A Data Model for Integrating GIS and BIM for Assessment and 3D Visualisation of Flood Damage to Building

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Abstract

Flood Damage Assessment (FDA) is a key component in modern risk management frameworks providing an effective basis for decision making and the treatment of the risks. Current FDA methods do not consider the distinctiveness of buildings in analysis and therefore, cannot analyse them on a case-by-case basis, which is necessary for a variety of applications like engineering and design evaluation. This is mainly due to the limited input data used in these methods. The information required for such micro-level FDA analysis includes on one hand, complete building information (well-represented in BIM) and on the other hand, flood information that is commonly managed by GIS. While the independent use of BIM and GIS cannot satisfy all the information requirements for detailed FDA, their integration can potentially be used for this purpose. However, existing integration methods are application-specific and their adoption for FDA is challenging. This paper presents a method for BIM-GIS integration to support the requirements of a detailed assessment and 3D visualisation of flood damage to buildings. The data modelling cycle was used to design a new data model as a profile of GML for this purpose. The model was evaluated using a case study and found effective to satisfy the required criteria for micro-level FDA.

1 Introduction

It has been recognised in the past decade that a management of flood risks which focuses solely on the hazard is not effective (Birkmann et al., 2013). Therefore, risk-based flood management commonly employs Flood Damage Assessment (FDA) to evaluate the potential consequences of flood in the identification of risks and decisions for their treatment (Thieken et al., 2005).

Efforts in the field of FDA have resulted in development of a variety of FDA methods to serve different applications at different spatial scales (i.e. Macro, Meso and Micro) such as risk mapping, vulnerability assessment or financial appraisal of damage. Within this context, a strong emphasis is made on buildings due to their significant economic importance (Messner et al., 2007). The internationally accepted standard method for FDA is the use of "damage curves" (Merz et al., 2010). Damage in this method is calculated using generalisation of buildings into classes (based on a few of their general characteristics like construction type or age) and applying a predefined curve (or function) to relate the damage level commonly to a single flood parameter, the inundation depth. While

In: B. Veenendaal and A. Kealy (Eds.): Research@Locate'15, Brisbane, Australia, 10-12 March 2015, published at http://ceur-ws.org

the effectiveness of the existing FDA approaches is confirmed for large scale applications investigating a large population of buildings (Messner et al., 2007), they are however found unfit for micro level applications (e.g. building design evaluation against flood) where a case-by-case assessment of the flood impacts on individual buildings is required (Pistrika and Jonkman, 2010). This is mainly because of the inability of these methods for capturing and use of a complete representation of the building in the assessment, due to their limited input data (Merz et al., 2010). In this way, uniqueness and distinct behaviour of building against the flood is not included in the analysis of damage. In addition, the outputs provided by these methods are limited to a single number for the overall building damage cost or only an indication of whether the building collapses or not for certain level of water and velocity. Other than these, no further information about the details and the location of damage at the building level is provisioned. Such details are important to reveal the sources of risk for a building for their treatment.

An effective case-by-case analysis of damage to a building at micro level requires the use of two sets of information: the flood parameters (e.g. depth and velocity) causing damage to the building components; and the building components that resist against the flood impacts and are unique to each building (Pistrika and Jonkman, 2010). Geographic Information Systems (GIS) are the key information management tools for the first set with a long history of use in this area. The major strength of GIS is on representation of outdoor and large scale features. However, even with the considerations of the recent efforts for 3D modelling of the details of the buildings in 3D city models (e.g. CityGML), the geospatial domain is still found inadequate for a complete representation of the semantic and geometric aspects of the building and therefore limited for the second set (Zhang et al., 2009). In contrast to GIS, Building Information Models (BIM) from the construction industry provides a comprehensive digital repository of building information. While the strength of BIM lies in the complete representation of every aspect of a building (e.g. geometry, materials and connections), it is restricted to small scale at a building level and currently cannot store geographically extended features like flood.

The independent adoption of BIM or GIS for a micro level FDA would be inadequate to support the information requirements for this application. However, their combination provides the potential to accommodate these requirements under one umbrella to serve the analysis and presentation of the damage to the building (Isikdag and Zlatanova, 2009a). For the overall benefit of integrating BIM with GIS for different applications, numerous efforts were made towards its realisation. These works however, are limited to either (a) addressing the underlying technical integration challenges by one or two-directional geometry or semantic conversion between the two at building level or (b) serving a specific use case (e.g. indoor-outdoor utility management or emergency response) with focus of the integration on the minimum requirements to satisfy the needs of that application. The specific focus of these works limits their adoptability and use for FDA and therefore there is a need for a solution for integration of BIM with GIS for this purpose.

In this paper, a method for combining the BIM and GIS at the data level is proposed to serve the information needs for a micro level assessment and 3D visualisation of potential building damage from floods. It is hypothesised that the use of this method can facilitate an information system to harness the combined strength of the BIM and 3D GIS, allowing for a case-by-case analysis of the building damage by the implementation of certain analysis types at a level of detail that the existing FDA methods are not sensitive towards. The outputs produced by such analyses can facilitate decision making by a range of stakeholders such as engineering and design firms, councils and insurance companies for improving the resilience of the community towards floods and their adverse impacts.

In the remainder of this paper, first, the research background as well as an overview of the related work for the integration of BIM with GIS is provided. Next, the design of the proposed integration method and its details are presented. Further, a demonstration of the integration using a case study is illustrated and the results are discussed. Finally, the paper is concluded and the future research directions are proposed.

2 Background and Related Work

2.1 Building Information Model

BIM is a rich and intelligent digital repository of building information and uses an Object Oriented (OO) approach to describe the characteristics (semantics and geometry) and behaviour of each building element as well as its relationships with others (Eastman et al., 2011). BIM uses Industry Foundation Classes (IFC) as its open standard to establish interoperability in the construction industry. Within the IFC framework, building, its components as well as other relevant construction industry data are described within a single information model enabling the management of such information throughout the lifecycle of a building/facility. Although BIM has a variety of applications and has been previously used for damage assessment for other hazards like fire and earthquake (e.g. Christodoulou et al., 2010), yet, it has not been considered for the case of FDA.

2.2 Geographic Information System (GIS)

GIS, on the other hand, is a platform for managing and presenting spatially referenced information. Within this domain, the exchange of geospatial data and the interoperability between systems are established using the Geographic Markup Language (GML). GML is an Open Geospatial Consortium (OGC) standard data model for defining the data types and constructs for describing the geographic features. With a more specific focus, the heterogeneous geospatial information about urban data (e.g. buildings, transport, vegetation and water bodies) at different levels of details is integrated within the framework of the 3D virtual city models such as CityGML (Dollner et al., 2006). CityGML is the most comprehensive urban information model within the geospatial domain to digitally represent a city in 3D. The building information in CityGML (and other existing GIS formats) however, is not as complete and mature as BIM and for this reason, multiple extensions (e.g. utility network in Hijazi et al., 2010) have been created separately over the past years to improve the model. CityGML and some of its extensions have considered flood depth (as a water body), however, they were solely used for 3D visualisation of the flood (Schulte and Coors, 2009) and did not include its other parameters (e.g. velocity) and temporal dynamics. These, in addition to the other limitations of CityGML to represent the building details, prevent its effective use for serving the requirements of the micro-level FDA.

2.3 BIM-GIS Integration

GIS and BIM originate from different domains and were developed for the specific needs of that field. Their integration creates a seamless and scale-independent view of the world across both domains. It can benefit a variety of applications that meeting their requirements would not be possible by independent use of BIM or GIS (Karimi and Akinci, 2010). This integration however is not simple due to the differences between the two. Such dissimilarities are discussed in terms of spatial scale, level of granularity, geometry representation methods, storage and access methods as well as semantic mismatches between them (Isikdag and Zlatanova, 2009b; Karimi and Akinci, 2010; El-Mekawy and Ostman, 2010).

Various attempts have been made for integrating BIM with GIS that can generally be classified into three groups: at *application, process,* and *data* levels.

At the application level, the integration methods use *reconfiguring* or *rebuilding* (Karimi and Akinci, 2010) where an existing GIS or BIM tool is either modified by software patches or is rebuilt from scratch to include the functions of the other. This method is generally costly and inflexible. On the other hand, process level integration methods like OWS-4 project by OGC (2007) use Service Oriented Architecture (SOA) to allow the participation of BIM and GIS systems in those tasks that require the capabilities of both while they simultaneously remain live and distinct. This method provides more flexibility than the first group. However, in this method, the challenges of integration are still to be resolved at the underlying data level to provide interoperability between these systems.

There are a variety of methods developed to integrate BIM with GIS at the data level. *Linking* methods such as ESRI ArcSDE facilitates data transfer between BIM and GIS software by an Application Programming Interface (API) at either side. *Translation/Conversion* methods such as FME (Safe, 2013) and the work by Nagel et al. (2009), on the other hand, were introduced to directly convert between GIS and BIM formats. This method commonly translates the data between IFC and CityGML. Loss of semantics, limitations in geometric conversion and sole focus on the major building elements and neglecting the other aspects (e.g. utilities or connections) are some of the concerns associated with these methods. To resolve the geometry transformation problem, a number of research (e.g. Li et al., 2006; Wu et al., 2010) was conducted which only partially addresses the overall integration.

In the more comprehensive and flexible integration methods, either a new data model as a "meta model" is developed to mediate between BIM and geospatial information at higher level; or a data model at GIS or BIM side (e.g. CityGML or IFC) is extended to incorporate the data from the other. The GeoBIM and utility network extensions by Van Berlo and Laat (2010) and Hijazi et al. (2010) are examples for CityGML. On the other hand, IFC-for-GIS project (IAI, 2005) intended to extend the IFC model to include information from geospatial world. A prominent example of meta models is the "Unified Building Model" (El-Mekawy et al., 2011) that the focus of the integration was to develop an intermediate data model for building for emergency evacuation purposes. In general, these models are application-focused and the integration is made for a particular use case with specific requirements. Therefore, the included concepts and relationships within these models may not suit other applications (with different functional requirements).

In this paper, an integration method for integration of BIM and GIS for micro-level assessment of flood damage on building is presented. It supplies the resistance parameters of the building at high level of details, flood information as well as the other geographically extended features (e.g. elevation) in one unified data model to use for assessment and 3D visualisation of the flood damage to building.

3 BIM-GIS Integration for FDA on building

The integration of BIM and GIS in this work is proposed at the data layer and implemented on the GIS side for utilisation of its spatial analysis tools for FDA calculations. The GML standard does not explicitly define the semantics of the geographic features (e.g. buildings or roads), and as discussed previously, there are limitations in representation of building and its components in the CityGML. For this reason, a new data model as a profile of GML is proposed to integrate the BIM information alongside the spatiotemporal dynamics of the flood information for assessing and visualisation of the damage on the building.

3.1 Methodology

The proposed data model in this paper was developed based on the "data modelling cycle" (Teorey et al., 2011). This methodology includes five steps for design and implementation of a data model. It commonly starts with the mapping of the real world concepts and their relationships to a conceptual model. The concepts and relationships in the model are identified for a particular or a number of use cases by employing a variety of data requirement gathering methods like survey, interview, review of relevant previous publications, etc. The conceptual data model is further translated to the logical data model defining the structure of the database. The last step in the process involves the development of a physical data model and its implementation (Elmasri and Navathe, 2011).

Next, the details of the above process for designing the proposed data model is explained, the outputs are presented and its benefits for use for a micro-level FDA are discussed.

3.2 Use case definition

Use cases are informal scenarios describing the expected behaviour of a system as a response to the needs of the stakeholder(s). Use cases are the basis of the extraction of the required functionalities and the data needs for system design.

In this study, the defined use case is related to the assessment and visualisation of the potential damage to a building from a riverine flood. It requires (i) the assessment of the building safety (structural stability) by assessing the damage to structural and load bearing components, (ii) the estimation of the total cost of repair/replacement of the damaged components (excluding its content), and (iii) the visualisation of the location and mode of damage at component level. This use case was detailed by investigating the land development process, a review of previous publications and liaising with engineering and design firms, councils as well as referral authorities (e.g. Melbourne Water) as potential users of the system outputs. The behaviour of buildings of different types may vary in flood situations and the processes for damage analysis on them may be different from one to another. In this research, the scope was limited to only one type which represents the most common Australian residential construction type: a single-storey slab-on-ground brick veneer house (Geoscience Australia, 2014).

3.3 Requirement analysis

Based on the definition of the use cases in Section 3.2, the vulnerable components of the selected house type were identified. This process involved a systematic and extensive review of the literature (e.g. HNFMSC, 2006; CLG, 2007), discussions with engineers and councils, as well as the resources and previous research on the vulnerability of houses in Australia provided by the Geoscience Australia. Our findings indicated that for the construction type in focus, the damage and the incurred costs are mainly from the impacts of floodwater contact and forces on the *floor covering*, *walls* (including cladding, framing, insulation and lining), *skirting boards* and *cornices*, *ceiling* and *its insulation*, *roof*, *windows*, *internal and external doors*, *eaves lining* and the *interior and exterior utilities (e.g. electrical)* depending on their location and materials.

Following the identification of susceptible components, further investigation was undertaken to identify and document (a) the modes of damage for each component from floodwater impacts, (b) engineering methods for their modelling and (c) the information inputs for these calculations. For the first two steps, Australian design and construction standards (e.g. AS3700 - masonry building design) and relevant documents for improving the house resilience to flood (e.g. HNFMSC, 2006; CLG, 2007) were used. Due to the limited space in here, the outputs of these two are not presented in here. Due to the diversity and large number of the extracted data requirements in step (c), only a subset of them is presented in Table 1 according to their importance. Other concepts like details of utility objects and types of different elements like coverings are omitted in this table.

Table 1: Example of the Extracted Data Requirement

Concepts	Details
Spatial Structures	Defining the spatial container for objects. It can have a corresponding element (e.g. building storey or a space in the building) that acts as the container object.
Terrain	Representing the elevation of the area. It is required to be in multiple levels of details. Terrain can be either point-based or surface-based.
Flood	The flood parameters using multiple representations: (a) Spatio-temporal point distribution of depth and velocity vectors (for use in damage calculation); (b) Surface representation of flood (e.g. water level surface).
Buildings	The footprint, address, height and the area.
Building components	Including storeys, walls, stairs, floors, foundation, beams, columns, roof, structural connections (e.g. wall ties), framing members, floorings, ceiling, soffit, skirtings and mouldings, doors, windows and cladding vents (e.g. airbricks).
Utilities	For example, electrical objects like switches, meter boxes and outlets.
Materials	Construction materials of the building elements (single material or multiple)
Cost info.	Including cost of repair/replacement of building and utility components; and the building value.

3.4 Data model design

According to the identified requirements, the conceptual data model illustrating the required concepts and their relationships was designed. Throughout the design process, a continuous investigation was undertaken to identify how these concepts are modelled in BIM (IFC) or GIS formats (GML and CityGML). This mapping was used to refine the design to improve interoperability and information translation between IFC or CityGML and the proposed model. The data model consists of seven packages inheriting its high level feature definitions from the GML. These packages are namely: the Core (CoreUrbanFlood), Terrain, Flood, Building, Utility, Valuation and MaterialDomain. In this paper, the UML class diagram was employed for developing and presentation of the data model. Due to the complexity of the model and limitations in space here, the attributes are not illustrated in the class diagrams. In addition, each package and their respective classes are colour-themed for the ease of read.

The "CoreUrbanFlood" package (see Figure 1) includes the necessary high-level objects for a micro-level FDA on a building. "UrbanFloodModel" concept is the highest level entity in the model defining an urban flooding scenario. It is a collection of defined materials, costs, spatial structures (explained in Section 3.3) and urban elements (_UrbanObject) representing the urban environment in a flooding situation. Urban objects can be the parcels (site), buildings, individual utility elements (_UtilityObject) or their aggregation as a system (UtilitySystem), flood representation (_FloodObject), and a simple or complex elevation model (_TerrainObject). Other urban objects like city furniture, roads, etc were beyond the scope of requirements in this research as the focus is only on damage assessment on buildings.

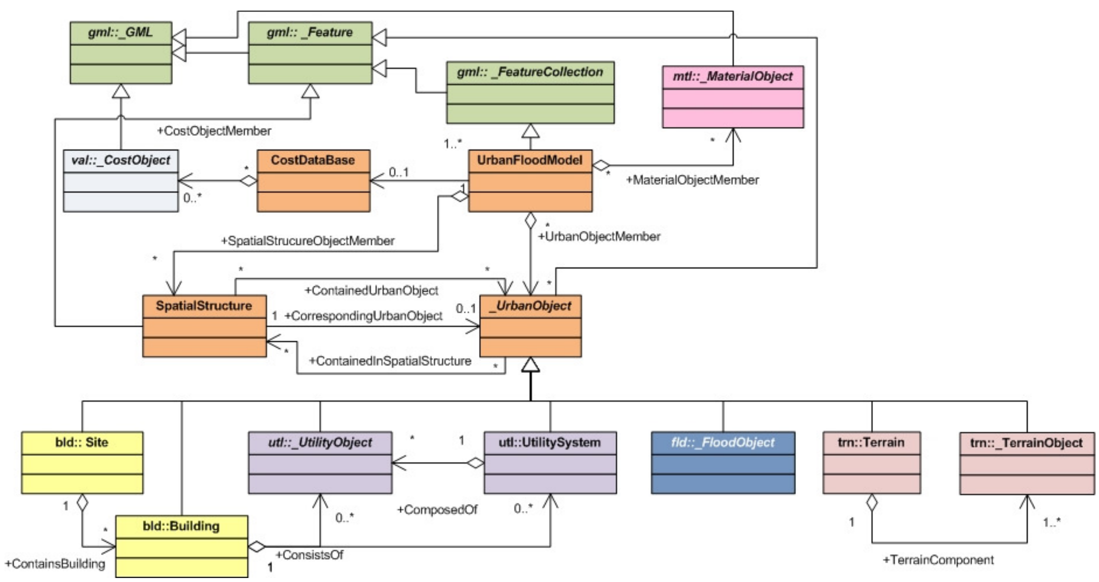

Figure 1: UML Model of the Core Package

The proposed data model adopts a subset of the "Digital Terrain Model" thematic model in CityGML 2.0 for its Terrain package (see Figure 2). An elevation object in here can be stored by an independent subtype of the abstract concept "_TerrainObject". It can be either a surface-based object (e.g. TIN) represented by "TinTerrain" or in a multi-point form using "MassPointTerrain". On the other hand, a single Terrain can be represented by an aggregation of a number of _TerrainObjects in different representation forms and levels of details within the "Terrain" object. Each _TerrainObject has a validity extent - represented by a polygon, to define its effective scope.

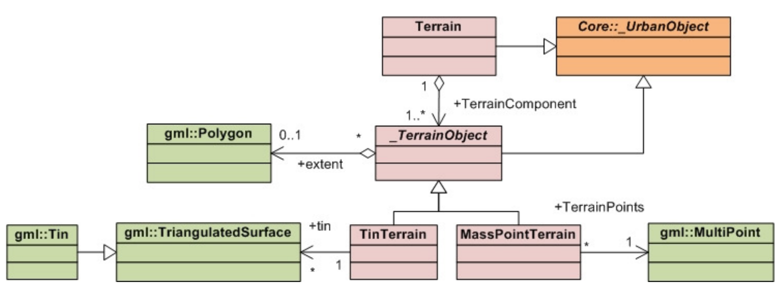

Figure 2: UML Model of the Terrain Package

The Flood package, illustrated in Figure 3, consists of the required classes to represent the flood information. Any flood in the model (_FloodObject) is described by its metadata (FloodMetadata) that provides information about its exceedance probability, flood duration, number of time steps, duration of each step and the units of measurement for depth and velocity. As a subtype of the abstract _FloodObject, the "FloodBody" represents the flood in urban area in either point coverage or GML surface forms. In GML, a coverage class (e.g. multiPointCoverage) uses the relationship between RangeSet and DomainSet to link the geometry with its attributes (see GML 3.2.1 specification for details). The flood extension for CityGML by Schulte and Coors (2009) was adopted in this work and extended via definition of an array of "FloodTimeSeriesElement" classes (containing water depth and velocity components of the flood for a particular time step) to accommodate the temporal aspects of the flood in addition to its spatial components.

Surface representation of the flood was specifically considered for its 3D visualisation. It can either be presented by a single MultiSurface object using "RepresentedBySurface" relation for the maximum depths; or using the aggregation hierarchy of timeSeriesSurfaces → TimeStep → _floodBoundarySurface classes, for a surface representation for each time step. While "floodSurface" and "FloodGroundSurface" are used for water level surface and the surface between water and ground, the "FloodClosureSurface" is used to close the enclosure when the flood geometry is not a closed volume.

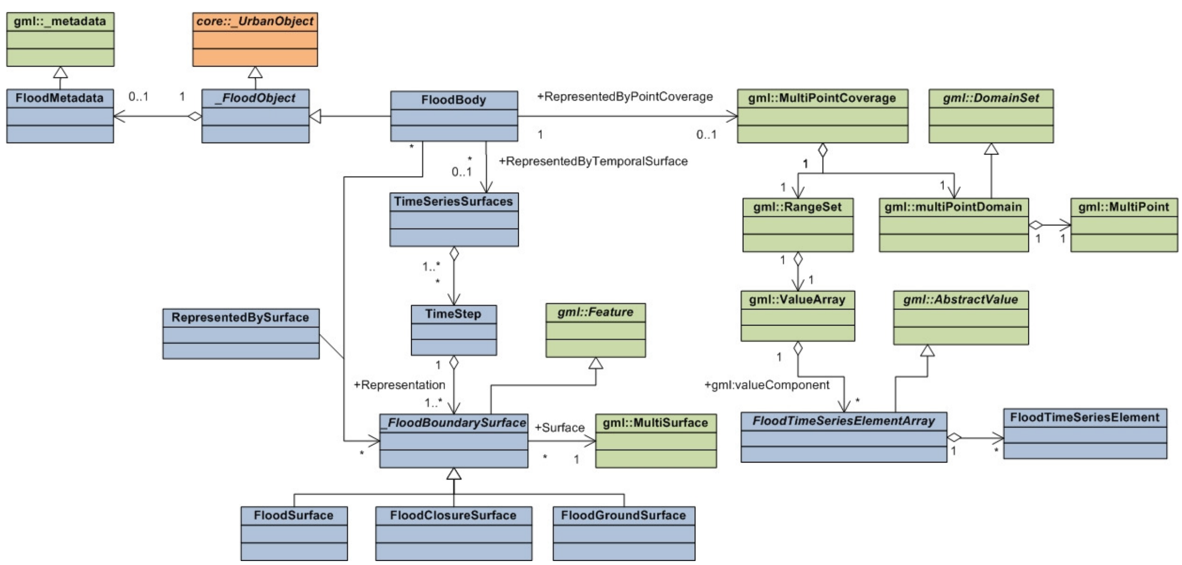

Figure 3: UML Model of the Flood Package

The valuation package (see Figure 4a) contains an abstract concept, the "_CostObject", that defines the value of a particular object. The "AssemblyCostObject" and "BuildingValue" realise the _CostObject for the repair/replacement value of building components or the construction cost of the building as a whole. Other information describing these classes include issuing institution, date of issue, currency type, etc.

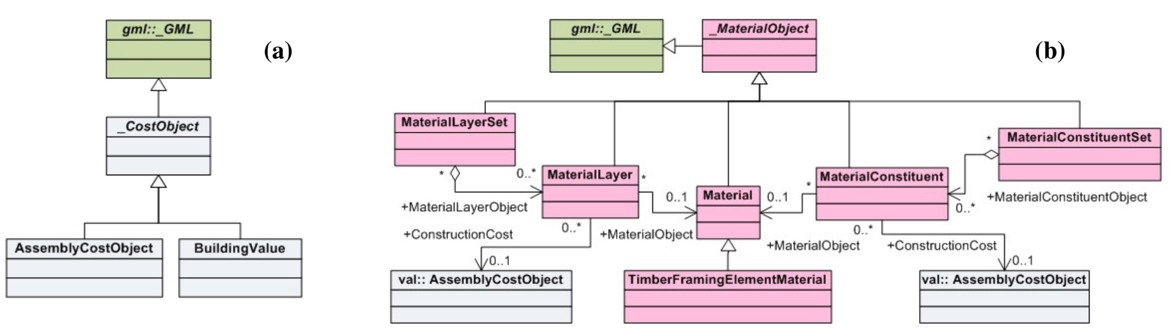

Figure 4: UML Model of the (a) Valuation Package and (b) MaterialDomain Package

The MaterialDomain package contains classes that define the construction materials of the building elements. As illustrated in Figure 4(b), this package consists of three kinds of material definition. "Material" class which defines a single material that can be directly assigned to a building component or be used as a layer in other material classes. "MaterialLayerSet" on the other hand, defines multiple materials as layers. An example here is a wall panel which includes the paint, lining and brick materials. The order of layers defines the position of the material in the object. "MaterialConstituentSet" is another material definition method which consists of one or more "MaterialConstituents" each of which defines the material of a part of component (e.g. "frame" or "glazing" in a window) indicated by its particular name.

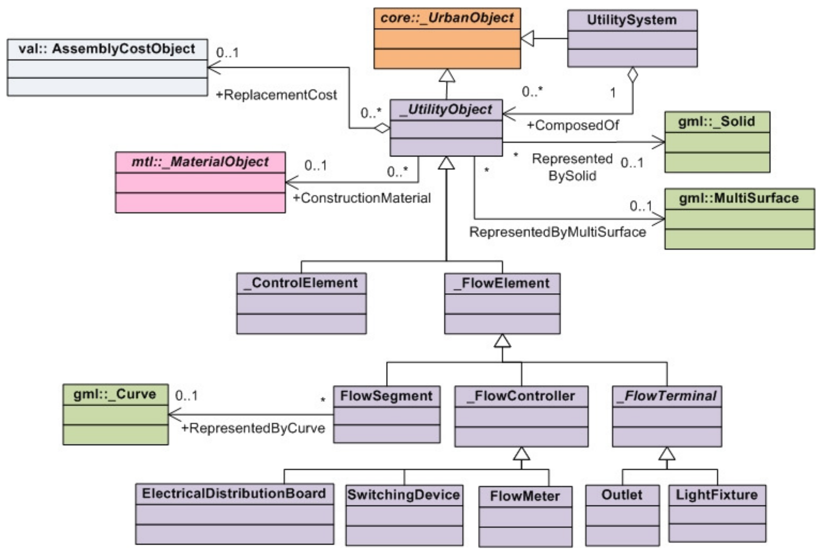

Figure 5: UML Model of the Utility Package

Utility package contains the classes related to the interior or exterior utilities of the house. This package is illustrated in Figure 5. The utility objects can be defined independently or under a particular system (e.g. electrical, water, fuel or HVAC). Each realisation of the abstract "_UtilityObject" class may have a replacement value and a material object defined. In terms of the representation, utilities are commonly presented by either a GML solid or multiSurface. In this research, for the utilities, the focus was concentrated on the electrical system elements such as lights, outlets, meters, switches and distribution boards which are defined under abstract classes "_FlowTerminal" and "_FlowController". In addition, elements such as cables can be defined using the "FlowSegment" class that can be represented by 3D line segments using a GML Curve. The "_ControlElement" class, on the other hand, is an abstract class reserved for future use to represent utility components that are used to impart control over the other elements in the system. These classes can be directly mapped to the distribution elements in the IFC data model.

The building package (see Figure 6) comprises the classes that represent the building and individual or an aggregation of building components. The "Site" class represents a parcel characterised by an address and a 2D polygon which can contain one or more buildings. Each building has a value associated with it (BuildingValue) and can be represented by either its 2D footprint or the aggregation of 3D geometries of its components (e.g. stories). A building consists of at least one storey defined by "BuildingStorey" class and may contain utility objects or systems, as well as any subtype of the abstract class "_BuildingElement". Each of utility or building elements has a damage state and replacement cost attributes associated with them that can be used for cost analysis.

The building components defined in the model include slabs (either foundation slab or floor represented by classes of similar names), structural beams and columns, walls (either simple or complex wall represented by its different components using the relationship "consistsOfParts" defined at its supertype), roof (can be defined in the same way as wall), stairs (represented as a single component or by railings and stairflights), framing members (representing the structural framing of the building other than columns and beams), coverings such as ceiling, flooring, soffit, cornices and skirtings), windows (sliding doors are defined similarly), doors, airbricks (vents) or any type of void opening. In addition to these components, "BuildingElementPart" defines a class for a generic part of any other element. Explicit classes for wall parts ("WallComponentElement" such as the cladding) or covering parts (e.g. ceiling insulation and lining) using "CoveringLayerElement" are defined in the model to represent these objects.

In this model, windows and doors are defined either as single object or a combination of a lining (its frame) and a minimum of one panel that may have their own geometry, material and cost. "Space" class in this model defines those elements for representing the internal (e.g. room) or external (e.g. the backyard) spaces for the building.

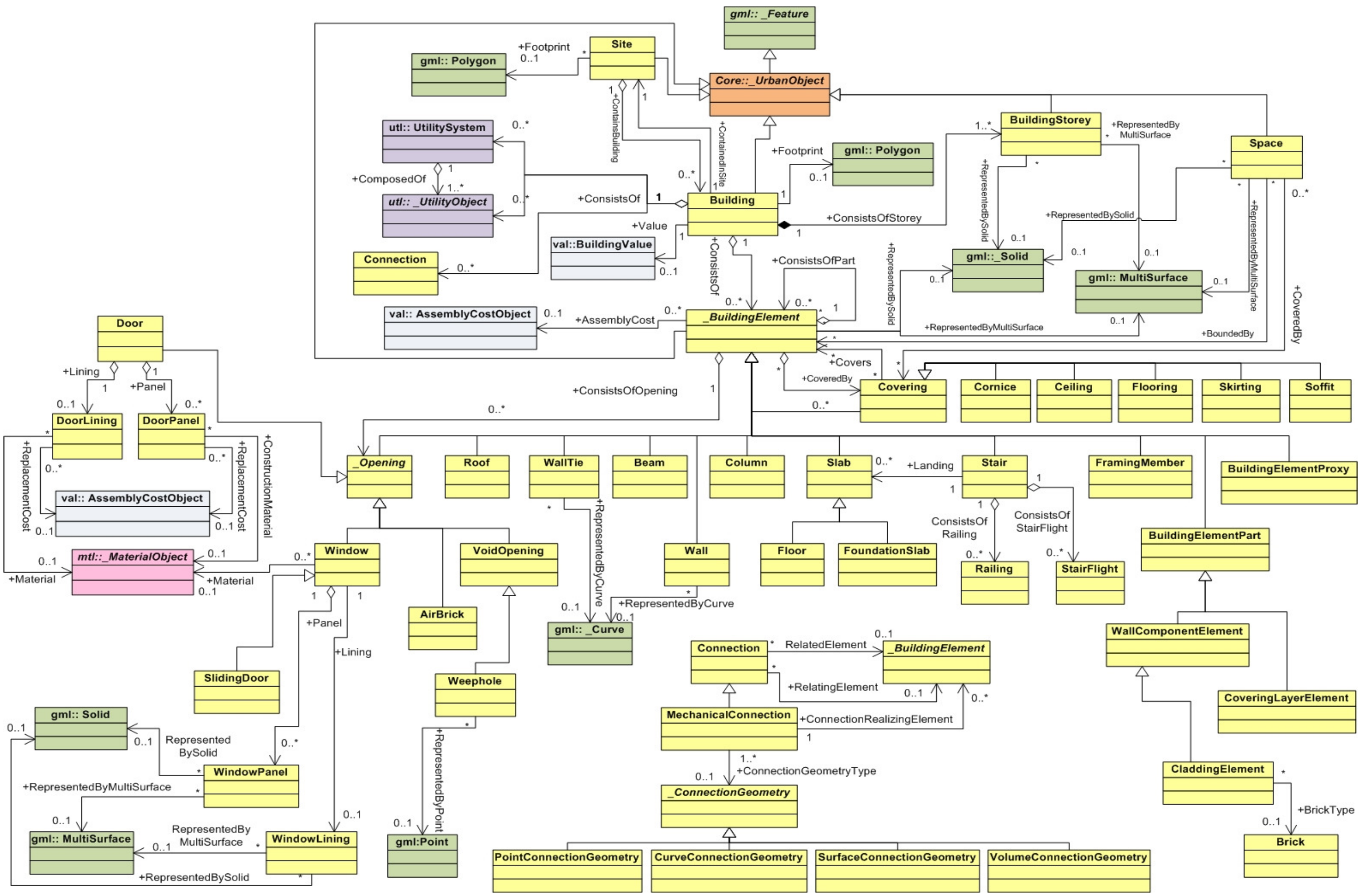

Figure 6: UML Model of the Building Package

On the other hand, "Connection" class here is the supertype for all connections defining a link between a _BuildingElement (related element) to another (relating element). The "Mechanical connection", is a specialised connection type that employs an additional linking _BuildingElement for the explicit establishment of the connection. An example here is the brick cladding to framing connection using "WallTie". The connection between the relating and related elements can be further detailed by the geometry type (point, curve, surface or volume) that either of the elements or the realising element connects to them. In the wall tie example, the connection is simplified by a PointConnectionGeomtry class that has a GML point defined on related and relating elements. The connection concept can easily be mapped to its counterpart in IFC model for integration purposes.

To support extensibility, the building model defines a generic class, "BuildingElementProxy" to be used for elements that are not explicitly defined in the current version of the model. A "Slab edge" is an example of this element.

3.5 Data Model Implementation

Subsequent to the design of the conceptual model discussed in Section 3.4, the logical and physical models were developed. XML file was selected in this research to implement the integrated information model. Therefore, the physical model was prepared in relation to XML schema specifications. According to the described UML packages in Section 3.4 and the designed physical model, an XML Schema was developed. It defines the structure of the XML file and rules for definition of objects in it. This schema comprises six namespaces, each of which corresponds to and implements one of the UML packages described previously in Section 3.4.

4 Case Study: Damage Assessment to a House in Maribyrnong

To verify the application of the designed integrated information model to serve the defined use cases in Section 3.2, and testing the hypothesis of the research, a case study was conducted in collaboration with Maribyrnong Council and Melbourne Water. In this study, damage to a selected house in Maribyrnong was evaluated and visualised.

The required data such as elevation model of the case study area, plans of the building under investigation, and the inputs for the flood simulation (e.g. river discharges) were provided by the council and Melbourne Water. The building value and the component costs, on the other hand, were obtained from the Office of the Valuer General and the Rawlinsons' Australian construction cost handbook 2014. The BIM model of the house was developed based on the provided plans and then exported to an IFC file. On the other hand, a 1-in-100 year flood (commonly used for planning) was simulated using MIKE 21 simulation package and the outputs (spatial distribution of depth and velocity) were exported to 1140 ESRI shape files, each corresponding to a time step. An in-house tool was used to extract flood parameters from these files into a single XML file. This XML file was then mapped to the flood concepts of the proposed model in Section 3.4 and the flood information, including its geometry and attributes, were stored.

In spite of the previous efforts explained in Section 2.3, there was no tool found that could provide a smooth conversion for both geometry and semantics of BIM data to GIS formats. Therefore, a semi-automatic process (illustrated in Figure 7) was designed in this research to import building information from IFC into the implemented database. In this method, the geometry and semantic information are obtained separately and then combined to be stored in the designed database. For geometry extraction, first the IFC elements are converted to ESRI geodatabase feature classes using the ArcGIS Interoperability Extension. Then each feature class is converted to CityGML using the export function in the extension. As the input objects are not known to the converter engine, the created objects in the output are in the form of "GenericCityObject" containing a multiSurface representation of the elements. On the other hand, the attributes and relationships between elements are obtained from an exported XML version of the IFC file and combined with their geometry using a unique identifier of IFC elements, the "TAG". Having the geometry and the semantics of the elements combined, they are then mapped to the proposed data model objects and stored in the database.

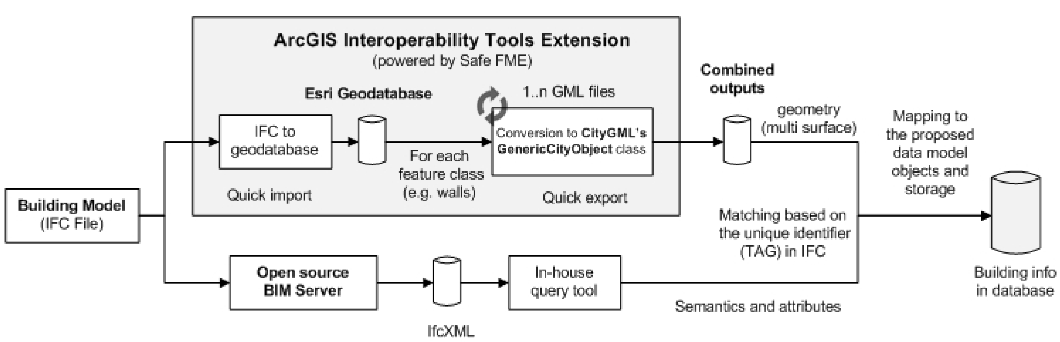

Figure 7: Converting the building information from IFC to the database based on the proposed data model

The flood parameters and building components were then used to evaluate the mode and level of damage to individual components. These calculations are based on the extracted engineering methods for assessing the damage (see Section 3.3) implemented in a prototype system. The cost of damage to each component was calculated based on its damage level and replacement cost. In addition, the geometry of the building components and colour coding were used to visualise the location as well as the level of damage in 3D.

5 Results and Discussion

The damage to the building and its components in the case study in Section 4 were assessed by use of the BIM and geospatial information together and the implementation of the functions extracted in Section 3.3. Figure 7 illustrates the study area and the visualisation of flood simulation outputs in 2D and 3D GIS.

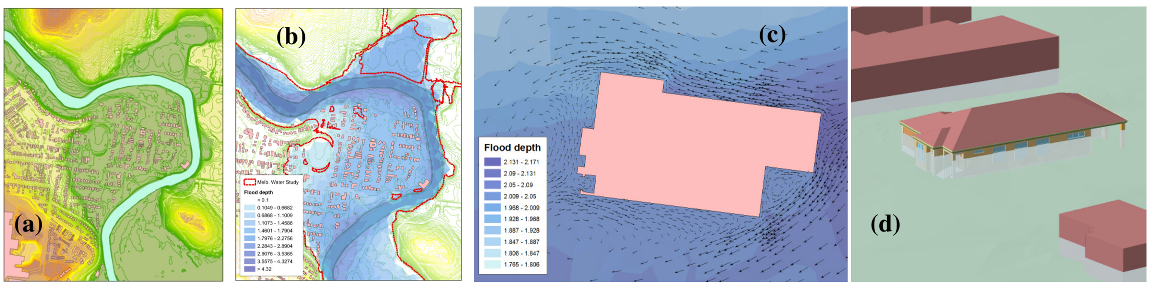

Figure 7: Case study for a house in Maribyrnong: (a) study area, (b) flood simulation output in the area, (c) flood parameters around the house, (d) 3D visualisation of the inundation level for the house

The damage analysis process showed no structural instability as the load bearing elements remained unaffected. However, the building suffered from approximately $51,000 damage to its other components (e.g. doors and flooring) from water impacts. This number is the sum of damage costs to individual elements which a subset of these costs is presented in Table 2.

Table 2: A subset of the damage to individual building components

Building Component	**Count**	**Total units**	**Unit of measurement**	**Unit cost (AUD$)**	**Total cost (AUD$)**
Hollow core door (std. 35mm thick)	13	13	each	151.00	1,963.00
Electric meter box	1	1	each	855.00	855.00
Double power point	30	30	each	45.00	1,350.00
Timber skirting	55	137.88	m	15.10	2,081.98
Carpet flooring	6	77.181	sqm	58.50	4,515.08
Timber flooring	1	101.027	sqm	205.00	20,710.53
wall lining (gypsum)	82	418.919	sqm	28.50	11,939.19
Insulation (Rockwool batts)	21	171.56	sqm	13.15	2,256.01

Figure 8 illustrates the 3D visualisation of the location and mode of the damage to building components using a 3D GIS tool (ESRI ArcScene). Elements in these figures correspond to the items presented in Table 2 and can be queried individually. While red represents total damage and replacement is required, green indicates no damage to the component. The grey elements is used for putting the turned on damaged items into the building context and represent those that user has turned their layer off for damage inspection.

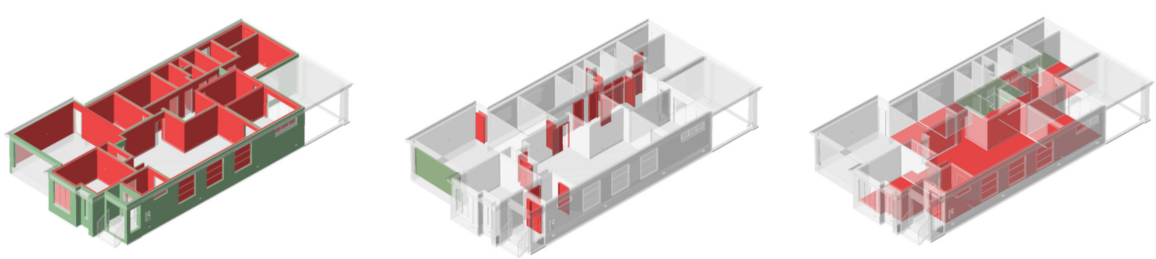

Figure 8: 3D Visualisation of Damaged Walls (left), Doors (middle) and Flooring (right) in ESRI ArcScene

From the above results, all three uses cases defined in Section 3.2 are shown to be successfully satisfied: the building structural safety was assessed and the cost of damage to individual components were estimated and visualised in 3D. The rich database based on the proposed data model in Section 3.4 was profitably used to integrate building information with flood parameters to assess the damage to the selected brick-veneer house at its component level and by taking into consideration its unique characteristics. This method provides a more detailed output illustrating the details of potential damage to a building that cannot be obtained by the current methods for FDA such as damage curves (presenting only a single number for building damage). Therefore, it can potentially overcome the limitations of current methods towards providing a better understanding of vulnerabilities in the building and facilitating an effective decision making for their treatment.

A range of stakeholders (e.g. engineering and design firms, councils, referral authorities as well as the building owners) can benefit from the outputs of the presented method. A majority of these parties are often challenged by similar questions such as "Is a particular development, proposed in an area with risk of flood, resilient to the potential risks and should be permitted for construction?" To answer this question, a tool based on the proposed integration method for BIM with GIS (similar to what was presented in this study) can facilitate engineers to test their designs against the mandated flood performance requirements from Australian Building Code Board. The alternative design options or mitigation measures may be considered for treating the vulnerabilities. In here, a cost-benefit analysis of their deployment using the proposed method can facilitate the selection of the most effective solution. On the other hand, referral authorities and councils can assess the planning and construction requirements of the proposed building more effectively by taking into account the details of the risks. Additionally, a feedback from the council for this study indicated that in case of disputes between owners and council taken to Victorian Civil and Administrative Tribunal (VCAT) in regards to refusal of a particular proposal due to risks, a non-engineering language such as the presented 3D visualisation in here can be beneficial for the communication of risks to owners for their better comprehension of the basis of the decision. The preliminary feedback from some of the aforementioned parties has been positive. However, further systematic investigation is required for understanding the value of the additional detailed information presented to them in this work.

The proposed integration method in this work can complement the use of damage curves for large-scale applications to create a multi-scale framework towards a better and more comprehensive understanding and treatment of the flood risks at different levels. It can help in improving the resilience of the community towards floods and their adverse impacts. The application of the proposed method, however, is limited to one or a few buildings where data and computation resources can be feasibly provided. For larger number of buildings at municipality or city level, the demand for such high level of detail damage evaluation for decision making would be small and other existing methods (e.g. curves) can suitably provide the required decision support.

6 Conclusions and Future Work

In this paper, a method for integration of BIM with GIS at the data level using a development of a new data model as a profile of GML was presented. The designed data model allows for a unified and consistent storage of the detailed representation of the building information alongside the flood parameters and other information (e.g. elevation model) in support of the micro-level FDA on buildings. The implementation of the data model and its use for assessing the damage to a selected building in a case study in Maribyrnong evidently supported the proposed hypothesis in this research: the BIM-GIS integration can facilitate a detailed assessment and 3D visualisation of damage costs to a building that is presently not supported by the type of inputs used in the current methods for FDA.

The preliminary feedback from the discussions with engineers and the council has been positive and a number of benefits are highlighted. Further research, however, is envisaged to systematically investigate the value of this extra and detailed information to the stakeholders involved in detailing the use cases in this research.

Furthermore, the data model presented in this paper was designed based on the analysis of the requirements for one particular construction type. The methodology used in this research can also be used for other building types and hazards to extend the data model for all types of buildings towards the development of a comprehensive repository of data for analysis of all types of buildings and events.

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