This is the Accepted Manuscript version of an article published by Elsevier in the journal *Automation in Construction* in 2021, which is available at: https://doi.org/10.1016/j.autcon.2020.103440. Cite as: Biljecki F, Lim J, Crawford J, Moraru D, Tauscher H, Konde A, Adouane K, Lawrence S, Janssen P, Stouffs R (2021): Extending CityGML for IFC-sourced 3D city models. *Automation in Construction*, 121: 103440.

Extending CityGML for IFC-sourced 3D city models

Filip Biljecki[a,*], Joie Lim[a], James Crawford[b], Diana Moraru[b], Helga Tauscher[a], Amol Konde[a], Kamel Adouane[a], Simon Lawrence[b], Patrick Janssen[a] and Rudi Stouffs[a]

[a]*National University of Singapore, Singapore*
[b]*Ordnance Survey, United Kingdom*

ARTICLE INFO

Keywords:
CityGML
IFC
ADE
BIM
3D city model
Singapore

ABSTRACT

Differences in the scope and intent of the contrasting IFC and CityGML data formats entail that converting the former to the latter results in loss of information. However, for some use cases it is beneficial to keep also particular information from IFC that is not native to CityGML, and achieving that requires mechanisms such as the CityGML Application Domain Extension (ADE). We develop an ADE to support retaining relevant information from IFC. Besides being driven by the particular source of the input data (IFC), this multi-purpose ADE is shaped after a discovery process that involved examining potentially applicable use cases in Singapore, doubling as an extension that is adapted to a set of use cases and the local geographic context. We implement the conceptual work by generating an enriched dataset (with an automatic conversion from IFC to CityGML), visualising it, and discuss its added value in a use case.

1. Introduction

The conversion of detailed architectural models stored in IFC to semantic 3D city models in CityGML is a topical subject [1–3]. Because CityGML is a data model designed for the geospatial world, much information during the conversion from IFC is inherently lost, such as energy-related features [4, 5]. Such loss of information is not necessarily a disadvantage because usually there is no need to generate an equally detailed counterpart in the geospatial domain, as use cases — especially those focusing on the urban scale and covering multiple buildings — would not have much benefit or would even suffer from excessively rich datasets [6].

Nevertheless, in certain situations such as energy simulations and indoor navigation, it is beneficial to preserve a subset of information that is not possible to store with the standard data model of CityGML. For extensibility, CityGML provides the Application Domain Extension (ADE), a mechanism to extend the standard data model, which among other advantages provides means to absorb rich information from IFC.

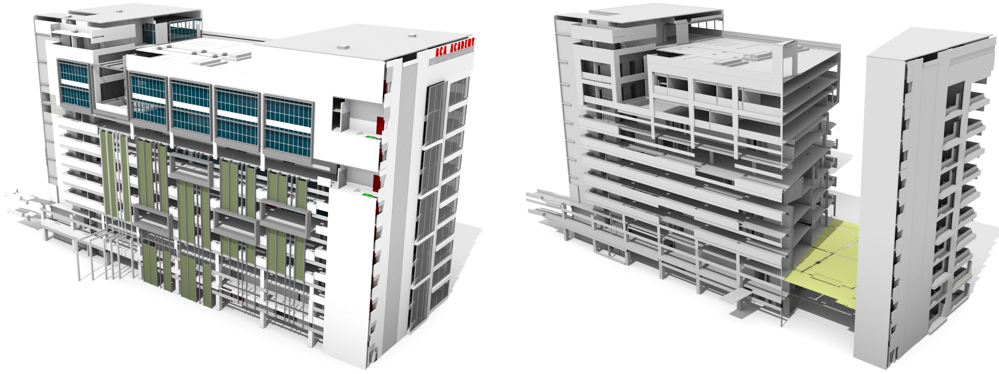
This paper stems from a research effort on the conversion of IFC to CityGML to integrate data originating from the architectural and construction domain in the geospatial environment serving different stakeholders in the government sector in simulations and analyses across multiple disciplines. In our work we develop an ADE that facilitates the conversion from IFC to CityGML. This topic is important as while the idea of bridging the two disparate domains is gaining currency in academia and industry, there are still many unanswered questions, especially related to data formats. We contribute to the body of knowledge by presenting an ADE that leverages on the comprehensive information provided by the IFC schema but balances usability and simplicity, and is influenced by practices pertaining to a local geography and users.

We investigate multiple aspects related to this subject. Most importantly, and in a generalised way facilitating replication, we tackle the research question: how to design a specification for 3D city models that takes advantage of the rich architectural source, and at the same time adheres to local practices and supports a selection of use cases?

We also wrote this paper to serve as a guide when designing an ADE and specifications in similar projects, i.e. we cover the entire and extended workflow of designing a data specification to its implementation in a dataset and software, which is uncommon in literature: Section 2 gives background information, describes the ADE mechanism, and related work; Section 3 introduces the workflow we followed and explains the rationale behind certain choices we made. Section 4 describes the multi-purpose localised (application-driven and context-driven) ADE we have designed, named IfcADE, along with more details about the selected use cases and their identified properties. In Section 5 we implement the specification: we convert an IFC dataset to a CityGML ADE-enabled counterpart that conforms to the presented specification and visualise it in two ways (desktop and web) portraying CityGML information beyond the standard model, and discuss the application in a use case: we give a demo of an indoor navigation instance that takes advantage of the availability of the features stored according to the ADE. Section 6 discusses the limitations of the work, caveats, and points of improvement in future.

Our work focuses on Singapore and three use cases (with indoor navigation being the focal point in the implementation and examples), and besides providing value in giving an insight into this development, we believe that from the scien-

*Corresponding author
filip@nus.edu.sg (F. Biljecki)
ORCID(s): 0000-0002-6229-7749 (F. Biljecki); 0000-0003-0411-8770 (H. Tauscher); 0000-0002-9255-8006 (A. Konde); 0000-0002-2013-7122 (P. Janssen); 0000-0002-4200-5833 (R. Stouffs)



(a) Input IFC model. (b) Output CityGML models (two variants).

Figure 1: Example of a conversion from IFC to CityGML within our project (following the methodology presented across multiple recent papers [4, 19–22]). Source of the architectural dataset: Building and Construction Authority (Singapore).

tific point of view our work is sufficiently generic that it can be scaled to other use cases and geographies. Besides mixing both local and use case contexts, other contributions of our holistic paper involve enhancing related work and covering the entire development life cycle — from design to implementation, visualisation, and utilisation in a use case, topics that are usually not covered.

2. Background

2.1. Conversion from IFC to CityGML

The two prominent data formats used in architecture, engineering and construction, and the geospatial world, respectively, are the buildingSMART standard Industry Foundation Classes (IFC) [7, 8] and the Open Geospatial Consortium (OGC) standard CityGML [9, 10].

Some of the benefits of bridging IFC and CityGML (and in general BIM and GIS) (Figure 1) involve taking advantage of GIS software/use cases that cannot be carried out with BIM datasets, integration of multiple sources of data (e.g. visualisation of architectural models in a geographic environment, and carrying out use cases that require data on multiple scales), leveraging more detailed data (both geometrically and semantically) in the geospatial domain, bypassing often expensive and tedious aerial and ground surveys (benefiting maintenance of data), supporting complex analyses of the data such as environmental and planning analysis, as well as enabling carrying out spatial analyses on buildings that are yet to be constructed [11–13]. There is a large number of use cases requiring indoor geometry and rich semantics, e.g. 3D cadastre [14], illuminance analyses [15], and routing [16–18], and as such they may benefit from 3D city models that are sourced from IFC.

Bridging these two disparate worlds does not only involve considering different data formats, but also different mindsets, use cases, stakeholders, and dealing with different lineages of data, translating the architectural view of the world to the geospatial [23, 24]. Besides 'slimming down' an IFC model from the spatio-semantic perspective (i.e. generalisation to obtain lightweight 3D city models facilitating use cases at the urban scale), the process of the conversion also involves adapting both the semantics and geometry to a different structure (e.g. translating the geometric representations and semantic classes). While there may be alternative approaches to BIM-GIS interoperability, such as keeping separate files with establishing links between them or having a joint database, the generally accepted technique is the conversion from one format to another, predominantly in the geospatial direction. Separate CityGML and IFC files would add a layer of complexity, as one would need to develop specific translation programs for specific applications.

Many projects have been carried out in this domain and have been extensively described [5, 25–35]. This paper is part of the project on the conversion from IFC to CityGML within the frame of Virtual Singapore, being preliminarily described in [4, 19, 20, 36]. In this paper, we follow up on the published work by focusing on one of the pillars of the project: the extension of the CityGML data model complementing the conversion and fitting use cases requirements and local context.

2.2. CityGML ADE

CityGML provides a generic domain-independent data model for the spatio-semantic modelling of topographic features in 3D in the application area of cities and landscapes. At the expense of keeping things simple, it might be considered limited and might not suit a large number of use cases and situations. For this reason, the CityGML data model is often extended using the ADE mechanism. An ADE enables augmenting the CityGML data model, extending it beyond its scope benefiting use cases and particular scenarios. A particular ADE can be specified with an XML schema definition file (XSD) and/or with Unified Modeling Language (UML) [37–39].

In the context of this research an ADE allows capturing additional information on top of the native CityGML data model, eventually enabling to keep a set of information we are interested in (Figure 2), i.e. it generally allows:

- Introducing new classes/features. For example, modelling solar panels as features with their own geometry (e.g. extent of the panels) and attributes (e.g. photovoltaic capacity).

- Adding new attributes to existing classes/features. For example, including the number of units in a building, an attribute that does not exist in the standard CityGML data model.

- Introducing/extending code lists of attributes. For example, adding new building types that do not fit in the existing code list provided by the CityGML data model. These enable modelling freedom and customisation of attributes, e.g. for aligning them to a national standard.

- Introducing non-standard geometries to existing classes/features. For example, the Noise ADE enables modelling noise barriers as lines [9, 40].

Many ADEs have been developed around the world for a variety of purposes [37]. For example, these include ADEs developed for a taxation use case [41], enabling metadata according to international standards [42], adapting the data model to store ancient Chinese roofs [43], extending CityGML for a national context developing a national 3D standard [44], improving the storage of terrain in CityGML [45], and facilitating the integration with other data models [46]. These few examples indicate the diversity of purposes ADEs are developed for.

Following the examination of the capabilities of the ADE concept, considering different options, and the literature review, we deem that developing an ADE is a convincing choice in facilitating the conversion from IFC to CityGML and preserving information valuable for applications. However, most of the related work focuses on one aspect, such as facilitating a single use case. In our paper, we go beyond that, as we combine multiple aspects developing an ADE that is (i) shaped after an input dataset (we examine the IFC data model and translate subsets that may be deemed relevant in the geospatial domain), (ii) serving specific use case(s) (given that we need to preserve features that are usually not available in the geospatial world but might be useful), and (iii) regarding a national context (i.e. local architecture, practices, and stakeholders).

Some disadvantages of the ADE mechanism are that in each domain there may be a specialised data format that is more suitable for each respective purpose and that most of the existing software does not support working with ADE-enabled datasets out-of-the-box. Those would have to take into account either a particular extended schema, which is not always an easy task [47], or the extension mechanisms in general, which is even more difficult. We did overcome some of these disadvantages with certain modelling choices and by implementing the work (Section 5).

An ADE is technically part of CityGML, but for the sake of clarity in this paper we refer simply to the basic CityGML data model as CityGML and everything else as extensions/ADE. For more information on the ADE concept the reader is referred to the review paper [37], which includes 44 examples of ADEs, modelling guides [39], and the latest adopted version of the CityGML standard [9].

2.3. Singapore

As it is the case with many other geographies, Singapore has certain particularities that warrant the development of an extension to CityGML. For example, localisations of CityGML have been made in the Netherlands, Sweden, and Turkey to adapt to the local context and to align to existing government practices [44, 48, 49].

Examples of distinctions from other countries usually prominent in the 3D city modelling world are that Singapore is located in Southeast Asia (i.e. CityGML has been developed by mostly European stakeholders inevitably conforming to their geographies and architecture), it has a tropical climate (having an impact on the selection and importance of use cases, and consequently possibly a set of required features that in other geographies are not acquired routinely), and it is a city-state (the different organisation of the government might reflect a set of GIS users and use cases different from other countries). An example of an architectural characteristic in Singapore is the presence of *void decks*, a publicly accessible sheltered space on the ground floor of residential buildings playing an important social and environmental role [50], a feature that might be beneficial to model, but is not provisioned for in CityGML.

Urban digital twinning and simulation in Singapore are largely carried out under the auspices of the Virtual Singapore programme spanning multiple research projects and have been described in several research papers focusing on improving acquisition, modelling, and usability of 3D city models in the local context [51, 4, 20, 52–54]. CityGML has already been subject to extensions to enhance the model adapting to the local context, e.g. the CityGML Vegetation module accommodating additional properties about trees that are characteristic to the government agencies in Singapore involved in managing and using such information [52].

Finally, it is relevant to note that the Government supports the adoption and implementation of BIM. It mandates the submission of BIM data for new constructions for regulatory approval [55], potentially providing a valuable source for acquiring and maintaining 3D city models on a large scale.

2.4. Overview of existing ADEs serving the conversion from IFC

While several papers present methodologies to convert IFC to CityGML (Section 2.1), only a few develop ADEs to conserve rich information [26, 25, 34, 31], and not all of them are focused on buildings.

De Laat and van Berlo [25] introduced the GeoBIM extension, enabling the preservation of IFC semantics and properties in CityGML without a particular use case in focus. About 10% of features from IFC have been considered important for general geospatial applications, and those have

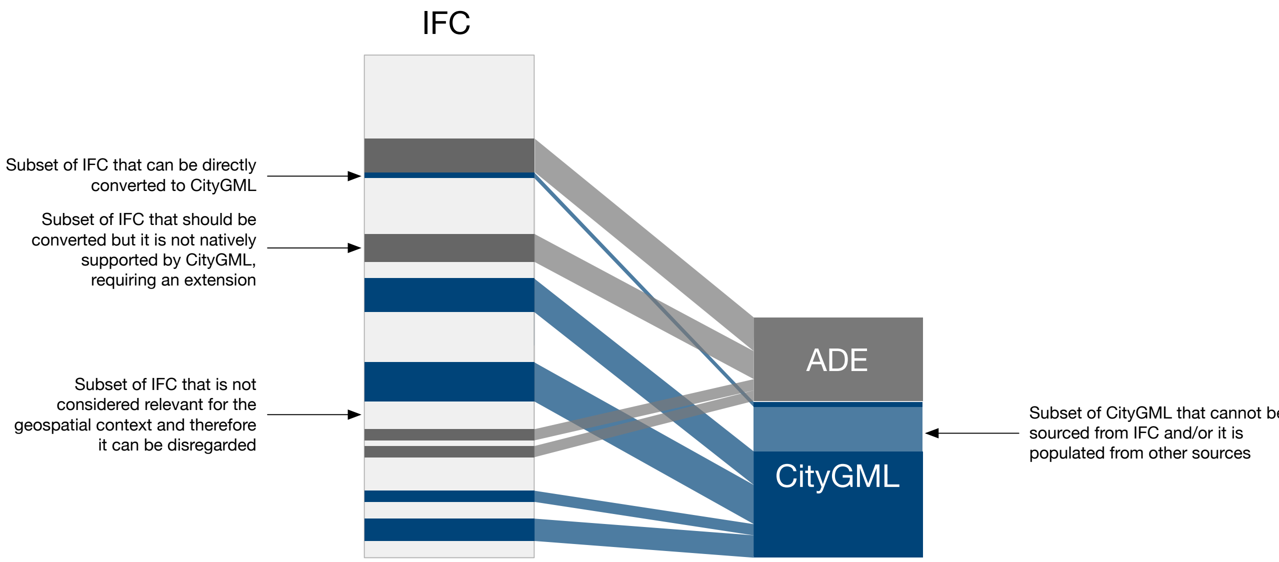


Figure 2: The motivation for an ADE in the context of the IFC to CityGML conversion. Given the substantial difference between the BIM and GIS domains, and their corresponding flagship formats IFC and CityGML, only subsets of IFC are relevant for the conversion to CityGML (the shaded lines indicate conceptually the correspondence among the two formats and an extension, and suggest the relation between different bits of data involved in workflows such as ours). However, not all are possible to be 'captured' by CityGML by default. Therefore an extension has to be created.

been included in the ADE. An example is the introduction of the attribute `OverallWidth` to the CityGML `Door` feature, mapped from the IFC class `ifcDoor`.

The work of Kutzner et al. [56] focuses on extending CityGML to accommodate utility networks, developing the Utility Network ADE. In their early work [31], researchers investigated sourcing relevant features from BIM. A relevant conclusion is that a direct 1:1 mapping between IFC and Utility Network ADE is feasible in most cases. Another ADE not focused on buildings is the PANTURA ADE [34], concentrating on bridges and with a particular use case in mind (analysis of the disturbance induced by bridge construction).

The Semantic City Model ADE has been introduced by Deng et al. [26]. The key novelties of their work is the support for multiple levels of detail, and modelling the topological relations between different features.

While these developments are valuable and provide a solid basis for our work, and with having in mind avoiding the duplication of existing work in the scientific community, nevertheless, we have decided to develop a new and independent ADE for multiple reasons: previous ones have been developed for older versions of CityGML, they do not adhere to our local context and our use cases, and an independent ADE allows for flexibility, freedom, and tailoring the data model without compromises.

3. Methodology and considerations

In this section we describe our methodology of developing data specifications for CityGML that takes advantage of the rich IFC information model, while being tailored to local practices and enabling a selection of use cases, which were chosen in consultation with the project stakeholders. We describe considerations for the design (Section 3.1), the discovery of requirements (Section 3.2), and the rationale behind the selection of features (Section 3.3).

3.1. Designing an ADE and basic principles

As it is the case with designing specifications, designing an ADE is not an exact science, and it is subject to choices that may be deemed subjective. This is especially the case when envisioning use case scenarios, composed of a mix of assumptions. Different users may also have different priorities even if they are part of the same use case [57].

First of all, because we are dealing with a multiplicity of purposes (e.g. more than one use case), a question that arises is whether it would be beneficial to design multiple extensions or a single one. Therefore, we identify three approaches for the design of an ADE (Figure 3):

Approach 1: Involves developing independent ADE data models for each use case. Therefore, each of the developed ADEs will have their data model structure with customised and new data packages, classes, and attributes. Thus, they will inevitably have an overlap, since multiple use cases may require the same subset of information. Most ADEs nowadays belong to this category as they are developed to suit a particular use case and domain, e.g. EnergyADE [58] and Cultural Heritage ADE [59].

Approach 2: A single ADE data model accommodating the data requirements for all use cases into a single structure. There are ADEs catering to multiple use cases, such as Dynamizer ADE [60], and they are largely found in the

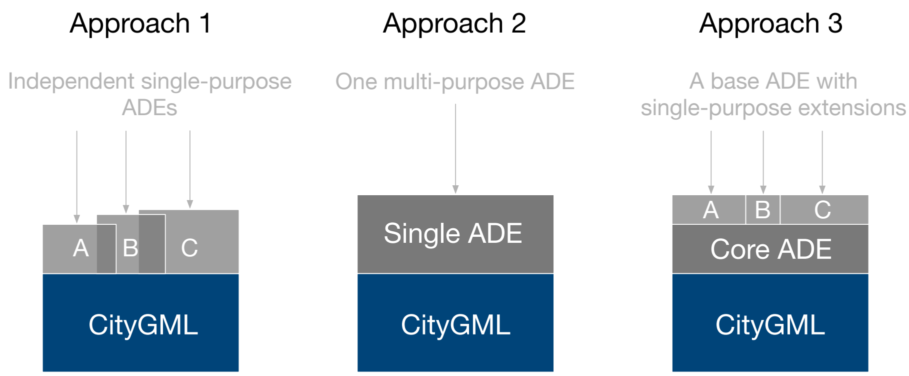


Figure 3: Three different options in designing an ADE that serves multiple purposes, i.e. use cases A, B, and C.

domain of national geographic information standards (e.g. [44, 61]).

Approach 3: An ADE data model with a shared core structure to which there are attached additional ADEs, i.e. new data packages or classes that are representative for each of the use cases (e.g. new data package with new classes/attribution for use case A, new data package with new classes/attribution for use case B and so on). This approach is in a way related to the cross-domain building models discussion by Knoth et al. [62], and it is akin to developing ADEs extending existing ADEs [63, 64].

In this work we choose the second option for easier maintenance and because it turned out (as it will become evident in the next section) that the resulting data model is not so large to have the necessity of partitioning it among multiple entities, and because there is an overlap between requirements of use cases (which is another advantage of our ADE as it provides support for multiple uses while not growing in complexity). Another advantage of developing a single ADE is that it benefits software developers since they would not need to consider multiple data models.

Even though this single extension provides features that are necessary for one use case but are irrelevant for another, it is important to note that while collecting the data it is not mandatory to populate all features in all circumstances (i.e. the same way CityGML supports storing roads and vegetation, that does not mean that all datasets have to contain them).

3.2. Discovery of use cases and local practices

We have analysed the content of IFC, i.e. what potentially useful information IFC can provide that are not included by default in CityGML. While this is partially a similar process and starting point as related work (Section 2.4), the quality of this analysis was improved significantly through conducting discovery sessions focusing on use cases with geospatial information domain experts and practitioners — for example, from urban planning and design, energy modelling, and land administration. Although in some cases, the intended information encoding/format these practitioners work with may not be CityGML, the discovery process provides the research opportunity to explore in-depth the particularities, relative importance, and nuances between information requirements from each of these geographic contexts (examples follow).

It is worth mentioning that the discovery process conducted in this research has been partly influenced by a separate 3 year discovery and learning process, led by geospatial domain experts from the UK's national mapping agency — Ordnance Survey. This process, carried out between 2015 and 2018, analysed information use and information requirements across practitioners and domain experts from more than 60 organisations across the UK's public sector, to create an evidence based, simplified classification framework for geospatial use cases. This research identified clear customer centric user stories focused around current and future user needs in the geospatial industry and beyond.

The outcomes from these separate pieces of work are complementary: a simple classification framework for organising the information requirements we identify from geospatial use cases; whereas the research adds how these requirements can be fulfilled using IFC as a potential information source. The relevant information from both have been combined in the design of the ADE, which is generic enough to be applied to different geographic contexts.

3.3. Selection of features/attributes

Selecting relevant features to extend CityGML with is the central point of the work. While we do not particularly distinguish between the different features in the ADE, this topic is important to keep in mind, especially for the implementation of sourcing procedures, that is, the conversion from IFC to CityGML. These are shaped after the three aspects mentioned in the previous section. On one dimension, we have:

0. Features that can be disregarded because they do not need to be translated into CityGML in our case, e.g. furniture.

1. Features that can be accommodated in the CityGML standard data model by default, e.g. walls.

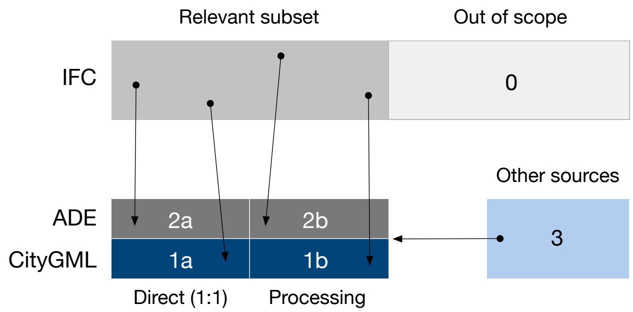


Figure 4: Different groups of features populating the CityGML data model from IFC, and a part from other sources. The annotations are explained in the text.

2. Features that require an extension in order to be preserved, e.g. elevators, since they are not explicitly available in the standard CityGML data model.

On another dimension, there are:

(a) Features that are conceptually available in IFC so they can be translated in a direct 1:1 (as-is) mapping from IFC to CityGML or to the ADE. This includes attributes such as building function (available in CityGML) and information about the material of a wall surface (it requires an extension to CityGML, but once such is available its sourcing should not be complicated).

(b) Features that can be derived after a degree of processing (or manually) because they are not directly provided by IFC, but are obtainable from the existing set of information in the IFC. For example, the number of storeys above ground and the number and location of access points for a room are not available explicitly in IFC, but could be derived.

The combination of these dimensions and aspects gives four principal groups of features, and in our work we have encountered instances of all of them: (1a) features that are directly mapped from the IFC model to the core CityGML model; (1b) features that are mapped after bespoke/additional processing during conversion into the core CityGML model; (2a) features that are directly mapped from IFC to the ADE model; and (2b) features that are mapped after additional processing during conversion into the ADE. Figure 4 conceptually illustrates the categories (and extends Figure 2), while Figure 5 gives a practical example. These are important to keep in mind for the implementation of the conversion.

During our work, we realised that while IFC provides the vast majority of information required for use cases, a small number of features/attributes required for the use cases cannot be sourced from IFC because it is either not available in the schema or it is rarely present in datasets, and will thus require supplementing it with additional data sources (category 3). For example, energy demand estimations would well benefit from data from IFC. However, it may require additional information such as the number of occupants of a building and the surrounding vegetation, which are usually sourced elsewhere.

4. IfcADE

In this section, we present the ADE we created, which we name IfcADE, and present its genesis and motivation for the key design decisions. For the IfcADE, we enhance features from the CityGML 3.0 Building and Construction modules. The version 3.0 of the standard is not yet adopted. Thus, we rely on recently available proposals [66–68] and the conceptual model available on Github [1]. Even though the new version of the standard is yet to be finalised and adopted, we have opted to focus on this version since it provides some advantages over the version 2.0 adopted in 2012, such as an improved consideration for indoor features (e.g. introduction of storeys and multiple levels of detail), and it will likely be adopted in the very near future [68]. Since we do not expect the final version of the standard to introduce breaking changes, and instead of continuously aligning the ADE to each new update of the data model, we plan to update the developed ADE after the final version of the CityGML 3.0 data model is adopted.

4.1. Description of use cases

We elaborate three use case scenarios with varying information requirements according to their geospatial context and application. We intend to demonstrate how the combination of different subsets from the standard CityGML model and the IfcADE offers the advantage for including enhanced semantic properties extracted from IFC — so that this can be replicated by others to build data models for use in other geospatial use cases. Singapore is often the subject of various related spatial analyses in research [69, 70], thus, as long as it does not compromise the current design, the ADE enables future enhancements that support new use cases. Furthermore, the data model also allows to regard additional IFC features that have not been included in this version, but in future may turn out to be worth including.

While a focus of the paper is also on adapting the data model to the local context, it is intertwined together with the use cases, and thus a separate discussion is not possible. For example, when considering use cases, we added features that are arising from the local context, e.g. code lists of building types in Singapore and the presence of void decks.

4.1.1. Energy

Energy analyses are a topical subject in 3D GIS [71–74], for example — estimating the energy demand for heating buildings and analysing energy-efficient refurbishment of buildings on a district level. Researching cooling behaviour of households is a particularly important topic in research in the city-state [75].

Therefore we have extended CityGML to provide information to carry out general energy analyses. For example,

[1] `https://github.com/opengeospatial/CityGML-3.0CM`

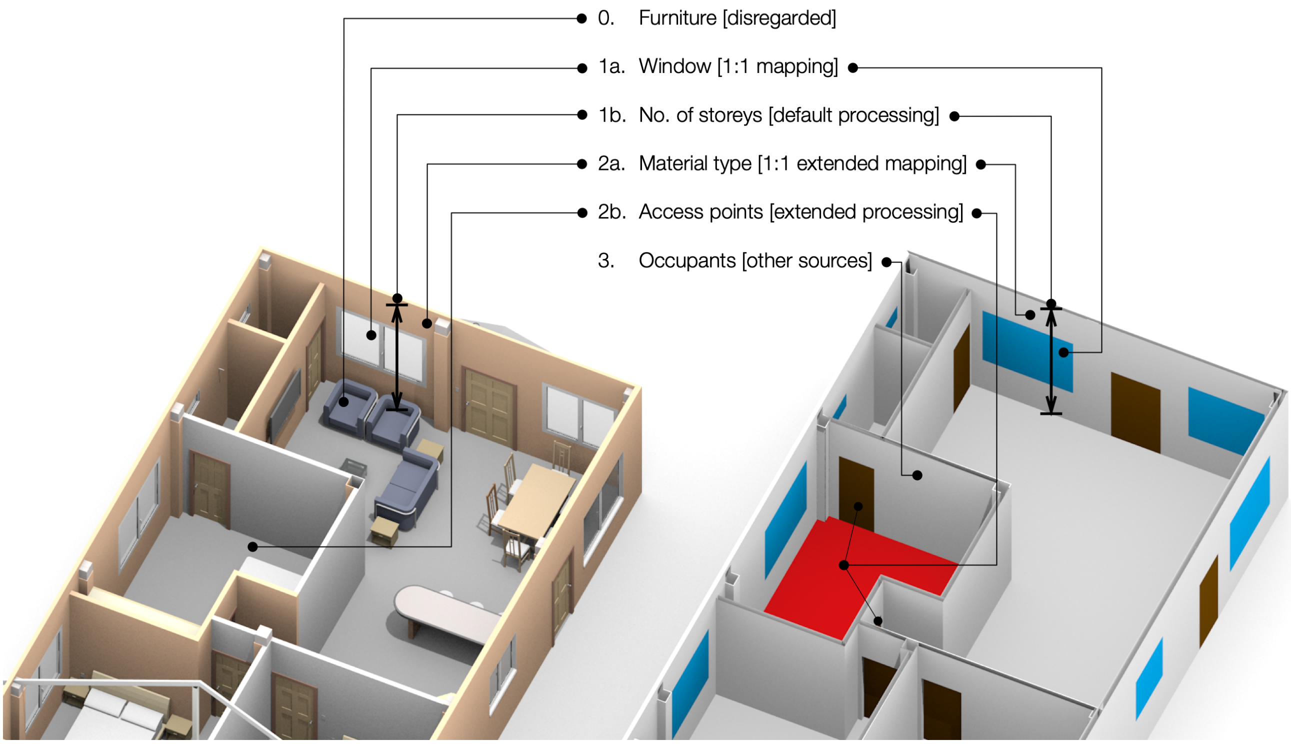


Figure 5: Illustration of the relation between IFC and CityGML showing examples of categories in Figure 4. Source of the IFC dataset (left) used to generate the illustration: Open IFC Model Repository, Department of Computer Science, University of Auckland [65].

the ADE accommodates information on volumes of rooms, airconditioning systems, and photovoltaic panels. Some parts of the extension have been inspired by the EnergyADE [58], and because this topic has been well researched and developed in related work, this use case will not be elaborated further in this paper.

4.1.2. Urban planning and liveability

Urban planning is a versatile use case with blurry boundaries and a wide range of applications. Providing an appropriately simplified model, which can be enhanced with useful semantic information from IFC may offer advantages in the types of visualisation and analysis that can be achieved, and aid answering questions such as:

- How much greenery is visible from specific windows and viewpoints of a building, and how does that affect valuation?
- What is the impact on the outdoor thermal comfort (e.g. facade material reflectivity)?
- How will a newly constructed building impact existing nearby units?
- What is the total floor area of all constructions in a certain plot?
- What is the area covered with vegetation on residential buildings?

The IfcADE caters to a few possible use cases in this domain, and there is much potential for new use cases to take advantage of some of the existing features. For example, with the increased availability of IFC datasets, in future it might be possible to investigate what proportion of the infrastructure and buildings within a region or city are accessible across certain types of mobility restriction.

For further reading in the use of 3D city models in urban planning and related domains the reader is referred to papers [76–84]. We have looked into these papers to understand the use cases and their requirements. For example, we added the number of occupants of a building [79], and floor area [80] in the developed data model.

4.1.3. Multi-modal routing

The third use case of routing provides an example of how enhancements to CityGML may provide support to a variety of applications. It is also the use case that we selected to focus on in the implementation (Section 5.3). Indoor accessibility, routing, and navigation within a building, or even indoor/outdoor accessibility between buildings, are increasingly popular topics in recent research [85], and examples that could benefit from data sourced from BIM. This use case is especially important in the context of urban models, facilitating navigation in the urban environment (i.e. navigation from a space in one building to a space in another building). There are some potential overlaps to be considered with IndoorGML [86], but this is outside of the scope and so is not explored in more detail in this paper.

In addition to indoor routing from point A to point B within a building, examples of the types of applications identified within the indoor routing and navigation use case are as follows:

- Effective citizen services — navigation: routing and navigation between locations within a building. For example, how to navigate to rooms or spaces in a building that are sufficiently large, or meet the specific needs or profiles of users — the presence of particular thermal, lighting, and ambient conditions.

- Effective citizen services — accessibility and mobility: providing choice and optimisation for the type of routes considering different mobility and accessibility requirements — for example, barrier-free accessibility taking into account routes that are wheelchair accessible or having automatic doors. Information such as this may be relevant in the context of Singapore's (and more broadly to other developed nations) ageing population and challenges of improving user experience in accessing or navigating through spaces within buildings. Therefore, information such as door access types could enhance existing use cases. Furthermore, this context-aware application is also extendable to other building typologies, and for other access and mobility requirements — elevators with a specific cargo capacity and sufficiently large door widths, in an industrial setting for example. Some of these have been described in detail in various research publications [87, 88].

- Asset management — facility management: navigation and routing that takes into account the names and locations of specific service locations (the locations of a sensor, fuse boxes, or specific utilities and services). The locations of particular walls and rooms as well as their materials construction and colour, could also be interesting, in cases where damage needs to be reported and/or fixed. Therefore facilitating planning and response to required maintenance activities.

- Protection of life — emergency response: locating the nearest or particular emergency equipment — for example, automated external defibrillator (AED), and how to adapt the design of spaces to improve access to AEDs. There is also an opportunity to provide information services to first response teams of medical professionals who may need to navigate through unfamiliar locations or provide situational coordination to others during critical or emergency situations.

- Protection of life — evacuation: analysing the optimal evacuation routes in case of fire in specific parts of a building. Optimising route planning could take into consideration corridor width (which may impact min/max time to evacuate people safely along certain escape routes), the size of doors, the direction of their opening including push-pull clearance which could affect the flow of people.

- Asset Management — security: for example, how to avoid or take into account certain areas within a building with restricted security clearance or access, which could affect navigation routes.

- Understanding commercial risk — asset and facility management: for example, a commercial company might need to evaluate the risks and impacts in case of a disaster/emergency with regards to their owned space, staff, and assets within the building. Having the right information within an ADE model could help them analyse where to best place their assets within the building (so that there is a minimum impact caused by flooding, stampedes, or riots) or how to best route their staff and move any objects in case of emergency — in order to minimise company losses. Likewise, this could apply to utility companies who would want to place their assets in the building in the most feasible place and efficient for their planned service and maintenance (this could be where its most appropriate for their network of assets such as cables/pipes or the nearest point to an entrance/exit door so that the maintenance engineer can access it quickly).

These context-aware scenarios may require specific attributes that are not provided by CityGML by default. Therefore we extend the data model and provide a template to source them from IFC. For further reading, the reader is referred to some of the many papers published in scientific literature on this topic [89–92, 16, 93–96].

4.2. Modelling decisions, mapping associations and design

The development of the data model is shaped after a set of decisions. In this section, we elaborate on the key approaches.

One of the most crucial modelling decisions we made is not to use sub-classes, even though these are one of the standard ADE mechanisms [37, 39]. Instead, to keep a neat organisation and to not compromise the standard data model, all additions are directly derived from GML features. We prefix such features with '`Ifc`' except for a few classes containing information frequently originating from other sources.

An advantage of such an approach is to make use of the standard data model and leave it intact as much as possible: instances of existing concrete CityGML classes are not affected by the ADE additions. This facilitates software that does not understand the ADE, to ignore the respective attributes, while still recognising the original CityGML classes and their attributes. For example, a room in CityGML has a standard class `BuildingRoom` with a few attributes. We have detected several additional attributes (e.g. whether it is accessible to wheelchair users) that should be stored, facilitating particular use cases. One approach would be to derive a new class from the existing class `BuildingRoom` inheriting the existing attributes and adding in the new ones. However, instead, our enhancement is designed as an independent class `IfcBuildingRoom` that is associated with the standard feature BuildingRoom and accommodates the additional set of attributes.

We identify the following entity types from IFC that are of relevance in this context: IfcMaterial, IfcMaterialSet, IfcBuilding, IfcRoof, IfcRoofType, IfcSlab, IfcTransportElement, IfcSpace, IfcLightFixture, IfcSolarDevice, IfcDoor, IfcWindow, IfcStorey, IfcBuildingStorey, and IfcRamp. We map them either to corresponding feature types in CityGML or create additional types for features that do not exist in CityGML, such as elevators.

Examples that are useful for use cases and that we introduced in the IfcADE model, in particular for the implementation of the indoor navigation use case which in focus of the implementation section of this paper, are: (i) IfcBuilding and its corresponding attributes such as: BuildingType (accompanied by a new code list), buildingName (in Singapore a building often has a name that in some cases is used in place of it its address), and voidDeck (another local particularity); (ii) IfcBuildingRoom with additional attributes indicating different types of access (e.g. whether a room is accessible from outside, whether it is accessible for the public); (iii) IfcElevator with corresponding attributes (e.g. liftNumber); and (iv) IfcDoor including information on its dimensions, passage, purpose, and direction of opening.

To be more specific, we give an example of the selected set of attributes that is preserved by focusing on the case of the modelling of windows, which in 3D city models are included for a variety of reasons. In the context of our use cases windows are important in all three of them: in energy they are valuable in estimating the heat/cooling loss, in navigation they are important for planning evacuation routes as windows can serve as an alternative escape, and in liveability it can be useful to assess the equity of views from apartments. The CityGML standard data model allows modelling windows, enabling the applications mentioned above. However, even though windows are described as openings in CityGML, it is not prescribed in which sense they are 'open', whether they establish a passage or a line of sight or both, and such information cannot be stored in CityGML by default (unless using generic attributes). While such information may not be necessary for the first and second use cases, the absence of such information is an issue with the navigation use case inhibiting the planning of escape routes in which extended information on windows may be important [97]. Therefore, we have extended the standard CityGML data model in modelling windows, introducing a boolean attribute navigable indicating whether the window is navigable or not.

Another modelling decision to highlight is the consideration of both boundary surfaces and volumetric elements, enabled by the new version of CityGML regarding IFC-sourced 3D city models. We have enabled the preservation of attributes in either case of boundary surfaces and constructive elements (e.g. see the feature IfcWall), depending on the spatio-semantic modelling decisions. It may be worth noting that this would not be possible with single inheritance. We are aware that the simultaneous use of both options can lead to redundancies and contradictions in the model. However, in this case we prefer a flexible solution over enforcement of good modelling practice through the schema.

The partial duplication of some features from the standard data model is a deliberate design choice to reduce ambiguity and smooth the way for the implementation. For example, the room name and room number are enabled in the ADE as two new and distinct additions, even though the current version of the CityGML 3.0 proposal allows modelling both concurrently in the same feature, but the approach as it is may add ambiguity and inhibit software implementation since it may not be clear which is which. With our approach, these information are streamlined in two separate attributes, reducing ambiguity and easing software implementation. This approach is also useful to make the lineage clear that this piece of information originates from IFC, in case there are multiple data sources. Our work indicates that having multiple use cases nowadays may require data integration from multiple sources, so choices such as this one regard that situation.

In order to support the localisation of the specification and reflect the use cases, we have also introduced new code lists that categorise possible values. For example, the building typology is in line with the categorisation in Singapore.

4.3. UML

Following the presented methodology and study, we have designed 14 classes containing 63 attributes, and 5 new code lists. The UML of the IfcADE is included in Figure 6, as an enhancement to features found in the Building and Construction modules of CityGML 3.0.

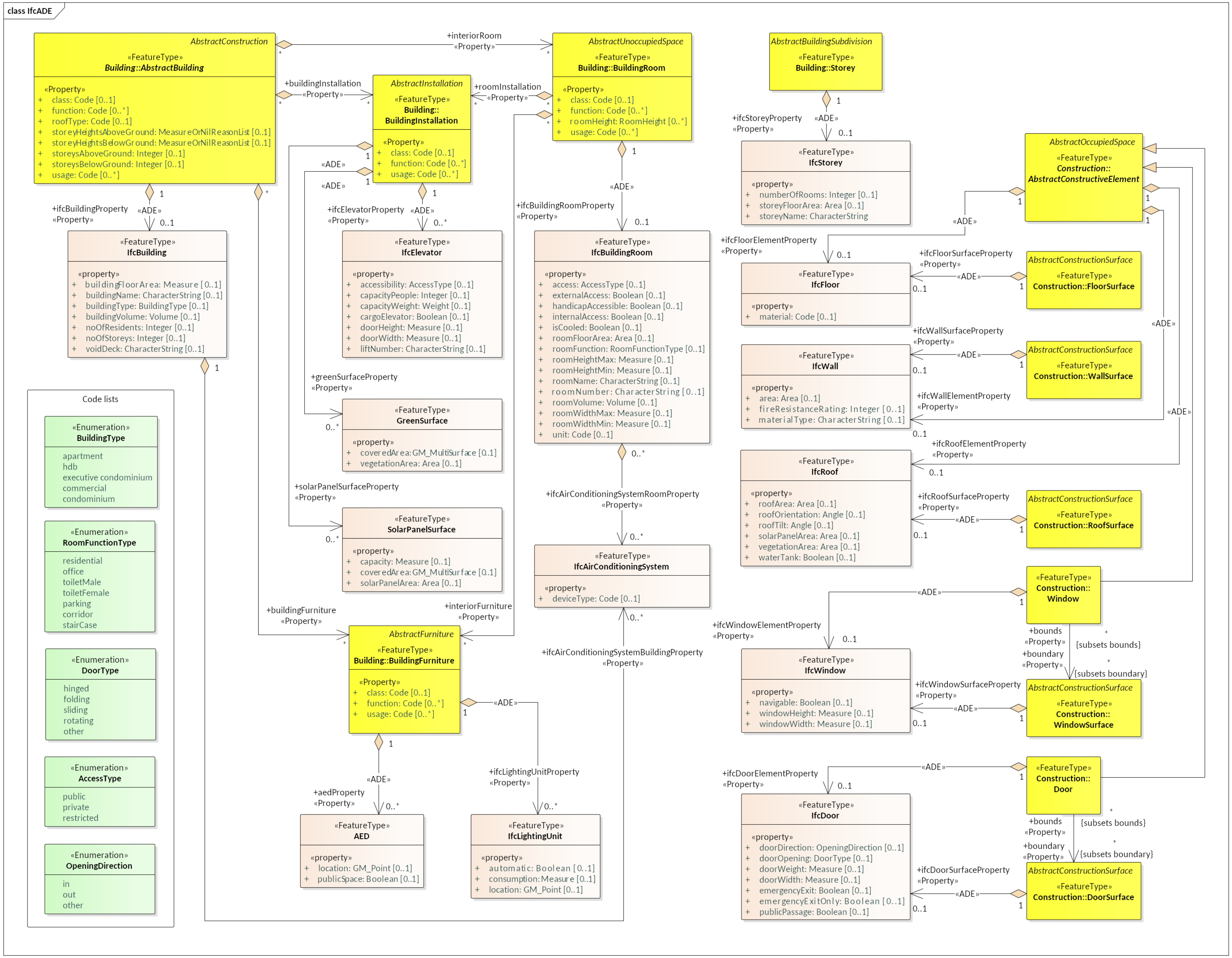


Figure 6: The UML diagram of the developed IfcADE (the added classes are in beige with the pertaining code lists in green), extending features from the standard CityGML Building and Construction modules (in yellow).

5. Implementation and demonstration

We have verified the feasibility of the ADE by generating (Section 5.1) and visualising (Section 5.2) an instance of the schema. Furthermore, while the focus of this paper is the design of the data model, and thus the implementation of use cases is out of scope, we also showcase an early demo of the use case of indoor navigation (Section 5.3) to give a better understanding of the benefit of the work.

5.1. Generation of the data

We have used the IFC dataset of a large non-residential building in Singapore (Figure 1), and converted it to CityGML with a selective conversion process that was designed to source the required information from IFC and output them to CityGML according to the developed ADE [4]. The following excerpt from an auto-generated instance of the ADE shows additional attributes for a building and a room, contained within the extended features `IfcBuilding` and `IfcBuildingRoom`, respectively:

```
<cityObjectMember>
  <bldg:Building gml:id="ifc-0
      PcOs3Gr9BD8TsNt7WYaK3">
      <ifc:ifcBuildingProperty>
        <ifc:IfcBuilding gml:id="gml-0
            PcOs3Gr9BD8TsNt7WYaK3">
          <ifc:noOfStoreys>11</ifc:noOfStoreys>
        </ifc:IfcBuilding>
      </ifc:ifcBuildingProperty>
      <bldg:buildingRoom>
        <bldg:BuildingRoom gml:id="ifc-3
            rdtWOORP9xx22XnTyVHz8">
          <ifc:ifcBuildingRoomProperty>
             <ifc:IfcBuildingRoom gml:id="gml-5
                 f069b48-09fe-4d69-bff0-1
                 ca8e5f445ec">
               <ifc:roomName>ANCILLARY OFFICE</
                   ifc:roomName>
               <ifc:roomHeightMin uom="m">3.6</
                   ifc:roomHeightMin>
               <ifc:roomNumber>133</ifc:
                   roomNumber>
               <ifc:roomHeightMax uom="m">3.6</
                   ifc:roomHeightMax>
               <gml:name>133</gml:name>
            </ifc:IfcBuildingRoom>
          </ifc:ifcBuildingRoomProperty>
          <gml:name>133</gml:name>
          <spaceType>closed</spaceType>
          <!-- GML geometry -->
        </bldg:BuildingRoom>
      </bldg:buildingRoom>
      <!-- ... -->
    </bldg:Building>
  </cityObjectMember>
</CityModel>
```

5.2. Visualisation of the generated dataset

As an ADE is an extended data model, most CityGML software packages either ignore or cannot handle these datasets containing features beyond the standard schema. We have visualised the dataset generated above in two ways: (i) in a cross-browser web-viewer customised to support the developed ADE [98] (Figure 7), and (ii) in the FME Data Inspector by loading the XSD representation of the ADE (Figure 8; this work doubles as a validation that the resulting ADE is properly developed). Both these examples reveal the additional features/attributes enabled by the ADE and show the same feature exemplified in the previous section.

5.3. Use case: indoor navigation

The utilisation of data in a use case and development of software enabling use cases is left as a separate topic for future work. However, in this section, we briefly give a sneak peek of the value the enriched data will enable in use cases. We have worked on the use case described in Section 4.1.3: indoor navigation, using a solution currently being developed by Ordnance Survey. Our ADE enables having room numbers and room names stored separately with less ambiguity (i.e. `roomNumber`; see Figure 6), and in this demo we have used these attributes, instead of storing them within the range of the standard data model.

However, because the software architecture of the indoor navigation system does not support CityGML, we had to convert the data to another format. This is not far from a real-world scenario, as CityGML is conceived as an exchange format, and it is not always intended to be used directly in a software. An example of routing between two rooms with a particular room number, using the same input IFC dataset as in the previous sections, is shown in Figure 9. While in this example we are not directly using CityGML because the software does not support it, the content of the resulting dataset is akin to the one we would obtain, containing additional features and resulting in the same outcome.

At this stage, we have developed the use case within a single building, and its extension to a larger scale (routing on the urban level between buildings) is a plan for future work. At the moment, this work is in progress giving here a sneak peek to suggest the implementation, and future work will also involve making use of other information such as wheelchair access.

6. Discussion, lessons learned, and limitations

6.1. Sourcing corresponding information from IFC

There are multiple points that need to be stressed when it comes to limitations of sourcing data from IFC.

First, the process of generating a dataset according to the ADE is inhibited by the availability of features in real-world IFC datasets. Conceptually the vast majority of the information required for this ADE and the use cases can be sourced from IFC. However, as it is the case with CityGML, IFC datasets in practice are not always rich with semantics, possibly leaving some required features unpopulated in practice.

Second, there might be a misclassification in the semantics (e.g. it is not always stored properly, preventing to take advantage of it), and different conventions on the spatio-semantic aspects may result in different interpretations during the production of the IFC-sourced CityGML datasets [36], which is also an issue on the geospatial end [99–101].

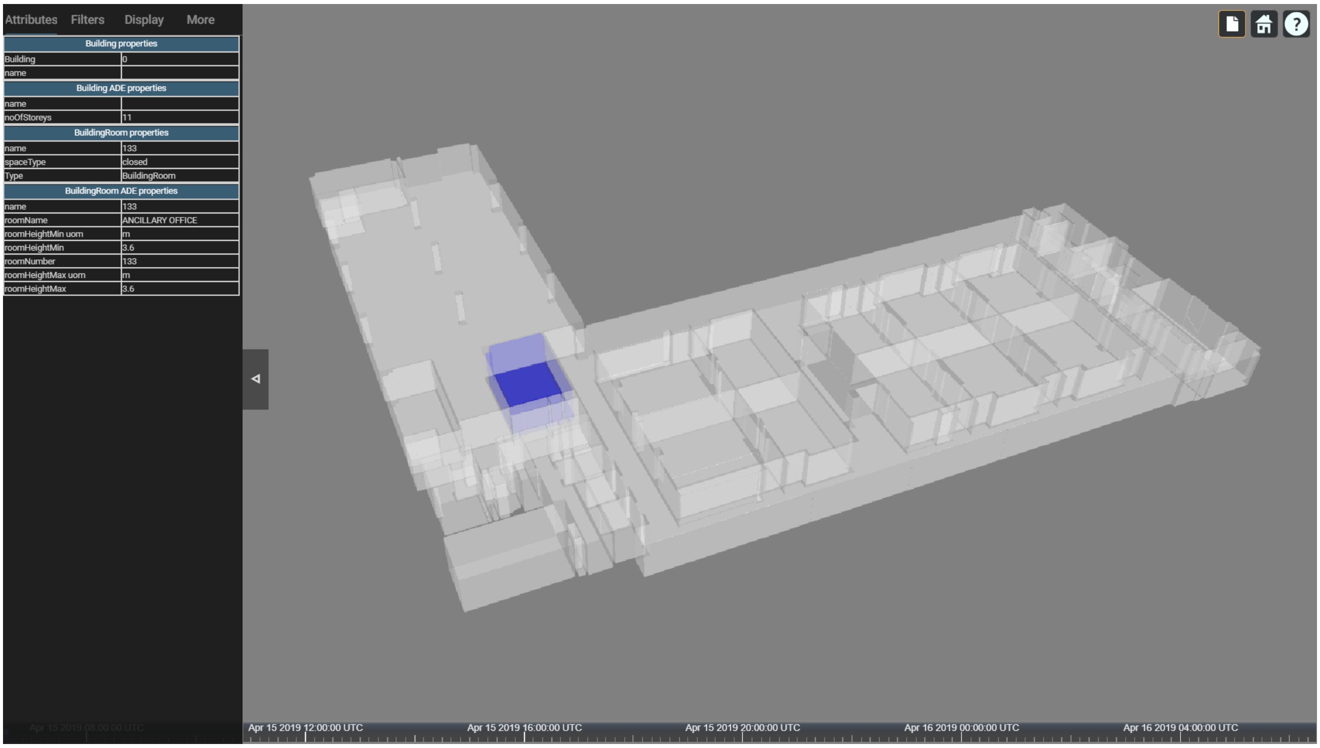


Figure 7: Viewing the generated file in a custom-built web-viewer [98]. The left side of the image shows the ADE attributes.

Third, many features cannot be mapped 1:1 from IFC. Some features should be acquired either manually or require substantial processing. For example, the number of storeys above ground of a building and its total height including basement: as straightforward as these appear to be, they are not explicitly available in the IFC model, and they might not always be trivial to compute, as IFC geometry can be complex to work with [102]. The building height is also subject to different interpretations [103, 104]. Therefore the availability of different features is highly dependent on the workflow/implementation. On the other hand, while the disadvantage of some of these attributes is that processing is required, after implementing such rules the availability of such features is virtually always warranted (e.g. it is always possible to calculate the floor area of a room, no additional semantic information is needed in the input IFC dataset).

It is a general information modelling question to trade-off defining a procedure to calculate a value against storing the calculation result explicitly in a data model. IFC allows both, with derived attributes to hold calculation procedures and base quantities to store values derived from geometry explicitly. Although the set of typical base quantities and included procedures may be reasonable for typical BIM use cases, specific requirements of geospatial use cases may not be covered.

Another challenge is the different structure of geometry and semantics between the two formats, entailing different interpretation on how to preserve certain features, rendering some portions of the work inevitably subjective. For example, a wall in IFC is represented in geometry and semantics differently than in CityGML.

Finally, there are limitations to the IfcADE because an analysis that requires specific information from IFC that has not been converted to CityGML + IfcADE will not be available.

6.2. Lack of compliant software and use case support

At the present time of the submission of this paper, version 3.0 of CityGML is under development and therefore at the moment there is not much software support for it. On top of that, one of the disadvantages of developing an ADE is that it is normally not supported by existing software. While we have thoroughly discussed use cases with different stakeholders and made an effort to tackle the implementation of the ADE, one of the limitations of the work is that it is difficult to realise the implementation of the ADE in use cases fully.

Much of the lessons learned in this research is related to use cases. It is often difficult to gather the specific requirements of a use case, inhibiting the development of a supporting data model. The problem boils down to one thing – software support, which is still lacking in 3D use cases. Such a limitation does not allow checking whether a series of use cases is served appropriately by a data model.

Software vendors often wait for the need to be expressed by their users before actually putting solutions in place within their software (along with the *chicken-and-egg* dilemma: whether there is a lack of software because there is no data, or there is no data because there is no software to work with it?). There-

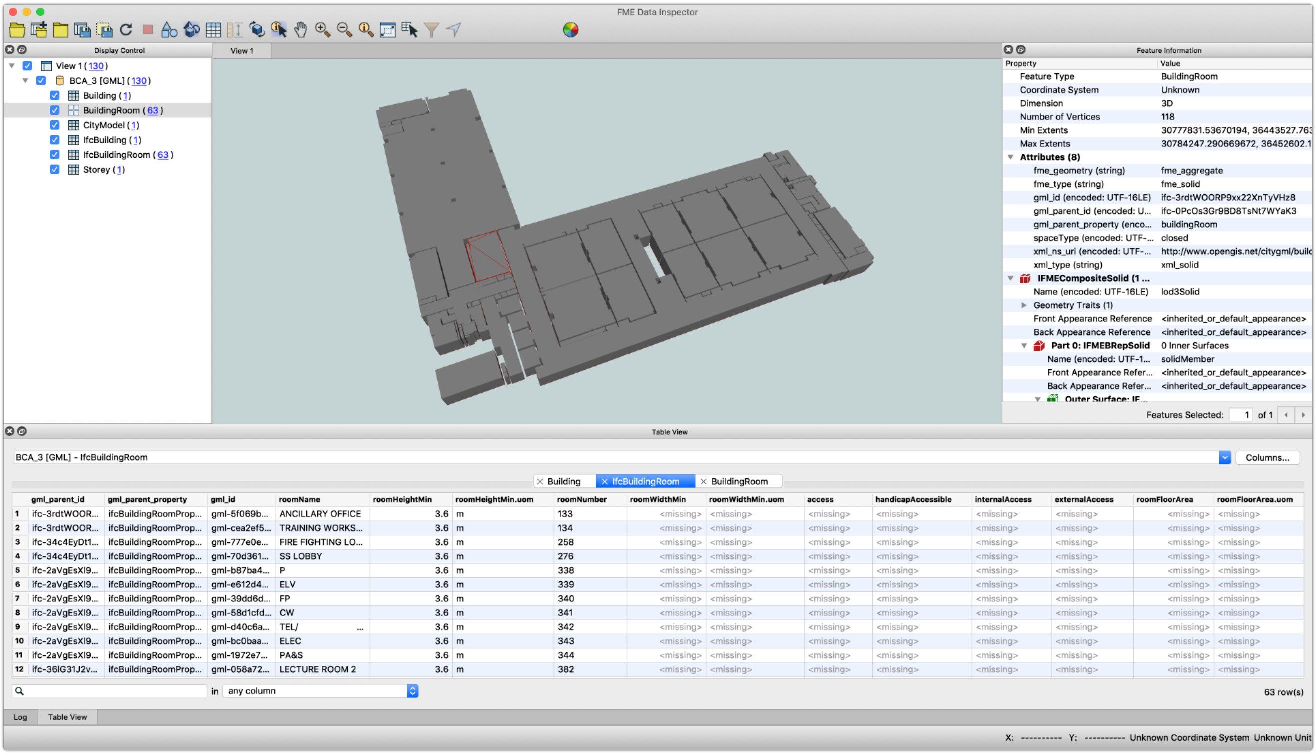


Figure 8: Viewing the generated file in the FME Data Inspector, revealing multiple room attributes enabled by the ADE (bottom panel).

fore, this shows there is a need for awareness being built for both users, stakeholders, and system suppliers in order to support datasets enriched with additional information.

Finally, as it is the case with developing data specifications, it is a challenge to balance simplicity and capacity. Tailoring and adding more features for particular use cases may add value and even enable additional applications, but at the same time it increases complexity and may discourage software developers to provide an implementation.

7. Conclusion

BIM datasets are promising to become a valuable source for 3D city models and their maintenance. Therefore it is important to adapt different aspects on the geospatial end, such as the development of enriched data models easing to bridge the two paradigms.

We have presented a cohesive CityGML ADE that is shaped after three orthogonal aspects: (i) regarding the input data and lineage (BIM/IFC); (ii) considering the local context (Singapore); and (iii) catering to multiple use cases (energy, urban planning, and navigation).

We described a rationale behind the development of an ADE, and stress on how we carried out a discovery process to reach the presented design supporting transfer of information between open 3D data standards IFC and CityGML. Therefore we believe that our work can be replicated elsewhere. Besides the investigation of use cases and the development of a specification, we implement the work rounding up the complete cycle: we (i) generated a dataset according to the developed specification; (ii) visualised the dataset with enhanced additions in two ways (desktop and web); and (iii) demonstrated the potential of using the dataset for a particular purpose: indoor context-aware routing highlighting the benefit of the enhanced tailored specification.

While forgoing the rich details from IFC is usually justified to maintain the generation of simple and lightweight 3D city models, we show that there is a benefit in keeping a certain subset of information and carrying it over to CityGML. The selection of such a subset was shaped after a detailed discovery process with stakeholders and analysing requirements of use cases. A byproduct contribution of our work is that we look into details in some practical use cases with real-world stakeholders and describe them.

While this is not the first ADE that was designed in a research project on BIM-GIS interoperability, it is in several ways a contribution, as the ADE offers support for a breadth of applications while not compromising simplicity, and the paper includes also topics uncommon in related work: it demonstrates an implementation, it describes use cases and the selection of features, and it reports usually undocumented deliberations — we carefully considered different modelling options, which we noted down and argued the pros/cons, potentially assisting fellow researchers with guidance in similar projects.

Although for a single application domain there may be a more suitable solution such as a dedicated standard, the advantage of the IfcADE is the range of applications that can

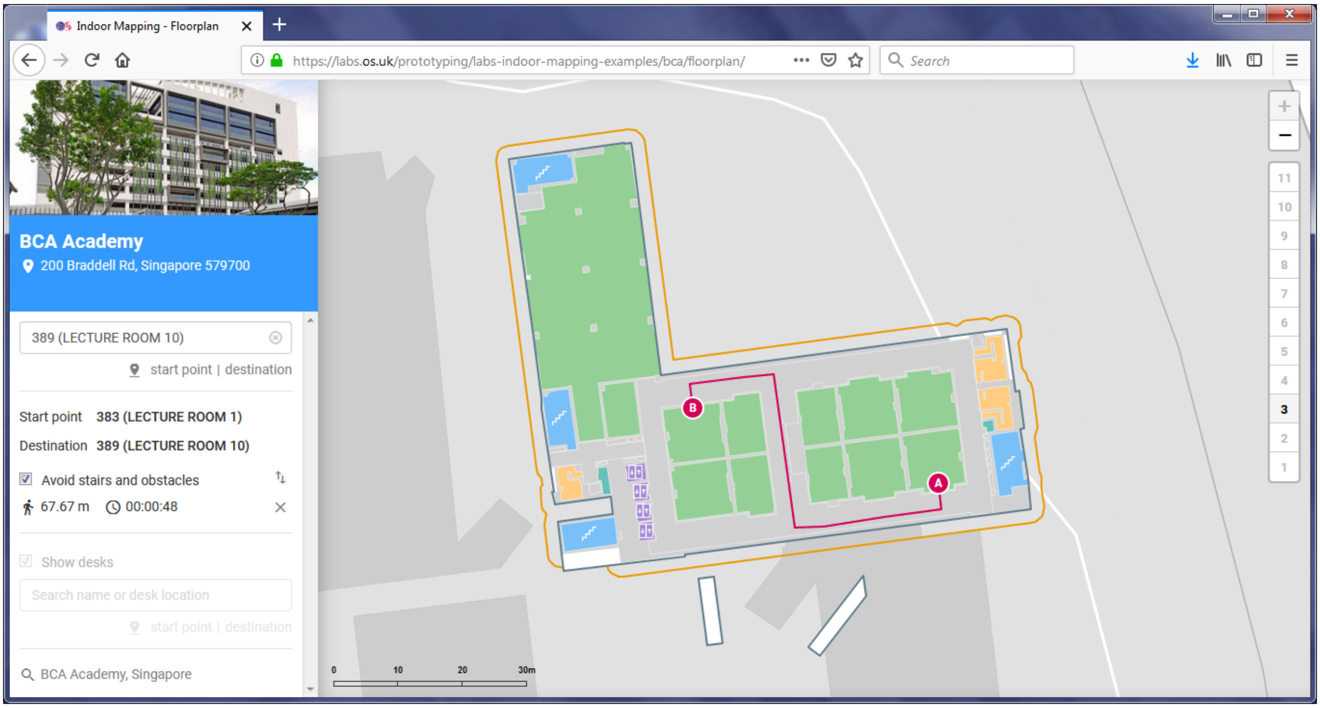


Figure 9: Implementation of indoor navigation making use of room numbers/names, as an example of additional attributes defined by our extension.

be supported while retaining the data in the same format.

As much as the extended data model pertains to specific use cases, some of the features may be considered rather generic and useful to multiple use cases. Therefore it might be beneficial to add some of these features in the standard CityGML data model, rather than having them in an ADE (e.g. information about the access of rooms). Vice-versa, the ADE has to be aligned to the final adopted version of the standard. After our ADE was designed, some of the attributes have been added to the data model, but we plan to wait for the adopted version of the standard and synchronise the two.

We deem this work mature, however, opportunities for future work are many as this ADE is intended to be a continuous development by stakeholders, following use case requirements, and developments related to software support and available datasets.

First, we plan to enhance the specification according to additional use cases. There are other use cases or applications that could be of interest in this particular geographic context to adapt the ADE to, such as outdoor thermal comfort [105], real estate valuation [70], mitigating noise [106], conforming to local standards assessing building performance [107], and aligning to 3D cadastre developments in Singapore [108]. In its present form, the developed ADE provides a well-founded basis for additional use cases because it potentially has an overlap with some of them, e.g. it already contains data on the material and other information that might be useful for managing cultural heritage [109, 110].

Second, a topic that would be interesting to pursue is the diverse selection of semantics according to different levels of detail of the indoor of 3D city models: there have been several research papers focusing on the topic which might be beneficial to align to [111–114, 67, 115]. In our implementation we did deal with two representations (Figure 1) and both support the ADE, but there is room for additional representations.

Third, a potential important research direction is the extension of other CityGML modules, such as transportation and vegetation. In this work, we have focused on buildings, as the most prominent topographic feature in our context. However, current and future use cases may also require other modules of CityGML. They are continuously subject to proposed extensions [116], and these developments will be important to follow in the context of smart cities and 3D data infrastructure.

Finally, we plan to investigate the translation of the extension to other data formats and encodings, such as CityJSON [117], potentially allowing more efficient utilisation of the datasets on the web.

Acknowledgements

We appreciate the building dataset provided by the Building and Construction Authority (Singapore). We gratefully acknowledge the input of Singapore Government agencies and their continuous communication and interest in our project: Singapore Land Authority, Government Technology Agency, Housing and Development Board, Building and Construction Authority, Urban Redevelopment Authority, and others. Suggestions and contact with Alex Babington, Tim Manners, Oliver Snowden, Tony Joyce, Jeremy Morley, and Carsten Roensdorf (Ordnance Survey), and Kavisha Kumar (TU Delft) are gratefully acknowledged. The comments of the reviewers are appreciated and improved the paper.

This material is based on research/work supported by the National Research Foundation under Virtual Singapore Award No. NRF2015VSG-AA3DCM001-008.

References

[1] X. Liu, X. Wang, G. Wright, J. Cheng, X. Li, R. Liu, A State-of-the-Art Review on the Integration of Building Information Modeling (BIM) and Geographic Information System (GIS), ISPRS International Journal of Geo-Information 6 (2) (2017) 53. doi:10.3390/ijgi6020053.

[2] F. Noardo, L. Harrie, K. Arroyo Ohori, F. Biljecki, C. Ellul, T. Krijnen, H. Eriksson, D. Guler, D. Hintz, M. A. Jadidi, M. Pla, S. Sanchez, V.-P. Soini, R. Stouffs, J. Tekavec, J. Stoter, Tools for BIM-GIS Integration (IFC Georeferencing and Conversions): Results from the GeoBIM Benchmark 2019, ISPRS International Journal of Geo-Information 9 (9) (2020) 502. doi:10.3390/ijgi9090502.

[3] H. Wang, Y. Pan, X. Luo, Integration of BIM and GIS in sustainable built environment: A review and bibliometric analysis, Automation in Construction 103 (2019) 41 – 52. doi:10.1016/j.autcon.2019.03.005.

[4] R. Stouffs, H. Tauscher, F. Biljecki, Achieving Complete and Near-Lossless Conversion from IFC to CityGML, ISPRS International Journal of Geo-Information 7 (9) (2018) 355. doi:10.3390/ijgi7090355.

[5] T. W. Kang, C. H. Hong, A study on software architecture for effective BIM/GIS-based facility management data integration, Automation in Construction 54 (2015) 25 – 38. doi:10.1016/j.autcon.2015.03.019.

[6] Y. Deng, J. C. P. Cheng, C. Anumba, A framework for 3D traffic noise mapping using data from BIM and GIS integration, Structure and Infrastructure Engineering 12 (10) (2016) 1267 – 1280. doi:10.1080/15732479.2015.1110603.

[7] buildingSMART, Industry foundation classes, Tech. Rep. Version 4, Addendum 2, buildingSMART International Limited (2016) [cited 15 August 2017].
URL http://www.buildingsmart-tech.org/ifc/IFC4/Add2/

[8] ISO, Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries (2013) [cited 13 April 2019].
URL https://www.iso.org/standard/70303.html

[9] Open Geospatial Consortium, OGC City Geography Markup Language (CityGML) Encoding Standard 2.0.0, Tech. rep. (2012) [cited 13 April 2019].
URL http://www.opengeospatial.org/standards/citygml

[10] G. Gröger, L. Plümer, CityGML – Interoperable semantic 3D city models, ISPRS Journal of Photogrammetry and Remote Sensing 71 (2012) 12 – 33. doi:10.1016/j.isprsjprs.2012.04.004.

[11] Z. Zhu, L. Zhou, C. Zhang, B. Lin, Y. Cui, M. Che, Modeling of Macroscopic Building Evacuation Using IFC Data, ISPRS International Journal of Geo-Information 7 (8) (2018) 302 – 25. doi:10.3390/ijgi7080302.

[12] Y. Chen, E. Shooraj, A. Rajabifard, S. Sabri, From IFC to 3D Tiles: An Integrated Open-Source Solution for Visualising BIMs on Cesium, ISPRS International Journal of Geo-Information 7 (10) (2018) 393. doi:10.3390/ijgi7100393.

[13] Y. Deng, V. J. L. Gan, M. Das, J. C. P. Cheng, C. Anumba, Integrating 4D BIM and GIS for Construction Supply Chain Management, Journal of Construction Engineering and Management 145 (4) (2019) 04019016. doi:10.1061/(asce)co.1943-7862.0001633.

[14] J. Stoter, H. Ploeger, R. Roes, E. van der Riet, F. Biljecki, H. Ledoux, D. Kok, S. Kim, Registration of Multi-Level Property Rights in 3D in The Netherlands: Two Cases and Next Steps in Further Implementation, ISPRS International Journal of Geo-Information 6 (6) (2017) 158. doi:10.3390/ijgi6060158.

[15] R. Southall, F. Biljecki, The VI-Suite: a set of environmental analysis tools with geospatial data applications, Open Geospatial Data, Software and Standards 2 (2017) 23. doi:10.1186/s40965-017-0036-1.

[16] T.-A. Teo, K.-H. Cho, BIM-oriented indoor network model for indoor and outdoor combined route planning, Advanced Engineering Informatics 30 (3) (2016) 268–282.

[17] U. Isikdag, S. Zlatanova, J. Underwood, A BIM-Oriented Model for supporting indoor navigation requirements, Computers, Environment and Urban Systems 41 (2013) 112 – 123. doi:10.1016/j.compenvurbsys.2013.05.001.

[18] H. Tashakkori, A. Rajabifard, M. Kalantari, A new 3D indoor/outdoor spatial model for indoor emergency response facilitation, Building and Environment 89 (2015) 170 – 182. doi:10.1016/j.buildenv.2015.02.036.

[19] H. Tauscher, R. Stouffs, An IFC-to-CityGML Triple Graph Grammar, in: eCAADe, Vol. 1, 2018, pp. 517 – 524 [cited 13 April 2019].
URL http://papers.cumincad.org/data/works/att/ecaade2018_265.pdf

[20] A. Konde, H. Tauscher, F. Biljecki, J. Crawford, Floor plans in CityGML, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. IV-4/W6 (2018) 25 – 32. doi:10.5194/isprs-annals-iv-4-w6-25-2018.

[21] J. Lim, H. Tauscher, F. Biljecki, Graph transformation rules for IFC-to-CityGML attribute conversion, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. IV-4/W8 (2019) 83 – 90. doi:10.5194/isprs-annals-iv-4-w8-83-2019.

[22] H. Tauscher, Creating and maintaining IFC–CityGML conversion rules, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. IV-4/W8 (2019) 115 – 122. doi:10.5194/isprs-annals-iv-4-w8-115-2019.

[23] Y. Song, X. Wang, Y. Tan, P. Wu, M. Sutrisna, J. Cheng, K. Hampson, Trends and Opportunities of BIM-GIS Integration in the Architecture, Engineering and Construction Industry: A Review from a Spatio-Temporal Statistical Perspective, ISPRS International Journal of Geo-Information 6 (12) (2017) 397. doi:10.3390/ijgi6120397.

[24] J. Zhu, X. Wang, P. Wang, Z. Wu, M. J. Kim, Integration of BIM and GIS: Geometry from IFC to shapefile using open-source technology, Automation in Construction 102 (2019) 105 – 119. doi:10.1016/j.autcon.2019.02.014.

[25] R. De Laat, L. Van Berlo, Integration of BIM and GIS: The Development of the CityGML GeoBIM Extension, Advances in 3D Geo-Information Sciences, Springer Berlin Heidelberg, 2011, pp. 211 – 225. doi:10.1007/978-3-642-12670-3_13.

[26] Y. Deng, J. C. P. Cheng, C. Anumba, Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison, Automation in Construction 67 (2016) 1 – 21. doi:10.1016/j.autcon.2016.03.006.

[27] S. Donkers, H. Ledoux, J. Zhao, J. Stoter, Automatic conversion of IFC datasets to geometrically and semantically correct CityGML LOD3 buildings, Transactions in GIS 20 (4) (2016) 547 – 569. doi:10.1111/tgis.12162.

[28] M. El-Mekawy, A. Östman, I. Hijazi, A Unified Building Model for 3D Urban GIS, ISPRS International Journal of Geo-Information 1 (3) (2012) 120 – 145. doi:10.3390/ijgi1020120.

[29] C. Ellul, G. Boyes, C. Thomson, D. Backes, Towards Integrating BIM and GIS—An End-to-End Example from Point Cloud to Analysis, Vol. 15 of Advances in 3D Geoinformation, 2017, pp. 495 – 512.

[30] A. Geiger, J. Benner, K. H. Haefele, Generalization of 3D IFC Building Models, 3D Geoinformation Science, Springer International Publishing, 2015, pp. 19 – 35. doi:10.1007/978-3-319-12181-9_2.

[31] I. Hijazi, M. Ehlers, S. Zlatanova, T. Becker, L. Van Berlo, Initial Investigations for Modeling Interior Utilities Within 3D Geo Context: Transforming IFC-Interior Utility to CityGML/UtilityNetworkADE, in: T. Kolbe, G. König, C. Nagel (Eds.), Advances in 3D Geo-Information Sciences, Springer, Berlin, Heidelberg, 2011, pp. 95 – 113. doi:10.1007/978-3-642-12670-3_6.

[32] U. Isikdag, S. Zlatanova, Towards Defining a Framework for Automatic Generation of Buildings in CityGML Using Building Information Models, in: J. Lee, S. Zlatanova (Eds.), 3D Geo-Information Sciences, Springer Berlin Heidelberg, 2009, pp. 79 – 96. doi:10.1007/978-3-540-87395-2_6.

[33] S. Jusuf, B. Mousseau, G. Godfroid, J. Soh, Path to an Integrated Modelling between IFC and CityGML for Neighborhood Scale Modelling, Urban Science 1 (3) (2017) 25. doi:10.3390/urbansci1030025.

[34] R. Sebastian, M. Böhms, P. van den Helm, BIM and GIS for low-disturbance construction, in: Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 2013, pp. 469 – 479 [cited 13 April 2019].
URL https://repository.tudelft.nl/view/tno/uuid:1ed10694-572f-433c-95be-f726c7704086

[35] T. Gilbert, S. Barr, P. James, J. Morley, Q. Ji, Software Systems Approach to Multi-Scale GIS-BIM Utility Infrastructure Network Integration and Resource Flow Simulation, ISPRS International Journal of Geo-Information 7 (8) (2018) 310. doi:10.3390/ijgi7080310.

[36] H. Tauscher, R. Stouffs, Extracting different spatio-semantic structures from IFC using a triple graph grammar, in: Intelligent and Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, 2019, pp. 605–614 [cited 13 April 2019].
URL http://papers.cumincad.org/data/works/att/caadria2019_038.pdf

[37] F. Biljecki, K. Kumar, C. Nagel, CityGML Application Domain Extension (ADE): overview of developments, Open Geospatial Data, Software and Standards 3 (1) (2018) 13. doi:10.1186/s40965-018-0055-6.

[38] L. Van den Brink, J. Stoter, S. Zlatanova, Modeling an application domain extension of CityGML in UML, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XXXVIII-4/C26 (2012) 11 – 14. doi:10.5194/isprsarchives-xxxviii-4-c26-11-2012.

[39] L. Van den Brink, J. Stoter, S. Zlatanova, UML-Based Approach to Developing a CityGML Application Domain Extension, Transactions in GIS 17 (6) (2013) 920 – 942. doi:10.1111/tgis.12026.

[40] A. Czerwinski, S. Sandmann, L. Elke, Stöümer, Sustainable SDI for EU noise mapping in NRW – best practice for INSPIRE, International Journal for Spatial Data Infrastructure Research 2 (1) (2007) 1 – 18.
URL http://www.ikg.uni-bonn.de/uploads/tx_ikgpublication/071105_EC_GI_GIS_fullpaper_Czerwinski.pdf

[41] V. Çağdaş, An Application Domain Extension to CityGML for immovable property taxation: A Turkish case study, International Journal of Applied Earth Observation and Geoinformation 21 (2013) 545 – 555. doi:10.1016/j.jag.2012.07.013.

[42] A. Labetski, K. Kumar, H. Ledoux, J. Stoter, A Metadata ADE for CityGML, Open Geospatial Data, Software and Standards 3 (1) (2018) 42. doi:10.1186/s40965-018-0057-4.

[43] L. Li, L. Tang, H. Zhu, H. Zhang, F. Yang, W. Qin, Semantic 3D Modeling Based on CityGML for Ancient Chinese-Style Architectural Roofs of Digital Heritage, ISPRS International Journal of Geo-Information 6 (5) (2017) 132. doi:10.3390/ijgi6050132.

[44] L. Van den Brink, J. Stoter, S. Zlatanova, Establishing a national standard for 3D topographic data compliant to CityGML, International Journal of Geographical Information Science 27 (1) (2013) 92 – 113. doi:10.1080/13658816.2012.667105.

[45] K. Kumar, H. Ledoux, J. Stoter, A CityGML extension for handling very large TINs, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. IV-2-W1 (2016) 137 – 143. doi:10.5194/isprs-annals-iv-2-w1-137-2016.

[46] L. Li, J. Wu, H. Zhu, X. Duan, F. Luo, 3D modeling of the ownership structure of condominium units, Computers, Environment and Urban Systems 59 (2016) 50 – 63. doi:10.1016/j.compenvurbsys.2016.05.004.

[47] Z. Yao, C. Nagel, F. Kunde, G. Hudra, P. Willkomm, A. Donaubauer, T. Adolphi, T. H. Kolbe, 3DCityDB - a 3D geodatabase solution for the management, analysis, and visualization of semantic 3D city models based on CityGML, Open Geospatial Data, Software and Standards 3 (1) (2018) 208. doi:10.1186/s40965-018-0046-7.

[48] H. Eriksson, T. Johansson, P.-O. Olsson, M. Andersson, J. Engvall, I. Hast, L. Harrie, Requirements, Development, and Evaluation of A National Building Standard—A Swedish Case Study, ISPRS International Journal of Geo-Information 9 (2) (2020) 78. doi:10.3390/ijgi9020078.

[49] S. A. Aydar, T. Yomralıoglu, E. D. Ozbek, Modeling Turkey National 2D Geo-Data Model as a CityGML Application Domain Extension in UML, International Journal of Environment and Geoinformatics 3 (3) (2016) 1 – 10 [cited 13 April 2019].
URL https://dergipark.org.tr/tr/download/article-file/294320

[50] O. G. Ling, T. T. Tan, The Social Significance of Public Spaces in Public Housing Estates, Public Space Design, Use and Management, NUS Press, 1992, pp. 69 – 81 [cited 13 April 2019].
URL http://www.worldcat.org/title/public-space-design-use-and-management/oclc/930609565

[51] K. Soon, V. Khoo, CityGML modelling for Singapore 3D national mapping, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-4/W7 (2017) 37 – 42. doi:10.5194/isprs-archives-xlii-4-w7-37-2017.

[52] L. Gobeawan, E. S. Lin, A. Tandon, A. T. K. Yee, V. Khoo, S. N. Teo, S. Yi, C. W. Lim, S. T. Wong, D. J. Wise, P. Cheng, S. C. Liew, X. Huang, Q. H. Li, L. S. Teo, G. S. Fekete, M. T. Poto, Modeling trees for Virtual Singapore: from data acquisition to CityGML models, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-4/W10 (2018) 55 – 62. doi:10.5194/isprs-archives-xlii-4-w10-55-2018.

[53] R. Van Son, S. Jaw, J. Yan, V. Khoo, R. Loo, S. Teo, G. Schrotter, A framework for reliable three-dimensional underground utility mapping for urban planning, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-4/W10 (2018) 209 – 214. doi:10.5194/isprs-archives-xlii-4-w10-209-2018.

[54] J. Yan, S. Jaw, R. Van Son, K. Soon, G. Schrotter, Three-dimensional data modelling for underground utility network mapping, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-4 (2018) 711 – 715. doi:10.5194/isprs-archives-xlii-4-711-2018.

[55] S. Ho, A. Rajabifard, Towards 3D-enabled urban land administration: Strategic lessons from the BIM initiative in Singapore, Land Use Policy 57 (2016) 1 – 10. doi:10.1016/j.landusepol.2016.05.011.

[56] T. Kutzner, I. Hijazi, T. H. Kolbe, Semantic Modelling of 3D Multi-Utility Networks for Urban Analyses and Simulations, International Journal of 3-D Information Modeling 7 (2) (2018) 1 – 34. doi:10.4018/ij3dim.2018040101.

[57] K. Wong, C. Ellul, User requirements gathering for a national 3D mapping product in the United Kingdom, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. IV-4/W6 (2018) 89 – 96. doi:10.5194/isprs-annals-iv-4-w6-89-2018.

[58] G. Agugiaro, J. Benner, P. Cipriano, R. Nouvel, The Energy Applica-

tion Domain Extension for CityGML: enhancing interoperability for urban energy simulations, Open Geospatial Data, Software and Standards 3 (1) (2018) 139. doi:10.1186/s40965-018-0042-y.

[59] I. Prieto, J. L. Izkara, F. J. D. d. Hoyo, Efficient Visualization of the Geometric Information of CityGML: Application for the Documentation of Built Heritage, Vol. 7333 of Computational Science and Its Applications – ICCSA 2012, 2012, pp. 529 – 544.

[60] K. Chaturvedi, Z. Yao, T. H. Kolbe, Integrated management and visualization of static and dynamic properties of semantic 3D city models, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-4/W17 (2019) 7 – 14. doi:10.5194/isprs-archives-xlii-4-w17-7-2019.

[61] P. O. Olsson, T. Johansson, H. Eriksson, T. Lithén, L. H. Bengtsson, J. Axelsson, U. Roos, K. Neland, B. Rydén, L. Harrie, Unbroken digital data flow in the built environment process – a case study in Sweden, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-2/W13 (2019) 1347 – 1352. doi:10.5194/isprs-archives-xlii-2-w13-1347-2019.

[62] L. Knoth, J. Scholz, J. Strobl, M. Mittlböck, B. Vockner, C. Atzl, A. Rajabifard, B. Atazadeh, Cross-Domain Building Models—A Step towards Interoperability, ISPRS International Journal of Geo-Information 7 (9) (2018) 363. doi:10.3390/ijgi7090363.

[63] K. Kumar, H. Ledoux, T. J. F. Commandeur, J. E. Stoter, Modelling urban noise in CityGML ADE: case of the Netherlands, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. IV-4-W5 (2017) 73 – 81. doi:10.5194/isprs-annals-iv-4-w5-73-2017.

[64] L. L. o. Scholtenhuis, X. d. Duijn, S. Zlatanova, Representing geographical uncertainties of utility location data in 3D, Automation in Construction 96 (2018) 483 – 493. doi:10.1016/j.autcon.2018.09.012.

[65] Open IFC Model Repository, House Sr. Dubal Herrera (Publishable under cc-by-3.0 licence) (2018).
URL http://openifcmodel.cs.auckland.ac.nz/Model/Details/314

[66] T. Kutzner, T. H. Kolbe, CityGML 3.0: Sneak Preview, in: 38. Wissenschaftlich-Technische Jahrestagung der DGPF und PFGK18 Tagung in München—- Publikationen der DGPF, Vol. 27, 2018, pp. 835 – 839.

[67] M. O. Löwner, G. Gröger, J. Benner, F. Biljecki, C. Nagel, Proposal for a new LOD and multi-representation concept for CityGML, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. IV-2/W1 (2016) 3 – 12. doi:10.5194/isprs-annals-iv-2-w1-3-2016.

[68] T. Kutzner, K. Chaturvedi, T. H. Kolbe, CityGML 3.0: New Functions Open Up New Applications, PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science (2020) 1 – 19doi:10.1007/s41064-020-00095-z.

[69] P. P. Yang, S. Y. Putra, W. Li, Viewsphere: a GIS-based 3D visibility analysis for urban design evaluation, Environment and Planning B: Planning and Design 34 (6) (2007) 971–992. doi:10.1068/b32142.

[70] S.-M. Yu, S.-S. Han, C.-H. Chai, Modeling the value of view in high-rise apartments: a 3D GIS approach, Environment and Planning B: Planning and Design 34 (1) (2007) 139 – 153. doi:10.1068/b32116.

[71] S. Paiho, J. Ketomäki, L. Kannari, T. Häkkinen, J. Shemeikka, A new procedure for assessing the energy-efficient refurbishment of buildings on district scale, Sustainable Cities and Society (2019) 101454doi:10.1016/j.scs.2019.101454.

[72] Y. Chen, T. Hong, X. Luo, B. Hooper, Development of city buildings dataset for urban building energy modeling, Energy and Buildings 183 (2019) 252 – 265. doi:10.1016/j.enbuild.2018.11.008.

[73] S. M. Murshed, S. Picard, A. Koch, Modelling, Validation and Quantification of Climate and Other Sensitivities of Building Energy Model on 3D City Models, ISPRS International Journal of Geo-Information 7 (11) (2018) 447 – 22. doi:10.3390/ijgi7110447.

[74] M. Bizjak, B. Žalik, G. Štumberger, N. Lukač, Estimation and optimisation of buildings' thermal load using LiDAR data, Building and Environment 128 (2018) 12 – 21. doi:10.1016/j.buildenv.2017.11.016.

[75] A. Salvo, Electrical appliances moderate households' water demand response to heat., Nature communications 9 (1) (2018) 5408. doi:10.1038/s41467-018-07833-3.

[76] T. Agius, S. Sabri, M. Kalantari, Three-Dimensional Rule-Based City Modelling to Support Urban Redevelopment Process, ISPRS International Journal of Geo-Information 7 (10) (2018) 413. doi:10.3390/ijgi7100413.

[77] G. Herbert, X. Chen, A comparison of usefulness of 2D and 3D representations of urban planning, Cartography and Geographic Information Science 42 (1) (2015) 22 – 32. doi:10.1080/15230406.2014.987694.

[78] M. Ranzinger, G. Gleixner, GIS datasets for 3D urban planning, Computers, Environment and Urban Systems 21 (2) (1997) 159 – 173. doi:10.1016/S0198-9715(97)10005-9.

[79] R. Trubka, S. Glackin, O. Lade, C. Pettit, A web-based 3D visualisation and assessment system for urban precinct scenario modelling, ISPRS Journal of Photogrammetry and Remote Sensing 117 (2016) 175 – 186. doi:10.1016/j.isprsjprs.2015.12.003.

[80] M. Brasebin, J. Perret, S. Mustiere, C. Weber, 3D urban data to assess local urban regulation influence, Computers, Environment and Urban Systems 68 (2018) 37 – 52. doi:10.1016/j.compenvurbsys.2017.10.002.

[81] F. C. Ahmed, S. P. Sekar, Using Three-Dimensional Volumetric Analysis in Everyday Urban Planning Processes, Applied Spatial Analysis and Policy 8 (4) (2015) 393 – 408. doi:10.1007/s12061-014-9122-2.

[82] K. W. Chen, L. Norford, Evaluating Urban Forms for Comparison Studies in the Massing Design Stage, Sustainability 9 (6) (2017) 987. doi:10.3390/su9060987.

[83] A. Koltsova, B. Tunçer, G. Schmitt, Visibility Analysis for 3D Urban Environments, Proceedings of the 31st International Conference on Education and research in Computer Aided Architectural Design in Europe, 2013, pp. 375 – 384.

[84] S. Yu, B. Yu, W. Song, B. Wu, J. Zhou, Y. Huang, J. Wu, F. Zhao, W. Mao, View-based greenery: A three-dimensional assessment of city buildings' green visibility using Floor Green View Index, Landscape and Urban Planning 152 (2016) 13 – 26. doi:10.1016/j.landurbplan.2016.04.004.

[85] J. Chen, K. C. Clarke, Indoor cartography, Cartography and Geographic Information Science 1 (114) (2019) 1 – 15. doi:10.1080/15230406.2019.1619482.

[86] K.-J. Li, G. Conti, E. Konstantinidis, S. Zlatanova, P. Bamidis, OGC IndoorGML: A Standard Approach for Indoor Maps, in: Geographical and Fingerprinting Data to Create Systems for Indoor Positioning and Indoor/Outdoor Navigation, Elsevier, 2019, pp. 187–207. doi:10.1016/B978-0-12-813189-3.00010-1.

[87] C. Nagel, Spatio-semantic modelling of indoor environments for indoor navigation, Ph.D. thesis, TU Berlin (2014).
URL https://www.dgk.badw.de/fileadmin/user_upload/Files/DGK/docs/c-727.pdf

[88] A. A. Khan, Constraints and concepts for the support of different locomotion types in indoor navigation, Ph.D. thesis, Technische Universität München, München (2015).
URL https://mediatum.ub.tum.de/?id=1233285

[89] A. Vanclooster, N. V. d. Weghe, P. D. Maeyer, Integrating Indoor and Outdoor Spaces for Pedestrian Navigation Guidance: A Review, Transactions in GIS 20 (4) (2016) 491 – 525. doi:10.1111/tgis.12178.

[90] M.-P. Kwan, J. Lee, Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments, Computers, Environment and Urban Systems 29 (2) (2005) 93 – 113. doi:10.1016/j.compenvurbsys.2003.08.002.

[91] L. Liu, S. Zlatanova, A "door-to-door" Path-Finding Approach

for Indoor Navigation, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. II-4 (2011) 45 – 51. doi:10.5194/isprsannals-ii-4-45-2014.

[92] K. Kim, J. P. Wilson, Planning and visualising 3D routes for indoor and outdoor spaces using CityEngine, Journal of Spatial Science 60 (1) (2014) 179 – 193. doi:10.1080/14498596.2014.911126.

[93] J.-C. Thill, T. H. D. Dao, Y. Zhou, Traveling in the three-dimensional city: applications in route planning, accessibility assessment, location analysis and beyond, Journal of Transport Geography 19 (3) (2011) 405 – 421. doi:10.1016/j.jtrangeo.2010.11.007.

[94] B. Elias, Pedestrian Navigation - Creating a tailored geodatabase for routing, 2007 4th Workshop on Positioning, Navigation and Communication, 2007, pp. 41 – 47. doi:10.1109/wpnc.2007.353611.

[95] J. Lee, A Three-Dimensional Navigable Data Model to Support Emergency Response in Microspatial Built-Environments, Annals of the Association of American Geographers 97 (3) (2007) 512 – 529. doi:10.1111/j.1467-8306.2007.00561.x.

[96] M. Aleksandrov, C. Cheng, A. Rajabifard, M. Kalantari, Modelling and finding optimal evacuation strategy for tall buildings, Safety Science 115 (2019) 247 – 255. doi:10.1016/j.ssci.2019.02.017.

[97] A. A. Diakité, S. Zlatanova, K. J. Li, About the subdivision of indoor spaces in IndoorGML, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. IV-4/W5 (2017) 41 – 48. doi:10.5194/isprs-annals-iv-4-w5-41-2017.

[98] J. Lim, P. Janssen, F. Biljecki, Visualising detailed CityGML and ADE at the building scale, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLIV-4/W1-2020 (2020) 83–90. doi:10.5194/isprs-archives-xliv-4-w1-2020-83-2020.

[99] G. S. Floros, C. Ellul, E. Dimopoulou, Investigating interoperability capabilities between IFC and CityGML LOD 4 – retaining semantic information, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-4/W10 (2018) 33 – 40. doi:10.5194/isprs-archives-xlii-4-w10-33-2018.

[100] H. Eriksson, L. Harrie, J. M. Paasch, What is the need for building parts? – A comparison of CityGML, INSPIRE Building and a Swedish building standard, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-4/W10 (2018) 27 – 32. doi:10.5194/isprs-archives-xlii-4-w10-27-2018.

[101] K. Arroyo Ohori, F. Biljecki, A. Diakité, T. Krijnen, H. Ledoux, J. Stoter, Towards an integration of GIS and BIM data: what are the geometric and topological issues?, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. IV-4-W5 (2017) 1 – 8. doi:10.5194/isprs-annals-iv-4-w5-1-2017.

[102] K. Arroyo Ohori, A. Diakité, T. Krijnen, H. Ledoux, J. Stoter, Processing BIM and GIS Models in Practice: Experiences and Recommendations from a GeoBIM Project in The Netherlands, ISPRS International Journal of Geo-Information 7 (8) (2018) 311. doi:10.3390/ijgi7080311.

[103] F. Biljecki, H. Ledoux, J. Stoter, G. Vosselman, The variants of an LOD of a 3D building model and their influence on spatial analyses, ISPRS Journal of Photogrammetry and Remote Sensing 116 (2016) 42 – 54. doi:10.1016/j.isprsjprs.2016.03.003.

[104] INSPIRE Thematic Working Group on Buildings, D2.8.III.2 INSPIRE Data Specification on Buildings – Technical Guidelines, Tech. rep. (2013) [cited 13 April 2019].
URL https://inspire.ec.europa.eu/id/document/tg/bu

[105] N. Nazarian, T. Sin, L. Norford, Numerical modeling of outdoor thermal comfort in 3D, Urban Climate 26 (2018) 212 – 230. doi:10.1016/j.uclim.2018.09.001.

[106] W.-J. Zhao, E.-X. Liu, H. J. Poh, B. Wang, S.-P. Gao, C. E. Png, K. W. Li, S. H. Chong, 3D traffic noise mapping using unstructured surface mesh representation of buildings and roads, Applied Acoustics 127 (2017) 297 – 304. doi:10.1016/j.apacoust.2017.06.025.

[107] R. Bozovic-Stamenovic, N. Kishnani, B. K. Tan, D. Prasad, F. Faizal, Assessment of awareness of Green Mark (GM) rating tool by occupants of GM buildings and general public, Energy and Buildings 115 (2016) 55 – 62. doi:10.1016/j.enbuild.2015.01.003.

[108] J. Stoter, S. Ho, F. Biljecki, Considerations for a contemporary 3D cadastre for our times, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-4/W15 (2019) 81 – 88. doi:10.5194/isprs-archives-xlii-4-w15-81-2019.

[109] R. Yaagoubi, A. Al-Gilani, A. Baik, E. Alhomodi, Y. Miky, SEH-SDB: a semantically enriched historical spatial database for documentation and preservation of monumental heritage based on CityGML, Applied Geomatics 1 (5) (2018) 41. doi:10.1007/s12518-018-0238-y.

[110] E. Colucci, V. D. Ruvo, A. Lingua, F. Matrone, G. Rizzo, HBIM-GIS Integration: From IFC to CityGML Standard for Damaged Cultural Heritage in a Multiscale 3D GIS, Applied Sciences 10 (4) (2020) 1356 – 20. doi:10.3390/app10041356.

[111] R. Boeters, K. Arroyo Ohori, F. Biljecki, S. Zlatanova, Automatically enhancing CityGML LOD2 models with a corresponding indoor geometry, International Journal of Geographical Information Science 29 (12) (2015) 2248 – 2268. doi:10.1080/13658816.2015.1072201.

[112] B. Hagedorn, M. Trapp, T. Glander, J. Döllner, Towards an Indoor Level-of-Detail Model for Route Visualization, 10th International Conference on Mobile Data Management: Systems, Services and Middleware, 2009, pp. 692 – 697. doi:10.1109/mdm.2009.118.

[113] S. Kemec, S. Zlatanova, S. Duzgun, A new LoD definition hierarchy for 3D city models used for natural disaster risk communication tool, Proceedings of the 4th International Conference on Cartography GIS, 2012, pp. 95 – 104.

[114] H.-Y. Kang, J. Lee, A Study on the LOD(Level of Detail) Model for Applications based on Indoor Space Data, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography 32 (2) (2014) 143 – 151. doi:10.7848/ksgpc.2014.32.2.143.

[115] L. Tang, L. Li, S. Ying, Y. Lei, A Full Level-of-Detail Specification for 3D Building Models Combining Indoor and Outdoor Scenes, ISPRS International Journal of Geo-Information 7 (11) (2018) 419 – 20. doi:10.3390/ijgi7110419.

[116] A. Labetski, S. v. Gerwen, G. Tamminga, H. Ledoux, J. Stoter, A proposal for an improved transportation model in CityGML, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-4/W10 (2018) 89 – 96. doi:10.5194/isprs-archives-xlii-4-w10-89-2018.

[117] H. Ledoux, K. Arroyo Ohori, K. Kumar, B. Dukai, A. Labetski, S. Vitalis, CityJSON: A compact and easy-to-use encoding of the CityGML data model, Open Geospatial Data, Software and Standards 4 (2019) 4. doi:10.1186/s40965-019-0064-0.