values, units and translations. The bSDD allows linking between all the content inside the database and is based on ISO 12006-3 for Industry Foundation Dictionaries (IFD).

To facilitate interoperability, buildingSMART asserts its commitment to 'sharable projects' and 'seamless collaboration' across domains and building lifecycles via the concept of openBIM. But, the transformation from file-based to object-based data exchange standards, systems and tools has yet to begin (Afsari, Eastman and Shelden, 2017). In their 'Technical Roadmap – Getting Ready for the Future', (*'Technical Roadmap'*) buildingSMART identify key requirements to drive these changes between 2020-2023 (buildingSMART, 2020, pp. 10, 17).

3.1.2 COBie

In 2015, COBie became an exchange standard published as part of the National Building Information Model Standard-United States (NBIMS-US), which includes the buildingSMART methodologies IDM, MVD, plus Industry Foundation Dictionaries (IFD) (Sacks *et al.*, 2018, P. 14).

COBie is an information exchange specification for the life-cycle capture and delivery of information needed by facility managers. Developed in 2007 by E. William East, for the U.S. Army Corps of Engineers, it specifies the minimum information set needed to operate and maintain buildings. COBie is the information exchange between the delivery team and client and is therefore a mini-MVD, but unlike other MVDs, it has an analogue spreadsheet representation which effectively replicates the IFC schema, or it can be delivered digitally in IFC format (cdbb, 2021).

3.1.3 MIMOSA

In the Oil & Gas sector, MIMOSA is a not-for-profit industry trade association which develops and encourages adoption of open, supplier-neutral information technology (IT) and information management (IM) standards and specifications enabling digitalisation and interoperability for asset life-cycle management. The MIMOSA solutions process seeks to avoid reinvention by leveraging existing standards such as ISA-95, ISO 8000, ISO 15926, and ISO 18435, which are part of a complex mosaic of relevant existing and emerging standards, each developed with a different focus. To achieve 'system of systems' interoperability, these standards should be used together in a repeatable and scalable manner.

To foster this outcome, the ISO Technical Committee 184/Working Group 6 published technical specification ISO 18101-1 which promotes a portfolio approach using different standards in a complementary manner, by utilising the OIIE (Open Industrial Interoperability Ecosystem) specification. To achieve interoperability in the asset-intensive industries, MIMOSA collaborates with other organisations to manage the development, validation and maintenance of the OIIE specification (MIMOSA, 2021). All standards and specifications included in the OIIE are licensed by their respective organisations and are validated to work with each other, and to support standardised industry use cases, using the OGI Pilot (Oil & Gas Interoperability Pilot).

3.2 Data Model & Exchange Format

3.2.1 IFC

IFC (Industry Foundation Class) is a non-proprietary, open standard, file-based method of transaction, defined by ISO 16739-1:2018. IFC development began concurrently with the founding of the International Alliance for Interoperability (IAI) in 1994, a consortium of 12 U.S. companies initially advising on developing a set of C++ classes to support integrated application development. IFC's evolution has continued under buildingSMART International since 2005.

buildingSMART's *'Technical Roadmap'* acknowledges impediments due to the file-based data exchange issues described earlier, and the need to transform IFC into an object-based data exchange to accord with exigencies for interoperability between software systems and web-based services (2020, p. 10).

3.2.2 CCOM

In the Oil & Gas sector object-based, rather than file-based, exchanges have been the primary method of data exchange. MIMOSA CCOM (Common Conceptual Object Model) serves as an information model for the exchange of asset lifecycle information, including engineering, asset, configuration, operation and condition data, required for the operation and maintenance of plant and complex facilities, but which can also be used to provide the contextual basis for defining and maintaining Digital Twins and for performing Big Data Analytics. The mission of CCOM is to facilitate interoperability between systems by allowing them to electronically exchange data through adaptors.

By adopting object-based concepts such as inheritance, CCOM provides a cleaner and more flexible model for Enterprise Application Integration (Mathew *et al.*, 2012). CCOM also provides a canonical XML representation of the object model that allows any type of CCOM object to appear at the root of a data exchange or at their position in the object hierarchy. This approach allows the entity of interest to be the focus of an exchange regardless of the context in which it might appear - for example, in asset or equipment hierarchies.

Both IFC and CCOM are information models designed to support information exchange across systems. IFC is currently undergoing revision to better support and implement object-oriented concepts to resolve the issues around file-based data exchanges. During this process, the CCOM information model and principles could be referred to and applied to the IFC information model. For example, CCOM supports lightweight incremental updates where the inclusion of related entities and data elements is optional thus exchanging only the information that was last changed, plus CCOM supports use of immutable and universally unique identifiers (UUID standard, ISO/IEC 9834-8:2008) for each entity.

3.3 Use Cases

To support interoperability across any industry, it is recognised that a consistent method for describing and specifying use cases is required. By describing use cases consistently, specific interoperability concerns can be addressed in a prioritised manner so that participants know what to expect when taking part in different sets of interactions.

3.3.1 buildingSMART Use Cases

Though IFC is the basis for full interoperability, each use case is defined with the IDM which is then mapped to the MVD by information technology experts. buildingSMART then release the MVD to the software vendor, following which testing and certification of implementations follow. IDM is implemented using the Business Process Model and Notation (BPMN), plus templates for exchange requirements which are a selection of entities and properties from the IFC Schema that are appropriate for particular use cases (buildingSMART, 2021c).

3.3.2 OIIE Use Cases

Beginning in 2007, representatives from the Oil & Gas and Petrochemical industries participated in an OpenO&M End-User Advisory Group with the aim of identifying the highest value use cases, matched to interoperability scenarios, for organisations to meet their business objectives (OpenO&M, 2020). These use cases are documented using the OIIE Use Case Architecture and are incrementally extended to incorporate new functionality. Each use case is validated by the OGI Pilot and new use cases are included based on guidance from industry partners (MIMOSA, 2020).

The OIIE Use Case Architecture identifies four components for describing use cases in a decomposable way: Use Cases, Scenarios, Events, and User Stories. Use Cases describe common interactions and context to achieve an interoperability goal and are decomposed into Scenarios. Each Scenario provides additional details and requirements on how to achieve an interaction based on a specific group of Events. The Event descriptions detail specific message exchanges and their requirements but are general enough to support different realisations of the exchanges across different protocols and data formats. Finally, these three components are tied together by User Stories, which abstract from the underlying components to provide a higher-level overview of interactions and to connect Use Cases in a logical flow.

3.4 Collaboration

3.4.1 BCF

The BCF (Building information modelling Collaboration Format) allows different BIM applications to communicate as 'issue' between project collaborators, alongside IFC data that has already been shared. Each BCF 'issue' is registered with a Globally Unique Identifier (GUID) confirming the status of the model and the domain users' responsibilities. It enables workflows which transfer XML data from captured views, either by emailed .bcfzip file exchange between team members, or via a web based exchange using RESTful server hub (buildingSMART, 2021a).

3.4.2 ISBM

In the Oil & Gas sector, OpenO&M ISBM (Information Service Bus Model) is an open specification that provides a vendor-neutral interface to the communication infrastructure of the OIIE Architecture. It is an open, supplier-neutral standard that can in theory be used by any industry, as it allows the transmission of any information model, including MIMOSA CCOM, ISO 15926, MESA B2MML and others. ISBM addresses a typical IT environment where a federation of systems is implemented from multiple software vendors that work together to support business processes by providing a standard interface. ISBM specification defines a SOAP (Simple Object Access Protocol) Web Service and a HTTP/JSON REST implementation of the ISA-95.00.06 Messaging Service Model (MSM) and further interoperability in application-to-application communications by exposing a single, standardised interface, instead of a custom-built interface, for every version and format of message exchange systems.

Unlike the BCF REST API which is used primarily for exchanging BCF issues between software applications, ISBM web-services provide a wide range of interfaces to act as the complete communication backbone of an ecosystem. We note that there is no corresponding open specification or standard used in the AECO sector to support intra-enterprise and inter-enterprise collaborative communication.

3.5 Reference Data & Dictionaries

3.5.1 bSDD

The bSDD is a library that contains objects and their properties for building and construction industry and is used to link concepts with similar meaning in different classifications, contexts and languages. The bSDD is used to search, identify and share objects and their properties. The bSDD is available as an open REST API which can be searched for concepts and their relationships in different classifications systems, including IFC. Each concept in bSDD is assigned a global unique identifier (GUID) which serves as a unique, language independent serial number. The use of bSDD can significantly improve communication in the construction industry by facilitating unification of technical terms regardless of the underlying language (buildingSMART, 2020, p. 23).

3.5.2 RDLs

The use of Reference Data Libraries (RDLs) is vital to achieve interoperability between systems in an enterprise and across enterprises because it enables all partners in a data exchange to have a common understanding of the data being exchanged. The OIIE utilises mappings to multiple external RDLs published by various organisations including, ISO 15926-4, CFIHOS RDL, ECCMA eOTD, IEC CDD and Energistics UOM, in addition to MIMOSA CCOM RDL which is the system of record for any managed reference data.

MIMOSA defines the OpenO&M Web Service Common Interoperability Registry (ws-CIR) specification which provides a standards-based, vendor-neutral approach for the construction of an object registration server. This specification supports a harmonised and standardised lookup of locally unique identifiers for an identical object, including data dictionary classifications and attributes, used in multiple information systems. Like bSDD, the ws-CIR attaches a Universally Unique Identifier (UUID) to each object to ensure its global uniqueness.

4 FINDINGS & RECOMMENDATIONS

Addressing our secondary research question - What can be learnt from the Oil & Gas sector's implementation of interoperability measures that is applicable to the AECO sector? – and based on the current state of knowledge analysed in the review of standards and systems, a synthesis of findings and recommendations are discussed.

4.1 Use Cases

By 2010, it was claimed that the IFC schema's 'breadth and flexibility… leaves room for errors' and that it had made no significant impact on interoperability due to the lack of flexibility and errors caused by use cases that were not clearly defining information exchanges between users (Eastman *et al.*, 2010). Since then, the challenges posed by the use of IDMs have been detailed in (Kahyun and Lee, 2018, p. 2), and buildingSMART intend to develop a new machine-readable standard to define IDS which will address known issues.

The concept of buildingSMART MVDs corresponds to the concept of OIIE Events since both focus on defining technical exchange requirements, while IDM corresponds to OIIE Use Cases, and exchange requirements corresponds to OIIE Scenarios. An issue identified in the definition of exchange requirements is that they should not be tied one-to-one to IFC schema, but that rather they should be mapped to the concepts in IFC (buildingSMART, 2020, p. 20). OIIE Scenarios follow this approach where data content requirements described in general terms are not tied to specific CCOM elements.

Recommendation: Development of the IDS standard would benefit from reference to OIIE Use Case Architecture and its adaptation of User Stories which provide a high-level graphical representation of interactions and events defined by one or more use cases, plus they provide a business level overview. This could remedy the lack of a graphical counterpart in buildingSMART's use case management to illustrate the logical sequence of related use-cases. Additionally, IDS could benefit from including the principle of event-driven based message exchanges, similar to OIIE Use Cases.

4.2 APIs

Currently, in the AECO sector, customised, proprietary API systems are available: Trimble Connect provide a cloud-based, data exchange server with connections between a limited range of proprietary software systems (Trimble, 2021); and, Autodesk's Forge assists development of APIs by certified partners or 'Systems Integrators' (Autodesk, 2021). Also, Speckle have developed an API delivered via GraphQL creating a comprehensive set of connectors to embed in design and analysis software to exchange geometry and data in a neutral, open format, cloud-based, 3D viewer (Speckle, 2021). buildingSMART are also developing an openCDE (Common Data Environment) API standard in recognition of a clear need for an object-based approach, and to achieve semantic connectivity.

Correspondingly, in the Oil & Gas sector, some proprietary APIs are available and implemented, but MIMOSA strongly advocates the use of standardised service interfaces to ensure interoperability across a range of software vendors' and suppliers' systems. In the OIIE framework, core standards and specifications define standardised interfaces and methods of data exchange, leaving responsibility for the details of individual components to the software vendors and suppliers (Kaur *et al.*, 2018, p. 6).

Recommendation: The use of standardised web service interfaces, instead of custom-built interfaces for each proprietary system's version and data format, is an effective way to achieve interoperability when developing APIs which are accessed either through REST API, SOAP web services or other mechanisms. This approach could be considered during the development of the buildingSMART API standard for web-based modelling languages to ensure scalability towards Smart Cities, Smart Buildings and Digital Twins.

4.3 Modularity

In the AECO sector, software applications are required to implement a subset of, rather than the full, IFC schema. These subsets are the MVDs, which also define the conformance level expected of software vendors' implementations. But this approach hinders interchangeability and does not guarantee interoperability between MVDs themselves because, as a subset of IFC, they can only be revised if the whole IFC schema is changed. Hence, buildingSMART is actively investigating ways to make the IFC schema modular.

In the Oil & Gas sector, the exchange of information across lifecycles and domains is achieved with a modular approach. This is achieved with a component that encourages commercial off-the-shelf (COTS) software vendors to provide OIIE compliant adaptors, which also enables plug-and-play between heterogenous systems and software. With OIIE, modularity allows software vendors to provide compliant adaptors facilitated by object-based data transformations and mappings (Grossmann *et al.*, 2013).

4.3.1 Modular Transactions

The transformation to object-based data exchanges is a significant step for the AECO sector (buildingSMART, 2020, p. 10)

> The STEP specific modelling techniques used to optimise file-based exchange is hindering the object-based access and exchange of (partial) IFC. Changing the objective to optimising IFC to 'be used in a transactional environment', instead of 'optimizing file-based exchanges' is a big cultural change.

File-based data exchanges often involve transferring large files with much information that has not been altered. For example, a change to a wall attribute of a multi-story building necessitates the packaging and sending of the entire multi-story building. By contrast, exchanging data with incremental updates involves publishing only the updates made since the last transfer, resulting in smaller data exchanges.

In the Oil & Gas sector, OIIE Use Cases are defined on an event-driven basis thereby inherently promoting the use of object-based message exchanges, rather than file-based exchanges. For example, the OIIE Use Case for publishing asset configuration updates to the relevant and interested systems is driven by the occurrence of the asset installation or removal event, which requires only a change to the association between an asset and a functional location at a given time.

Recommendation: Modularity is more effectively implemented at object level because transformations and mappings are typically object-based definitions, allowing modularity and the separation of mappings into smaller, more understandable, and maintainable partial transactions. In the AECO sector, there is a need for modularity to differentiate the responsibilities of buildingSMART from users, and to enable separate revisions to modules or MVDs. Modularity will also provide better predictability in exchanges between IFC and Digital Twins which are based on use cases. A modular approach would be a central feature of the standards and systems ecosystem and consistent with views expressed in the *'Technical Roadmap'* (buildingSMART, 2020, pp. 17) as it would provide shorter release cycles of IFC, faster support of new IFC versions in software vendors' implementations, instant support of new modules or extensions, and stronger interoperability between modules' extensions and domains.

4.4 Standards & Systems Ecosystem

The Oil & Gas sector identified a strategy implemented at the industrial digital ecosystem level to facilitate the required levels of interoperability provided by the OIIE specification.

Recommendation: An ecosystem, approach provides a consistent theoretical basis for the changes needed to facilitate interoperability in the AECO sector. An ecosystem approach would ensure reliability by addressing the requirement for integrated standards as an essential component in the implementation of object-based transactions. For example, it would integrate AECO delivery and operations standards presently governed separately by buildingSMART and COBie. Though outside of the scope of this research we also recommend that an ecosystem approach should address integrated technological and management processes, essential for interoperability to be implemented fully, by promoting integrated project delivery (IPD) and partnering contracts with embedded requirements for administering and implementing technological interoperability.

5 CONCLUSION

This research has presented a preliminary comparison of standards and specifications used in the AECO and the Oil & Gas sectors with the aim of achieving interoperable data exchange. The primary theme identified and reported throughout the paper is the need for the AECO sector to move onwards from file-based towards object-based data exchange, the default method in the Oil & Gas sector. Furthermore, we confirm that this evolution is necessary for the realisation of Smart Buildings, Smart Cities and Digital Twins which are dependent on the provision of semantic connectivity and full interoperability between different systems through standardised interfaces.

These issues have been addressed through examination of the Oil & Gas sector's aim to achieve standards based interoperability across its ecosystem, implemented via a standardised use case architecture, web-based interfaces for message exchanges, and by actively utilising reference data for semantically accurate data exchanges. Similarities between the nature of the two sectors suggest that these OIIE principles may be successfully transferred to the AECO sector.

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