Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 00 (2017) 000–000

Procedia Engineering

www.elsevier.com/locate/procedia

International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016

Proposal for an open data model schema for precinct-scale information management

Jim Plume[a]*, David Marchant[a], John Mitchell[a], Otto Newhouse[a]

[a]*UNSW Australia, Faculty of Built Environment, UNSW Sydney 2052, Australia*

Abstract

This paper reports on a project currently underway to investigate how an open exchange standard for modelling information at the scale of an urban precinct can be used to support integrated solutions to achieve low carbon targets in the built environment. The project is part of a major research initiative to deliver on low carbon targets in Australia. The project builds on the concept of BIM to develop an object-oriented approach to modelling the built environment at a broader urban scale, focusing in the first instance on a precinct, being any region within an urban context that can be regarded as an integrated whole for the purposes of planning, design or management. This approach is referred to as precinct information modelling (PIM) and provides a key mechanism to bridge the information modelling gap between building scale (BIM) and the spatial scale. The paper argues the case for such an approach, proposing that the current IFC data model, and recent work that is investigating how that data model can be extended to handle transport infrastructure elements such as roads and bridges, can be adapted with modest extensions to serve this purpose. The paper describes this approach, proposing an initial data model and addressing several key strategies and principles that influence the work (e.g. commonality of concepts to maintain semantic integrity and the use of data dictionaries to define concept hierarchies). The paper offers a review of current approaches, reflects on a couple of trial implementations and provides a discussion of how this work can be carried forward.

Keywords: precinct information modelling; spatial modelling; open data; digital built environment; data exchange standards

---

* Corresponding author. Tel.: +61-2-93854816
E-mail address: J.Plume@unsw.edu.au

1. Introduction

There has been growing interest over the past 5-10 years in the development of digital representations of the built environment at a broad scale. 3D City models are now used routinely for urban planning and scenario analysis, generally used for visualization, over-shadowing and determination of sight lines. Emerging trends in the development of smart cities rely on ubiquitous access to digital data through the use of sensors, smart meters and location-based mobile apps linked to real-time data and spatial models of the built environment. The Internet of Things, facilitated by embedded RFID tags, adds a further dimension to create visions of a virtual digital built environment that mirrors and connects to the physical world and, in doing so, facilitates and enhances the way people use and enjoy built space.

The work reported here focusses on a specific aspect of that larger picture, taking as the starting point a "digestible" part of the built environment referred to as a precinct, being any region within an urban context that can be regarded as an integrated whole for the purposes of planning, design or management. A precinct might be the subject of an urban renewal project, or it may be a new (or existing) housing estate, a neighbourhood linked to a transport node, or even a rural area in need of agricultural management.

This leads to the definition of a precinct information model (PIM) as a comprehensive 3D digital database representation that contains all the information needed to support planning, design, development, construction, management, operation, use and retro-fitting of urban precincts. It is a concept that very clearly derives from the concept of building information modelling (BIM), a technology (or more precisely, a process enabled by a technology) that is gaining wide acceptance across the construction sector to achieve better design outcomes at lower cost across the entire supply chain. Significantly, BIM is now becoming a misnomer as the same technology and approach is being adopted in the delivery of large infrastructure projects such as roads, bridges, railways and tunnels. Importantly, the focus of much of this innovation is on life cycle modelling, and particularly, the development of new asset management strategies.

From a technical perspective, PIM is really an extension of BIM, but its significance goes far beyond that simple characterization. A PIM allows the placement of a BIM within its geospatial context, both in terms of the immediate neighbourhood as well as the wider socio-economic or geographic context. It moves the focus away from the design or management of a single built facility (and the risk of ignoring its interactions) to a view of the built environment as a complex, but integrated, whole. This is crucially important from the perspective of this particular research project where the focus is directed towards the minimisation of carbon emissions throughout the entire life cycle of a precinct: carbon can minimised in the all-of-life management of individual buildings, infrastructure, urban space and service utilities, but the impact is multiplied if these entities are managed in a cooperative fashion, especially where end user engagement is leveraged through better access to information. This reflects the view expressed of Osman and El-Diraby [1] who argue that the interoperation of domain information in land use, infrastructure and public utilities in the management of utility inventories has positive flow-on effects for capital budget allocation; the routing of new infrastructure in high density urban corridors; and the appreciation of the surrounding land use.

Since the physical world is made up of constructed elements or managed natural features, generally planned or designed for human convenience, it is natural to construct a PIM as a collection of objects (building, bridge, road, park, etc.) and then associate property/performance data or information with those objects. Importantly, that data may be drawn from all kinds of existing sources through live database links: usage data, planning data, utility data, social data, product performance data, etc. The result is a rich information repository, linked to spatial data and processes for analysis, at a scale that supports the development of integrated solutions to address the complex issue of carbon management in the built environment.

A key aspect of this work is a focus on open information exchange standards, based on the premise that integrated solutions rely on interoperability of information across diverse software applications and throughout all stages in the life of a precinct. To create those standards, data schemas are developed that define how to describe the entities that constitute a precinct in a comprehensive and accurate manner, while linking those concepts to associated object libraries that hold property data for commonly-used entities. This is illustrated in Fig. 4 (near the end of the paper), and hinges on the provision of a single point of truth (though not necessarily held in a single database) that can receive or deliver information sets (or sub-models) that satisfy the needs of a specific process, activity or analysis. To that end, this work aims to contribute to the development of an open standard (an extension to the existing ISO standard ISO 16739:2013, commonly referred to as IFC) for handling and processing information at the scale of a precinct.

This paper reports on early progress in that work, and specifically some of the principles that are adopted to inform the development of the approach.

2. Background

The context of this work can be framed across three distinct domains of enquiry, each acting as a key driver for this research.

2.1. Low carbon built environment & global urbanization

Among the many social and economic challenges that confront human society, there are two that concern the custodianship of the physical world: climate change and the traditional reliance on non-renewable, carbon-emitting energy sources and production processes; and the rapid spread of urbanisation, particularly in developing economies.

In a strategy released in February 2015 and aimed at the development of a Digital Built Britain, the UK Government identified what they refer to as Level 3 BIM as a key technology for the delivery of a low carbon built environment [2] (p.14). Central to that initiative is the recognition that open standards for information interoperability at a scale that goes beyond individual buildings and other civil infrastructure projects is essential to that program [2] (p.24). That position, taken very publicly by a major world economy, reflects the impetus and relevance of this work.

Linked to the demand for a low carbon built environment is the threat of accelerated global urbanization. The volume of global construction output is forecast to grow by more than 70% to $15 trillion worldwide by 2025 [3]. The need to sustain that world-wide growth, while maintaining design and construction quality, provides an enormous challenge to the construction sector, especially when the carbon implications are also considered.

In order to meet that challenge, it is imperative that better ways of managing information and processes are developed, with PIM offering a key strategy in meeting that challenge.

2.2. Life cycle built environment management

Effective management of the built environment across the two dimensions of time and scale is critical to the achievement of low carbon outcomes.

The temporal dimension follows the life cycle of a construction project: evidence-based planning decisions, followed by realization through informed design, leading to efficient delivery based on virtual construction and prototyping at all scales, and effective asset management and operation to end of life. This relies on the availability of consistent information throughout that process and the smooth transfer of that information from one stage to the next.

The second dimension means being able to work with information at all scales: this begins with construction products that have low embedded and operational carbon; using BIM technologies to deliver and maintain low carbon buildings and infrastructure; integrating those solutions across the scale of a precinct, including the facilitation of end-user engagement and understanding of how to interact with the built environment through model integration and mixed reality applications. According to these objectives, it is anticipated that both BIM-based collaboration of stakeholders as reported by Volk, et al. [4] and BIM-federated interoperable models as described by Ronzino, et al. [5] will be enabled with the inclusion of precinct facility infrastructure. Ultimately, the expansion to a city, urban or regional scale will be supported through this approach.

The precinct data model proposed in this work is designed to meet the demands of both those dimensions, informed by an exemplar precinct in Sydney, as discussed later in this paper.

2.3. Integration of spatial and built environment modelling approaches

The third contextual domain of the work is the growing debate around how to integrate BIM and spatial modelling approaches. Both are concerned with using digital models to inform understanding and facilitate management of the physical world, but approach that task from quite different perspectives.

Several reports and publications have appeared that discuss how these approaches might be integrated. For example, the Fall 2010 issue of JBIM, the Journal of Building Information Modelling in the US was devoted to the theme, with a general focus on the importance of linking BIM to geospatial location [6]. Gomez, et al [7] have implemented a Campus Landscape Information Model that demonstrates an approach to integrating BIM and GIS. Mommers [8] wrote a 2-page opinion piece in Geospatial World under the title, “The Crossover Revolution”. More recently, a comment piece appeared in the web-based newsletter Infrastructure Intelligence, produced by the US Association for Consultancy and Engineering, putting the case for integrating BIM & GIS [9].

Over the last few years, there has been a growing dialogue between the international standards bodies concerned with two approaches. At its plenary meeting in Toulouse in June 2012, the ISO/TC 211 committee (broadly responsible for international standards in the spatial sector) established an “Ad hoc group on BIM/GIS”. That group held an inaugural joint workshop in Seoul on 12 October 2012 to initiate discussions on the relationship of the BIM and GIS sectors. This was attended by members from the two ISO Technical Committees representing spatial (ISO/TC 211) and construction (ISO/TC 59/SC 13), as well as representatives from buildingSMART (responsible for the IFC standard) and the OGC (Open Geospatial Consortium). The group met on a couple of occasions in subsequent years, leaving as a legacy an on-going commitment to collaboration in the development of standards across both sectors.

A relatively modest extension to the IFC data model that encompasses the essential entities that constitute the built and natural environments, combined with related technologies that support open and comprehensive object definitions, will provide a robust basis for integration of information models across the two domains as discussed elsewhere by Plume, et al. [10]. Through the PIM, such an approach can make information in interoperable models accessible to both stakeholders and end-users as anticipated by Ronzini, et al. [5], with the addition of different scenarios and use cases that include operation and maintenance as well as facility energy management at the precinct scale. The challenge is to limit the complexity of the data model so that it remains sufficiently expressive, without becoming too cumbersome to implement in software. With research shifting from BIM-centered information management [11] toward a more loosely-coupled federated approach described in Scherer, et al. [12], the functionality of PIM is being extended through judicious use of ontologies. To supplant the data model, a semantic enrichment of the model is applied is a similar way to that proposed by El Asmi, et al. [13], with the distinction of expanding the scope of the current buildingSMART standard for libraries and ontologies. In addition, the PIM project enables the connection to external data sources through both object instances and object types.

3. IFC Schema Extension for Precincts

The IFC schema is historically focused on the modeling of buildings, but there are currently projects underway to define extensions for transport infrastructure works such as roads, bridges, railways and tunnels, including related entities such as earthworks, signage, switching and signaling. Put simply, the focus on precincts in this work can be thought of as covering the concepts that capture the many other entities that make up an urban precinct (and not only physical entities). The result is a complex network of information where nodes are facilities that include both buildings and infrastructure. Much as for individual buildings reported in [14] and in [15], each facility node can be enriched with data, classification categories, files and web service activations. In addition, the PIM captures related aspects of precinct infrastructure and land use planning, and enables further room for extension in both scope and scale. Moreover, its ontological approach is based on ISO 12006-3:2007 for the AECO (Architecture, Engineering, Construction and Operation) domain implemented in the evolving buildingSMART Data Dictionary (bsDD). This work has led to a review of the current schema and that identifies an approach for its extension to encompass precinct-level concepts. In doing so, some key principles emerge that are essential to provide a consistent data model for IFC model standard extensions up to a broader precinct, and ultimately urban, scale. These presented here as a way to promote constructive debate within the standards community.

There are several aspects to the IFC schema that could be considered, but this analysis concentrates on three that are most relevant at this stage. These are the classes that are defined in IFC dealing with: spatial concepts; elements (the fabric of constructed facilities); and typology.

One purpose of constructed facilities in the built environment is to provide space in which activities can occur, whether that is an enclosed space in a building, a traffic lane on a motorway, or civic space in an urban context. IFC in its current form (IFC4) has a very clear spatial hierarchy: a site aggregates one or more buildings; a building aggregates one or more building storeys; and a building storey aggregates one or more spaces. How can that map to corresponding concepts when dealing with infrastructure and other features of the built environment in a consistent and useful fashion?

The first thing to consider is the concept of “site”. Within the IFC schema, site is defined as the area where construction works are carried out. In common practice, that may be considered as equivalent to the legal land parcel where a proposed building is sited, but clearly that is not always the case. It could be, for example, an area temporarily assigned within a larger land parcel, or an area that straddles more than one legal lot where those lots are under the one ownership. A road reserve is an example of a project site that may span many contiguous land parcels. In addition, we must consider strata titles in apartment buildings where an owner’s legal title can refer to a collection of non-contiguous spaces (for example, the owner’s apartment itself, plus a car parking space, and a separate storage space). Fig. 1 illustrates a spatial model of such a strata title consisting of non-contiguous spaces within an apartment block (not shown in the figure).

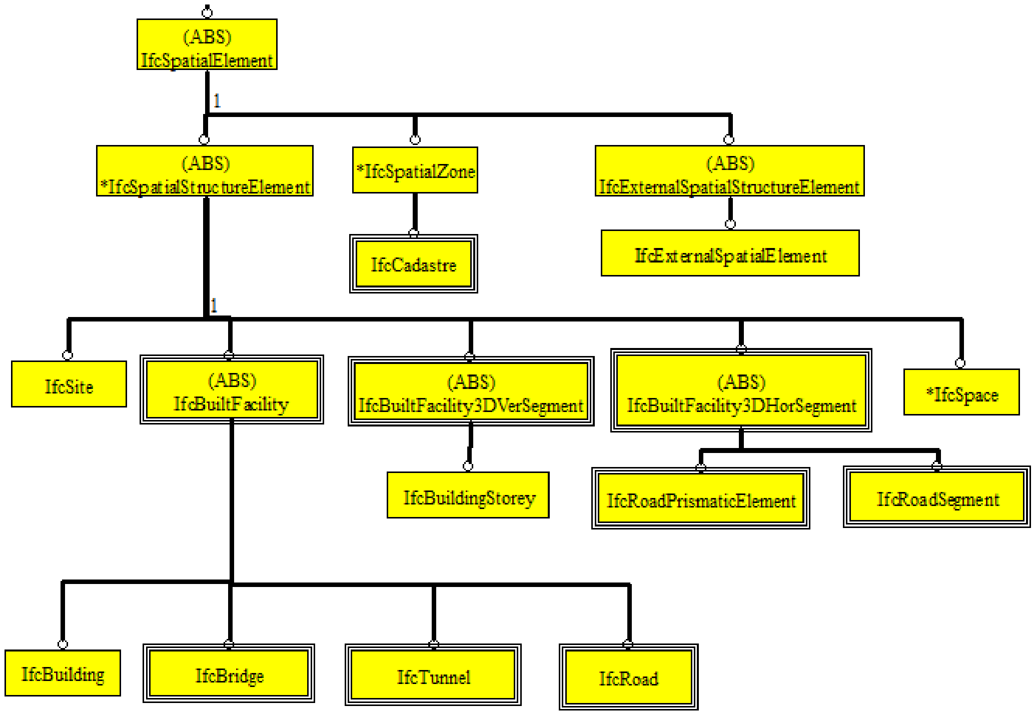

Fig. 1. Proposed spatial extensions to IFC4 (shown with double outlines)

This suggests that the site concept should be distinct from the legal concept of cadastre in order to ensure that legal entitlement and geolocation information about property ownership is cleanly separated from the concept defining where a construction activity is carried out. To accommodate this, a new entity *IfcCadastre* in introduced as a subclass of *IfcSpatialZone* (an entity introduced in IFC4) to hold the legal and spatial definition of property (see Fig. 2).

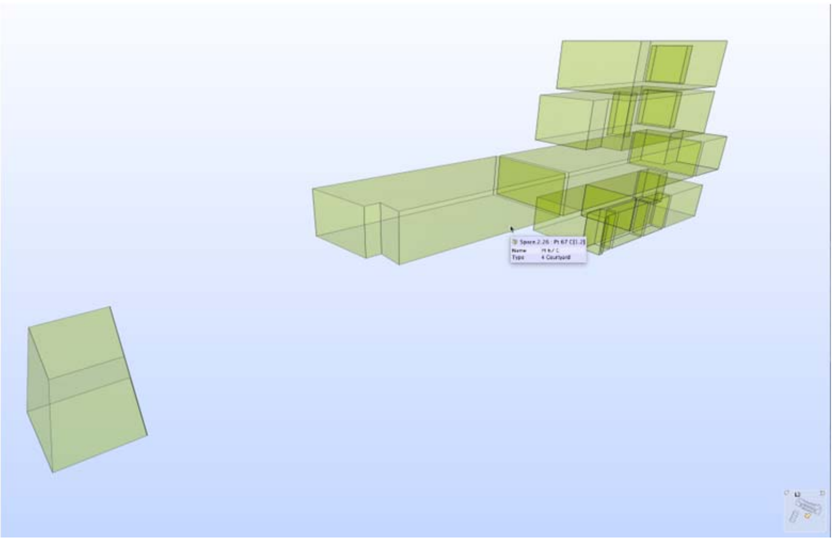

Fig. 2. A complex stratum (3D cadastral lot) in a multi-apartment development

The second level in the spatial hierarchy in IFC4 is the concept of “building”. This is generalized to cover all forms of constructed facility: buildings, roads, railways, bridges, tunnels and so on and is illustrated in Fig. 2. Note the insertion of a new abstract entity, *IfcBuiltFacility* as a subclass of *IfcSpatialStructureElement*, with *IfcBuilding* then made a subclass of that entity. New entities such as *IfcBridge* are then added at this same level alongside *IfcBuilding*. In this way, a single spatial hierarchy of entities is retained within IFC while allowing the ability to expand beyond a purely building-centric focus to a more generalized built facility focus.

Next, the concept of “building storey” in IFC is similarly generalized. Building storeys are vertical subdivisions of a building, while many linear infrastructure entities such as roads and railways can be defined in terms of horizontal spatial segments. For example, a road is composed of segments (length of road between intersections) and the intersections themselves. Therefore, two new abstract concepts are introduced for vertical and horizontal sub-divisions of constructed entities, *IfcBuiltFacility3DVerSegment* and *IfcBuiltFacility3DHorSegment* respectively, and defined as subclasses of *IfcSpatialStructureElement*. The existing entity *IfcBuildingStorey* is then relocated to be a subclass of the vertical subdivision concept *IfcBuiltFacility3DVerSegment*. Two entities are then drawn from Ifc-Bridge and IFC for Roads (as proposed by Lebegue [16]) that address the horizontal segmentation issue, and include them as sub-classes of *IfcBuiltFacility3DHorSegment*: *IfcRoadSegment* and *IfcRoadPrismaticElement*.

No changes are proposed to the current *IfcSpace* entity since its interpretation as a geometrically defined volume is sufficiently generic for use within all types of built facility. An *IfcSpace* can be used for a room in a building, or for linear infrastructure elements such as traffic lanes, or bike paths. These infrastructure elements can be aggregated by a road segment in the same way that rooms are aggregated by a building storey. Similarly, external open spaces such as courtyards or urban squares can be represented as spaces.

The addition of the three proposed abstract classes (*IfcBuiltFacility*, *IfcBuiltFacility3DVerSegment* and *IfcBuiltFacility3DHorSegment*) provide the means to differentiate many types of built facility spatial element, but do not fundamentally change the existing logic of the IFC spatial hierarchy.

Building elements and components are defined in IFC as subclasses of the abstract super-class *IfcBuildingElement* (Fig. 3). This entity may be renamed *IfcBuiltFacilityElement*, corresponding to the same generalization that encompasses all built facilities in the IFC spatial structure described above. Further subclass entities are introduced under this in a “flat” fashion to accommodate new concepts required to represent precinct (or urban) features, being careful not to duplicate concepts already defined, since many of the existing element concepts in IFC4 can be equally applied to corresponding infrastructure elements.

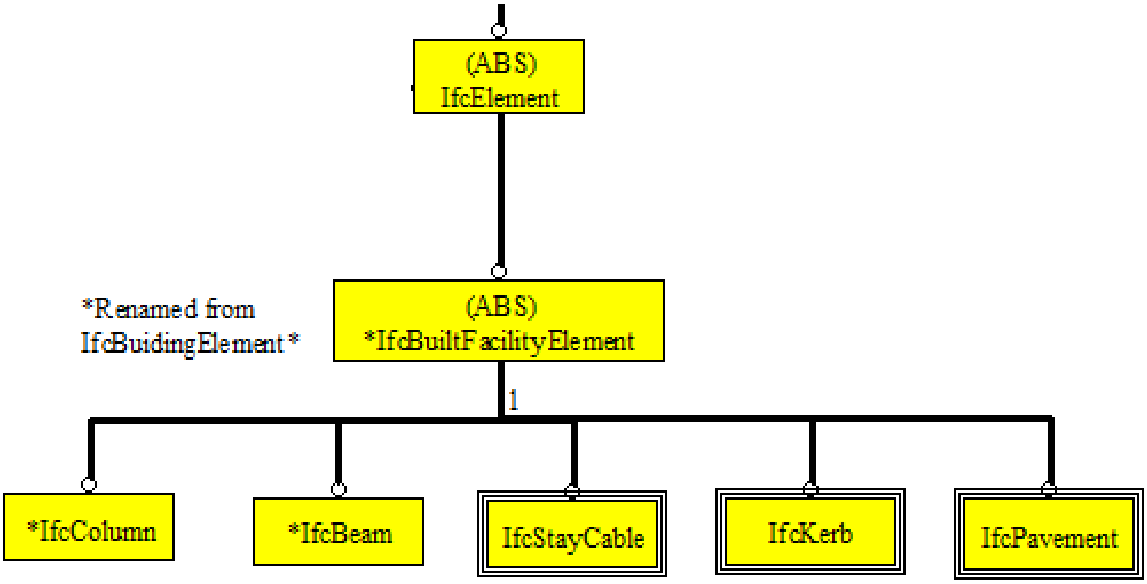

Fig. 3. Testing of element extensions proposed by others (shown with double outlines)

For example, *IfcRailing* can be used to represent bridge balustrades, road barriers, and even fences, rather than requiring new specialized entities for those elements. It is therefore important to define entities with generic characteristics rather than specialize too prolifically within the IFC schema.

At the precinct scale of design, urban features may be thought of as generic types. For example, one spatial zone of a precinct could be planned to contain 100 freestanding 3-bedroom houses, 200 apartments, and so on. At this stage in the urban planning process, each house and each apartment block is defined generically, with no need for further detail resolution. This has led to further reflection on the way types are managed in IFC. The number of types defined as subclasses of *IfcTypeObject* in IFC4 has significantly increased over previous versions of IFC. However, not all entities defined in IFC4 have a corresponding type entity. In particular, there is currently no *IfcBuildingType* – a type which could be useful for broad brush precinct planning such as discussed above.

In principle, there should be a type entity corresponding to each defined spatial or element entity in the schema. Any instance of an object within a model could then be associated with the corresponding type using the objectified relationship *ifcDefinedByType*. That would provide a consistent approach to typing, and obviate the need for the current practice in IFC of embedding type information in an object definition through type attributes (*ObjectType* and *PredefinedType* with associated enumerations, inherited from the *ifcObject* class). Those attributes could be phased out in later versions of IFC.

To support this approach, a significant task within the current research project is to develop a precinct Object Type Library (OTL), using the bSDD to manage typology, rather than embed those type definitions explicitly within the schema. The type entities within this OTL will be associated via web services with external reference data, in particular low carbon metrics. For example, rather than define unique IFC concepts for urban features such as a “school”, “3-bedroom house”, “apartment block”, “factory”, etc., the alternative approach is to propose the single *IfcBuildingType* entity, with the specializations made by identifying the instances of that type with reference to the appropriate concept in the bsDD. This allows more flexibility to accommodate many use cases across geographic jurisdictions and language groupings in a much more flexible, consistent and robust manner.

This approach aligns with initiatives in Europe, such as the DURAARK project (http://duraark.eu/), which proposes an ontological framework for a semantic digital archive of architectural knowledge. Similarly, in the Netherlands, generic object type libraries that include highways and waterways (Rijkswaterstaat), railways (ProRail) and a nationally harmonised library (CB-NL) are discussed by various researchers ([17], [18]). Such a linked data approach is expected to facilitate object standardisation nationally and enable the reuse of generic objects across the built environment sector. In a similar way, at a building level, Steel, et al. [19] describe an approach for the storage of reusable building model components using the buildingSMART Data Dictionary (bsDD).

4. Exemplar precinct model

In order to test this precinct modelling approach, a PIM database repository has been established for a precinct located in Sydney, referred to as the Broadway Precinct. This is being undertaken in collaboration with a separate research project (called “Empowering Broadway”) that is investigating how to transition an existing urban region to a low carbon precinct by developing localized, shared management of energy and water services. The precinct is made up of two tertiary education campuses (buildings and associated open space), a television media organization and a new (under development) mixed-use commercial, retail and residential complex on an old brewery site. The overall precinct includes a network of major and minor roads, a disused railway tunnel and service utility networks, including some green infrastructure elements built into the new development. As such, it offers a very comprehensive example of an urban precinct.

The precinct modelling strategy for this project is illustrated in Fig. 4. The data schema (including the data dictionary) are shown on the left and define the structure of the model. The precinct model itself has links to various external data sources, both directly through links from object instances in the model to operational data (where appropriate) or geo-located data (accessed using spatial queries), and indirectly to data linked to objects held in the common object library. Applications can then access the information held within the PIM to carry out any kind of analysis or management process that may be required.

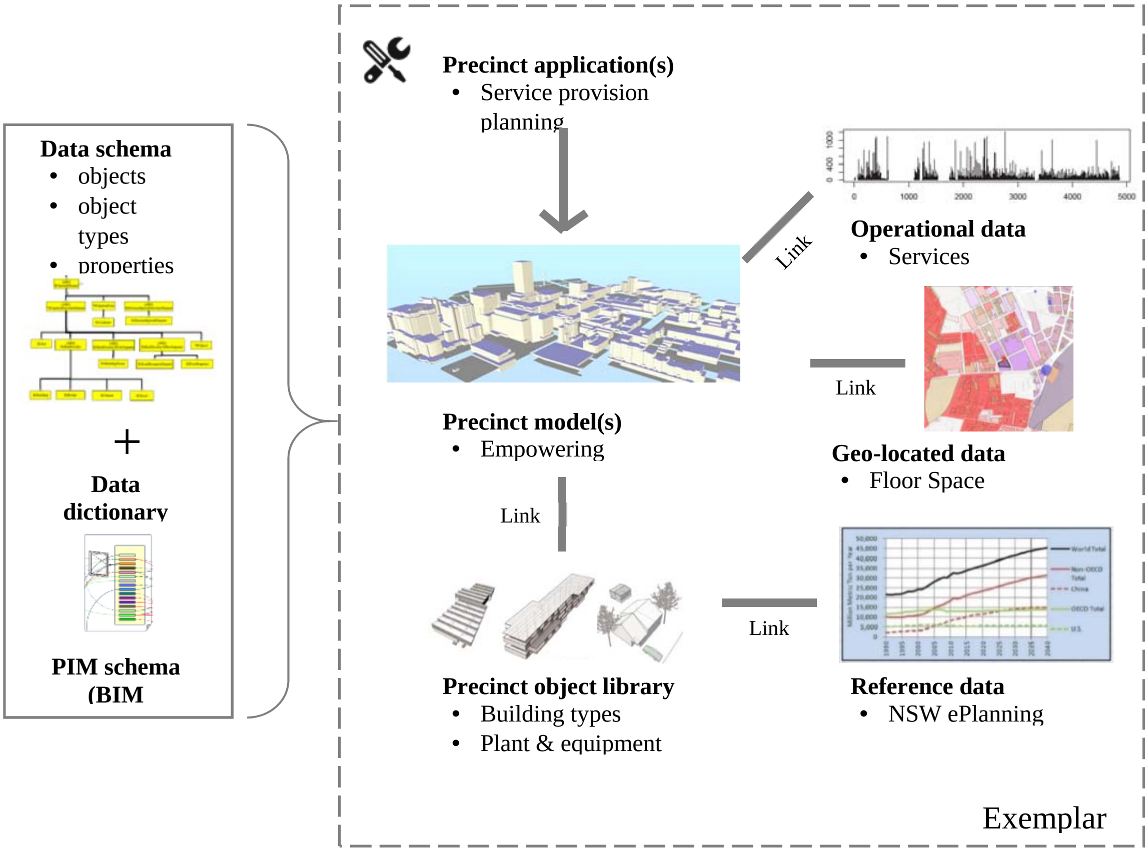

Fig. 4. Organisation of the precinct model for the Broadway precinct

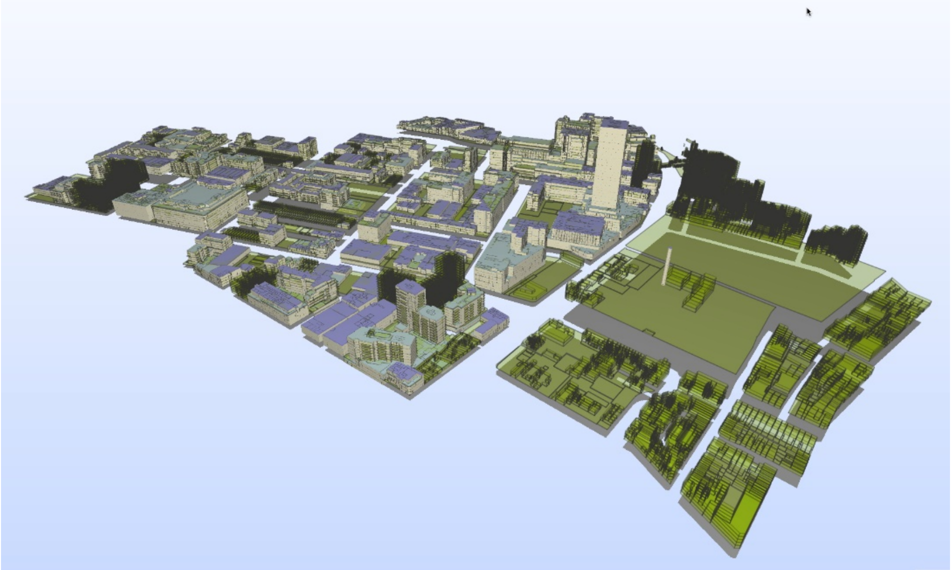

Fig. 5. A data visualization of the precinct model in Broadway, Sydney, Australia

The Broadway Precinct model (Fig. 5) provides a specific use case that informs the work reported here, to develop the structure of the proposed PIM schema as discussed in the previous section, while also providing the data needed to support the research into precinct transition strategies.

Development of the PIM schema relies on the advice and testing of experts. As well as architects and consulting engineers, to date the project team has liaised with urban and landscape designers, surveying and civil infrastructure software vendors, local and state government authorities, as well as the major client stakeholders and their facility managers within the Broadway precinct. The next phase will address expansion of the initial PIM schema tested through pilot implementations for specific use cases.

5. Conclusion

The ideas reported in this paper represent a work in progress. A consideration of the needs for integrated solutions to address the challenge of low carbon living at a precinct scale has led to the recognition that precinct planning is much the same as any intervention in the built environment and can benefit from robust information modelling.

The framework developed here for precinct modelling strikes a balance between a comprehensive data model that attempts to represent every conceivable entity in a precinct and the use of a data dictionary to provide type definitions and associated attributes. The principles that have guided the development of the data model have been explained, along with a framework that supports linkages to external data, affording a mechanism to integrate with spatial information technologies.

Future work will test the implementation of the schema in the context of the Broadway Precinct in Sydney, ensuring that it addresses the needs of a precinct in transition to an integrated low carbon solution. In doing so, it will contribute to the on-going international work on standards and processes to support the evolving digital built environment.

Acknowledgements

This research is funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative. The authors would also like to acknowledge the three major industry partners associated with this project: Brookfield Multiplex, AECOM and buildingSMART Australasia.

References

[1] Osman H, El-Diraby T. Ontological modeling of infrastructure products and related concepts. *Transportation Research Record: Journal of the Transportation Research Board*, 2006;159–67.

[2] UK Department for Business, Innovation & Skills. *Digital Built Britain. Level 3 Building Information Modelling – Strategic Plan*. Policy Paper, UK construction industry: digital technology, UK: Department for Business, Innovation & Skills; 2015. Available on-line (last accessed 23/06/15): https://www.gov.uk/government/publications/uk-construction-industry-digital-technology

[3] Anon, *Global Construction 2025*, Report: Global Construction Perspectives and Oxford Economics. 2013: July. Available On-Line (last accessed 23/06/15); http://www.globalconstruction2025.com/

[4] Volk R, Stengel J, Schultmann F. Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Automation in Construction*, 2014;38:109–27.

[5] Ronzino A, Osello A, Patti E, Bottaccioli L, Danna C, Lingua A, Acquaviva A, Macii E, Grosso M, Messina G. The energy efficiency management at urban scale by means of integrated modelling. *Energy Procedia*, 2015, 83:258–68.

[6] JBIM, *Journal of Building Information Modelling*, Official publication of the National Institute of Building Sciences, US: buildingSMART Alliance;2010; Fall.

[7] Gómez P, et al, Campus Landscape Information Modeling: Intermediate Scale Model that Embeds Information and Multidisciplinary Knowledge for Landscape Planning. In: *Proceedings of the XVII Conference of the Iberoamerican Society of Digital Graphics: Knowledge-based Design* [Blucher Design Proceedings, v.1, n.7]. São Paulo: Blucher; 2014; 61-65.

[8] Mommers B, “The Crossover Revolution”, *Geospatial World*, 2014; March; 62-63.

[9] Gilbraith I Digital Infrastructure – the future of engineering, Comment, in *Infrastructure Intelligence*, US: Association for Consultancy and Engineering; 2015; May. Available on-line (accessed 15/06/15): http://www.infrastructure-intelligence.com/article/may-2015/digital-infrastructure-%E2%80%93-future-engineering?utm_medium=email&utm_source=transactional&utm_campaign=weekly-email

[10] Plume J, Owen B, Simpson R, Hobson A. *Integration of Geospatial and Built Environment - National Data Policy.* Joint buildingSMART - SIBA Position Paper, SIBA; 2015.

[11] Guruz R, Katranuschkov P, Scherer, Raimar, J., Kaiser J, Grunewald J, Hensel B, Kabitzsch K, Liebich T. Ontological Specification for the Model Integration in ICT Building Energy Systems. In: Guruz R, Katranuschkov P, editors. *ISES Deliverable D8.7*. Brussels; 2012; 8–30.

[12] Scherer R. J., Kartanuschkov P., Kadolsky M., Laine T. Ontology-based building information model for integrated lifecycle energy management. In: Guruz R, Katranuschkov P, editors. *ISES Deliverable D8.7*. Brussels; 2012; 24–32.

[13] El Asmi E, Robert S, Haas B, Zreik K. A standardized approach to BIM and energy simulation connection. *International Journal of Design Sciences & Technology* 2015; 21:59-81.

[14] Vanlande R, Nicolle C, Cruz C. IFC and building lifecycle management. *Automation in Construction* 2008; 18:70–80.

[15] Ioannidis A, Tzovaras D, Malazavos C. Occupancy and Business Modelling. In: Guruz R, Katranuschkov P, editors. *ISES Deliverable D8.7*. Brussels; 2012; 54-71.

[16] E. Lebegue, *IFC-Bridge & IFC for Roads*, Presentation, BuildingSmart Infrastructure Room. Munich; 2013; October.

[17] Luiten GT, Bõhms HM, van Nederveen S, Bektas E. Distributed modeling for road authorities. In: *Proceedings of the CIB W78 2013*.

[18] Dankers M, van Geel F, Segers NM. A web-platform for linking IFC to external information during the entire lifecycle of a building. *Procedia Environmental Sciences*, 2014; 22:138–47.

[19] Steel J, Drogemuller R, Toth B. Model interoperability in building information modelling. *Software & Systems Modeling*, 2012; 11:99–109.