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FLEXIBLE GENERATION OF SEMANTIC 3D BUILDING MODELS

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ABSTRACT

The paper presents a new 3D semantic building model dedicated to urban development. It provides the following special semantic features: storeys, passages, opening objects, and building variants, modelling different levels of detail and design respectively temporal variants. The model also includes a parametric part supporting easy generation of buildings and building variants in the urban design phase. In order to make the powerful tools of the CA(A)D world accessible to city modeling, a toolbox is being developed for transformation of IFC data. These extensions and addition facilitate multiple utilization of city models and thus enhance sustainability of modeling.

1. INTRODUCTION

3D city models are used in more and more sections of economy and public administration. A central part of a city model is the 3D building model. Traditional applications like planning of cellular phone networks or flood protection require geometric models with low level-of-detail, containing no or only little semantics. In the last years, new applications for 3D city models arose in the areas of tourism, business development, town planning and urban development. This increased the need for more sophisticated and geometrically complex models. Still in most cases, the models are only used for visualisation purposes. Therefore, almost all 3D city models actually available contain no semantic information, or the semantics is only represented in form of attributes.

Because generation and maintenance of 3D city models is very expensive, there is an increasing need to develop more applications for 3D city models. This is only achieved with semantic models, where all geometry-parts are associated with a semantic meaning (e.g. denoted as building, wall, balcony, …), and each semantic item is further described with specific attributes. Based on such kinds of model, new applications for 3D city models can be realized in the area of town planning and urban management: e.g. generation of environmental reports, checking of building applications, emergency and catastrophe planning, or traffic simulations. Furthermore a semantics driven visualization enhances usability of the model. Explicit semantic information generally facilitates interoperability and the development and usage of intelligent support modules for urban development.

In the QUASY (Quartierdaten-Managementsystem) project of Forschungszentrum Karlsruhe (BENNER et al. 2004), corresponding data formats, methods and tools are investigated. This paper deals with different techniques for the three-dimensional semantic modelling of buildings. The object model of a building used in QUASY is shortly presented in chapter 2. It is structurally very similar to the CityGML-model (Kolbe et al. 2005).

Two different application scenarios are regarded: In early stages of the planning process, models with low level of detail are sufficient, but they have to be adapted and changed easily. This calls for the usage of a parametric building model. Such a model, suited for buildings with arbitrary floor plan and different roof types, is presented in chapter 3.

In later stages of the urban planning process, or in case a gap in an ensemble of existing buildings has to be closed, geometrically and semantically much more detailed models are needed. For this, specialized CA(A)D-systems like ArchiCAD (GraphiSoft) or Architectural Desktop (Autodesc) are available. These systems are equipped with a standardized interface for data exchange which is widely accepted in the architectural area: The so-called IFC (Industry Foundation Classes) standard. The IFC product data model has been defined and is managed by the International Alliance for Interoperability (IAI). The problem of transforming design oriented CA(A)D-data into the utilisation oriented QUASY model format is addressed in chapter 4.

2. THE QUASY OBJECT MODEL OF BUILDINGS

The UML diagram of the building model used in QUASY is shown in figure 1. A building (QuBuilding) is associated with addresses, and refers to terrain-intersection lines (QuTerrainIntersection), modeling the intersection of the outer building shell with the terrain. A building furthermore is composed of one or more building parts (QuBuildingPart). The building parts of a building differ in their central structural or geometrical parameters like, e.g. number of storeys or ridging height.

A building part refers to a number of non-geometrical attributes (e.g. year of construction, function, usage), and aggregates different variants (QuVariant), each of them containing a complete geometrical and semantical model of the building part. The concept of variants can be used very flexibly. A variant may be associated with a certain level-of-detail of the model, a concept frequently used in CityGML. But variants may as well describe different planning states of temporal situations of the building. The attributes of a variant can be separated into 3 groups:

- Volume, surface, and curve geometry without semantically meaning. These elements model the outer shell of the building part without any sub-structures.
- Building components with specific semantic meaning. Like the geometry model mentioned above, the union of these components models the outer building shell. In addition, also the internal structure of the building (rooms, passages, inner walls) can be regarded. Geometrically, building components are modeled as aggregation of surfaces, representing the surfaces of the building which are visible from inside or outside.
- A parametric description (QuParameterModel), which can be used for instantiating both the pure geometrical model and some of the building components. This is further discussed in the next paragraph.

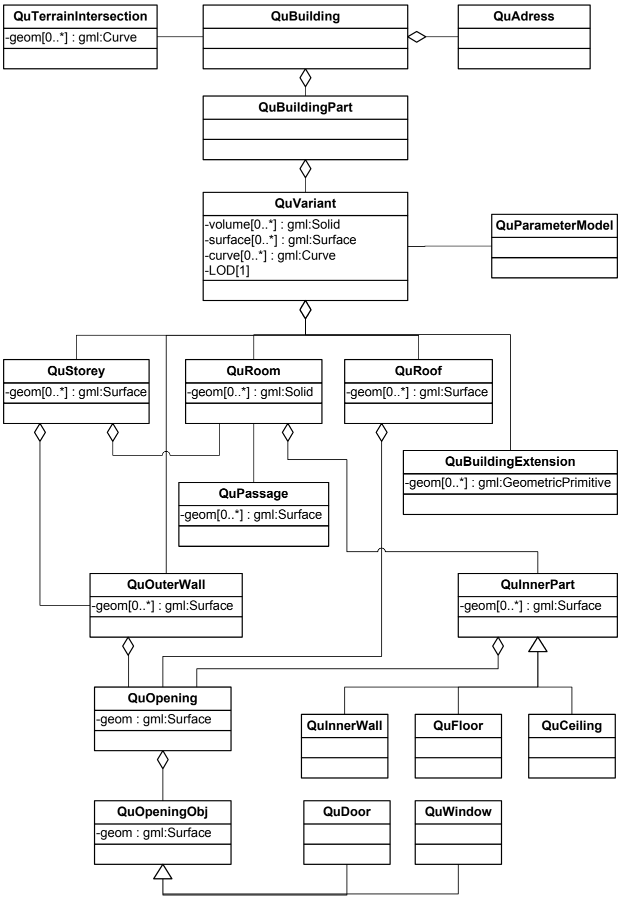

Figure 1: The QUASY 3D Building model

The structure of the building component model has been adopted from the architectural area. It consists of the different object classes.

- Storeys (QuStorey), vertically structuring the building part and modeling the floor plates.
- The outer building shell is composed of outer walls (QuOuterWall), roofs (QuRoof), and building extensions (QuBuildingExtension) like balconies or stairs. Optionally, an outer wall can be associated with a storey.
- Internally, a building part consists of rooms (QuRoom), which, like outer walls, can be associated with a storey. A room has an own (volumetric) geometry, and can optionally aggregate inner parts (QuInnerPart) like inner walls (QuInnerWall), floors (QuFloor) and ceilings (QuCeiling). Furthermore, a room can refer the passages (QuPassage), connecting it with other rooms. With this feature, the room-topology is explicitly represented.
- The surfaces representing an inner part, an outer wall or a roof may contain holes for doors or windows. The corresponding object classes can refer to openings (QuOpening), modeling the holes with a separate geometry. The door or window filling the opening is modeled as opening object (QuOpeningObject) associated with the opening.

To enable QUASY to administrate arbitrary attribute data, each semantic object can incorporate a vector of tuples (name, type, value, description) to represent non geometric data.

Compared with CityGML, this model shows some similarities, but also a number of differences. The concept of variants is more flexible and general as the level-of-detail modelling provided in CityGML. This standard neither contains a parametric model of the building, nor a model for building storeys or passages. Therefore, in CityGML the room topology is only implicitly represented by means of geometry elements addressed form two adjacent rooms. In the QUASY model the internal components of a building (inner walls, floor, ceiling) are aggregated by the corresponding room, in CityGML they are aggregated by the building part.

3. PARAMETRIC GENERATION OF BUILDING MODELS

The generation of 3D building models on basis of a parametric description has a number of advantages. Parametric models are easily generated and adapted and provide for a very compact description. In the context of urban design, parametric modeling is a quite natural approach, because it is based on cadastral information (e.g. the floor plan) of a building. On the other hand, parametric models are always limited in the geometric and semantic complexity which can be handled. In case of building models, this especially concerns different roof types, the structuring of facades by means of openings (doors, windows) or extensions (balconies, stairs), and the internal structure of a building (rooms, passages).

In QUASY, each variant of a building part can be associated with a set of parameters. On basis of these parameters, the geometry of the whole building part (volume and surface), as well as the geometry of the corresponding storey, roof and outer wall objects can be generated automatically. The UML structure of this parametric building model is shown in figure 2. It has the following parts:

- The vertical structuring and height of a building part are defined by the number of storeys (above and under ground level), storey height and ridging height. Actually, only buildings with constant ridging height are regarded.
- The floor plan of a building part is modeled as a two-dimensional, closed polygon. The outer walls (QuOuterWall) of the building part are generated by a vertical extrusion of the floor plan polygon.

- Each building storey (QuStorey) geometrically is described by its corresponding floor surface. This surface is a copy of the floor plan polygon, placed at the correct vertical position.
- The ridge consists of polygonal ridge lines, which itself consist of an array of ridge points. The roof geometry (QuRoof) is specified by an attributed association of floor plan points with ridge points. These attributes determine the type of the corresponding roof or wall surface (i.e. whether it is a gable, the side of a saddle-roof, or part of a hipped roof), and the roof excess.

The other building components shown in figure 1 actually cannot be generated parametrically. An extended parameter model regarding also openings like doors and windows, rooms, and simple building extensions is possible, but has not yet been realized.

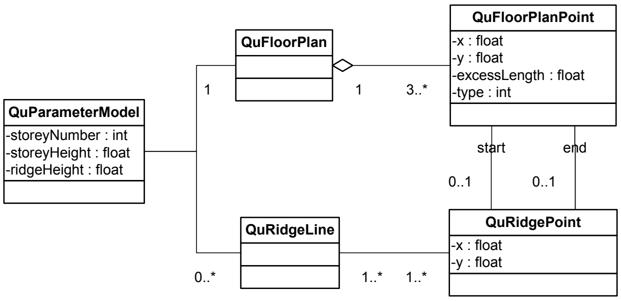

Figure 2: Parametric building model

4. GENERATION OF BUILDING MODELS BASED ON IFC-MODELS

The framework for converting data from IFC to the QUASY building model is the IfcWallModificator. This is an IFC based application for reading and displaying the content of an IFC file, both graphical and alphanumeric. For handling and manipulating the geometrical data of a product data model a geometry kernel is available.

4.1 *Industry Foundation Classes (IFC)*

IFC is designed to provide an universal basis for the information sharing over the whole building lifecycle (Eastman, 1999). The IFCs are based-upon the EXPRESS language which is part of the STEP standard (ISO 103030) for the product data exchange (IAI, 2005). In this activity version IFC2x2 is used (IFC, 2005).

The schema of IFC is quite complex. In order to demonstrate the building structure, an informal UML schema of the IFC is shown in figure 3. This model is reduced to the relevant objects for our algorithms and therefore the entities for the relationship between objects aren't shown.

The IFC model is represented with space-enclosing structures (IfcSpatialStructureElement). Special space-enclosing structures are the project (IfcProject), sites (IfcSite), buildings (IfcBuilding), storeys (IfcBuildingStorey) and rooms (IfcSpace). IfcSpatialStructureElement is derived from IfcProduct, which refers to a location (IfcLocalPlacement) and a geometrical representation (IfcShapeRepresentation). Building objects (IfcBuildingElement) like walls, roofs or doors can be assigned to the elements of the space-enclosing structure.

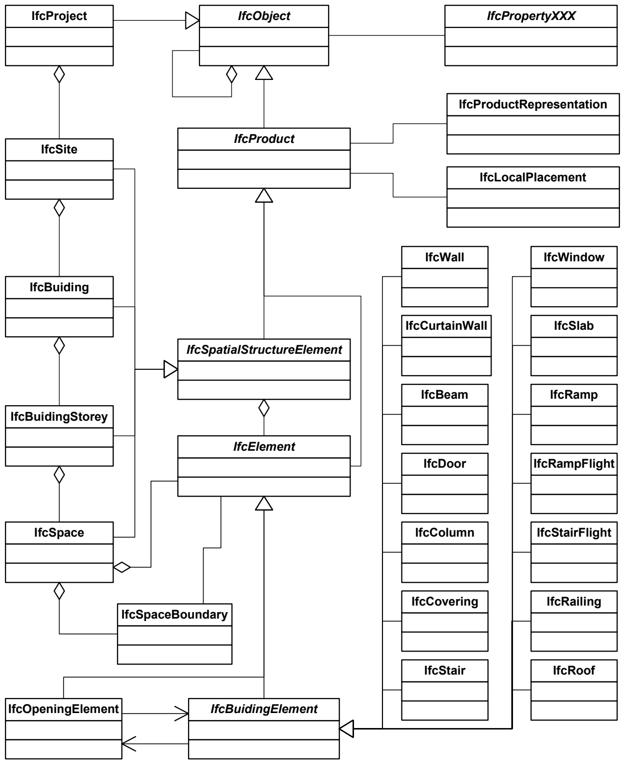

Figure 3: Informal IFC-schema

The geometric representations of IFC are based upon the geometric model schema part 042 of STEP. This part is very versatile and a lot of its alternatives are not used in IFC practise. Most of the used geometries for building elements are solid models. A solid model is defined as the shape of a IfcProduct, in which all interior points are connected. The following solid models are used:

- Facetted boundary representation - a simple form of boundary representation in which all faces are planar and all edges are straight lines.
- Extruded area solid - defined by sweeping a bounded planar surface. This planar area can contain inner boundaries, which are swept into holes of the resultant solid. Possible swepping surfaces are:
  - 2D base profiles (polyline, composite curve)
  - Parametric profiles (I-Shape, U-Shape, …)
- Constructive Solid Geometry (CSG) - a collection of so-called primitive solids, combined using regularized Boolean operations (addition, subtraction, union).

These different types of solids can be modified with the CSG-method. For example a wall and an opening are separate geometric objects. With a relationship between wall and opening element, implicitly a Boolean operation is defined, which is executed by the framework.

The UML diagram of IFC additionally contains an object IfcSpaceBoundary. This entity constitutes a relation between a room and a Building element.

4.2 *Mapping of IFC data into the QUASY building model*

Between the building model IFC and the city model QUASY there is a significant overlapping of information content, but no one-to-one mapping of the data. IFC is mainly used to exchange data between actors from different domains during all phases of the design and construction process of a building. Much information from the IFC file is not relevant for a city model. For example, all the data from the HVAC (Heating, Ventilation, Air Conditioning) domain like pipes, flow rates or air change rates are irrelevant and can be ignored.

The extraction of the relevant semantic objects is the first step in the mapping process. It is followed by the extraction of outer elements (i.e. building elements being connected with the outer shell of the building), the execution of Boolean operations on the geometry (e.g. punching of window openings into walls), the extraction of the outer element's visible surfaces, and the generation or extraction of connecting surfaces (e.g. embrasures). By this procedure, building elements are typically reduced to the facets corresponding to the outer shell of the building or building elements. In table 1 the corresponding elements for the mapping from IFC into QUASY are shown.

IFC	QUASY
IfcSite	QuRelief
IfcSite	QuTerrainIntersection
IfcBuilding	QuBuilding(Part)
IfcBuildingStorey	QuStorey
IfcSlab (FloorSlab)	QuStorey
IfcRoof	QuRoof
IfcSlab (RoofSlab)	QuRoof
IfcWall	QuWall
IfcBeam	QuWall
IfcColumn	QuWall
IfcCurtainWall	QuWall
IfcOpeningElement	QuOpening
IfcDoor	QuDoor
IfcWindow	QuWindow
IfcSpace	QuRoom
IfcSpaceBoundaries	QuRoom - QuInnerWall - QuFloor - QuCeiling
IfcSpaceBoundaries	QuPassage
IfcCovering	QuBuildingExtension
IfcStair	QuBuildingExtension
IfcRailing	QuBuildingExtension
IfcRamp	QuBuildingExtension
IfcStairFlight	QuBuildingExtension
IfcRampFlight	QuBuildingExtension

Tab. 1: IFC-QUASY mapping

4.3 *The outer shell*

The base algorithm to map IFC data into a city model (QUASY building model or CityGML) is to determine the outer shell of a building. As this information is not provided explicitly, it has to be generated from the geometry of the building elements.

At first, the declaration of the semantic building structure is used to extract the information. This produces all relevant building elements for each building storey. From this subset, so called "footprints" are generated for each building storey and for the building itself. A footprint is a two-dimensional geometric structure, generated by vertically projecting all relevant building elements and merging the projections. Outer and inner contours are taken into account, therefore courtyards can also be detected with this method.

Because walls, columns and slabs are the most relevant building elements, two footprints are generated. The first footprint is for the elements representing the vertical structure: walls (IfcWall / IfcWallStandardCase) and columns (IfcColumn). The second footprint is for the horizontal structures, the floor slabs (IfcSlab with the definition FloorSlab).

In a next step, the building elements related to the footprint have to be detected. With a geometric comparison, the building elements touching the footprint are identified, and the corresponding surfaces are stored with a relation to the building element. Additionally, information about the location of these elements is given, and they can be marked as inner or outer elements.

In IFC, a building element can have openings (IfcOpeningElement) and inside of the opening one filling element (IfcWindow / IfcDoor) can be placed. This composition is identical to the definition in QUASY. Hence the outer surfaces are processed and the openings are cut out. Together with the geometry of an opening element the embrasures can be generated and added to the QuWall.

With the difference of the footprint containing walls and the footprint containing slabs an excess length between the two footprints can be identified. With this method it is possible to identify corbels and segments of slabs that belong to a flat roof or a terrace.

Finally, the footprint is used to reduce the geometry of the roofs. If the roof slabs are separate, they at first are merged to one roof. In a second step, the footprint boundary is projected on the upper faces of the roof and stamp out the contour. This technique will also be used for slabs.

The result is the blank shape of the building's outer shell. The differences are shown in the figures 4 and 5. Figure 4 is the initial situation, the whole building model described by IFC. In figure 5 the extracted and reduced QUASY building is displayed. For visualisation purposes the front part of the roof has been removed. The calculation of the embrasures aren't completely implemented, therefore the gaps between doors / windows and the walls appear.

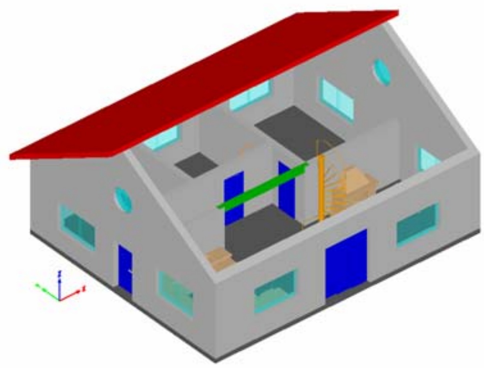

Figure 4: Detailed IFC building model

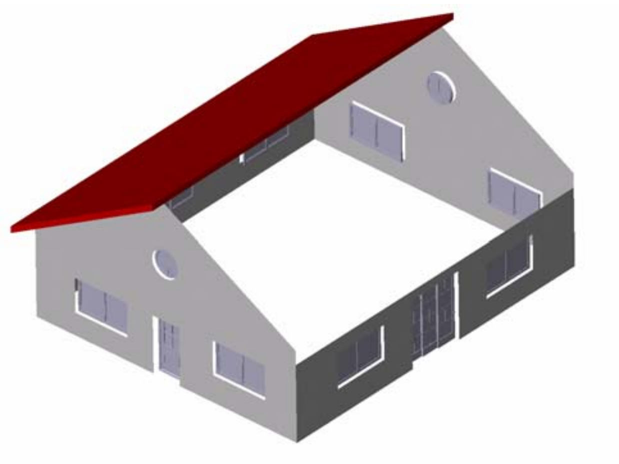

Figure 5: Reduced geometry in QUASY

4.4 *The internal rooms*

In the QUASY model, rooms are defined either for building parts or for building storeys. This definition is very close to the IFC definition. Therefore, there is a one-to-one mapping of the pure room geometry into the QUASY room geometry (QuRoom). In many cases, more detailed information about the relationship between building element and its connected rooms is needed. For this purpose, in IFC the IfcRelSpaceBoundaries are defined. This entity contains a reference from element to room, and has its own geometry representing the joint face between both objects. The relation can either be a physical connection between a room and a building element, or a virtual connection between two rooms or the outside. In QUASY the element QuPassage has a similar role. The QuPassage is of particular interest for disaster management, because it can be used for calculating escape routes.

For a room, QUASY supports inner walls, floors and ceilings. The IFC types of the related objects are known. Therefore it is easy to transform the data into the corresponding QUASY objects. A differentiation of floor and ceiling is not directly supported in IFC, both are declared as IfcSlab. In this case, a geometric check is required to assign the surface to the correct QUASY object.

The declaration of the entity IfcRelSpaceBoundaries is optional, and not all CA(A)D systems are supporting it. At the moment these data are only exported if the information is provided in the IFC file, and not automatically generated from the room geometry.

4.5 *The relief*

In IFC the Entity IfcSite contains an optional geometry for the relief. For this object all the different types of geometry are allowed. In most cases a geometric set (composition of any 2D or 3D curves), boundary representation (solid model) or as surface model are used. For the export to QUASY the geometry elements are split into triangles.

4.6 *Building extensions*

At the moment it is realised to generate the outer shell for a whole building complex, using and keeping the IFC semantic and exporting these data into QUASY. Parts of a building or building storey are intended in IFC but not yet used in existing CA(A)D systems. Therefore it is a nontrivial task to detect such details at the outer surface of a building without a semantic analogy. To identify these objects heuristic methods have to be used.

Examples for building extensions in the architectural manner are:

- Annexes
- Balconies
- Oriels
- Loggias
- Dormers
- Chimney

For oriels the method to identify this object in the geometry of a building or building storey will be exemplified. In practice an oriel is recognised by the fact, that the floor slab corbels outwards of the regular floor plan of a considered building storey. This starts up with the same distinguishing characteristic which is used to identify a balcony. But the building objects placed on this corbel are different. For a balcony there are either one or more railings, undefined objects (IfcBuildingElementProxy), or walls with a low height. Compared to that, an oriel has walls with full height of a storey and in these walls is at least one window.
The usage of heuristic methods for identification is not simple, and not all special cases can be covered. Therefore a user interaction could be necessary.

If one of the above listed architectural elements is found, the related faces from the outer shell will be removed and added to a QUASY object of the type QuBuildingExtension with a corresponding attribute code.

5. SUMMARY AND OUTLOOK

In this paper a new building model has been presented, dedicated to urban development applications. In terms of semantic complexity, the QUASY model lies in-between the CityGML standard and the IFC standard. In addition to CityGML it provides especially the following semantic extensions: storeys, passages, opening objects, and building variants, modelling different levels-of-detail and design respectively temporal variants. The QUASY model represents utilisation oriented semantic objects which are geometrically described by surfaces visible for the user of the building.

The generation of buildings in the QUASY system is supported by a parametric building model mainly based on floor plans, which can be edited interactively, and selected parameters describing the third dimension especially of the roofs. Future developments could be the extension of the parametric model to include further details of the building as for example doors, windows or balconies.

More complex buildings for QUASY are derived from CA(A)D data as the most important source of building data. The special problems of this transformation process between the CA(A)D-IFC-Format and QUASY were described in detail.

In the future the IFC transformation and extraction algorithms have to be completed and extended. Especially the task of making implicitly given semantics explicit, that means, the automatic derivation of semantic objects (e.g. balcony) from geometric representations by heuristics, seems to be a useful extension. A first step in that direction could be an editor for the interactive generation of semantic objects on the base of a geometric model (e.g. vrml, 3ds) by selection. This would be of practical use because geometric models are already available for many cities.

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