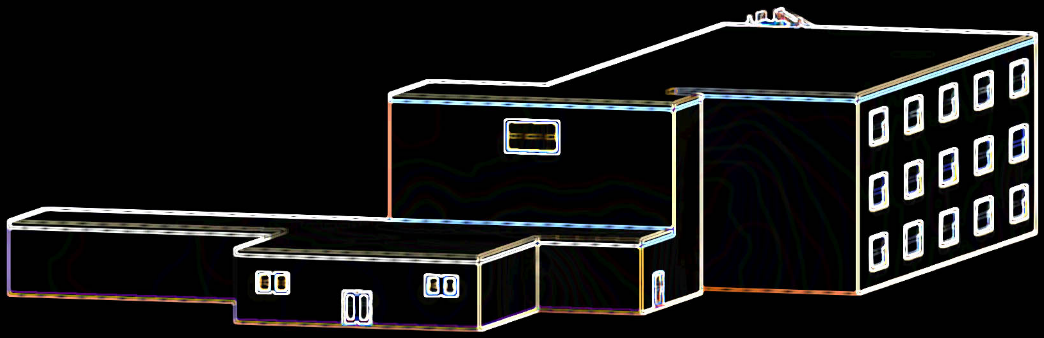
National Technical University of Athens

Interdisciplinary Programme of Postgraduate Studies “Environment & Development”

Investigating communication capabilities of CityGML and IFC for 3D city modelling



Master Thesis

Georgios S. Floros
Supervisor Professor: Efi Dimopoulou

Athens, September 2017

NATIONAL TECHNICAL UNIVERSITY OF ATHENS

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Investigating communication capabilities of CityGML and IFC for 3D city modelling

By

Georgios S. Floros

Examination Committee

Prof. Efi Dimopoulou	Prof. Yorgos Photis	Lect. Claire Ellul
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Athens, September 2017

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One journey draws to an end, while another one is about to begin. During my undergraduate and graduate studies at the National Technical University of Athens I have forged a well-rounded theoretical and technical background in the field of engineering. There have been, however, multiple obstacles and difficulties that I needed to surpass. The one and only person that helped me selflessly for more than three years is Prof. Efi Dimopoulou. She is not only my mentor, but she has introduced me to a fascinating new world. Under her guidance, I have achieved goals I could not even imagine. So, all I want to say is: “Thank you, Professor” and I promise you that I will always try to prove myself worthy of the faith you have placed in me.

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This thesis is a luminous beacon for me for multiple reasons. The conclusions of my studies so far can be summarized in two well-known words:

Carpe Diem

To: Evaggelia Maria and Spiros Goulielmos Aris

The following paper has been produced as part of the current thesis:

Floros, G., Pispidikis, I. and Dimopoulou E. [2017]. INVESTIGATING INTEGRATION CAPABILITIES BETWEEN IFC AND CITYGML LOD3 FOR 3D CITY MODELLING. Will be presented *at the 12th International 3D GeoInfo Conference*, Oct. 2017, Melbourne, Australia.

The following papers are relative works in the field of 3D Data Integration:

Floros, G., Solou, D., Pispidikis, I. and Dimopoulou, E. [2016]. A ROADMAP FOR GENERATING SEMANTICALLY ENRICHED CITYGML MODEL VIA TWO DIFFERENT METHODOLOGIES. In *Proceedings of 11th Joint International 3D GeoInfo Conference,* Oct. 2016, Athens, Greece.

Floros, G. and Dimopoulou, E. [2016]. INVESTIGATING THE ENRICHMENT OF A 3D CITY MODEL WITH VARIOUS CITYGML MODULES. In *Proceedings of 11th Joint International 3D GeoInfo Conference*, Oct. 2016, Athens, Greece.

Floros, G., Tsiliakou, E., Kitsakis, D., Pispidikis, I. and Dimopoulou, E. [2015]. Investigating Semantic Functionality of 3d Geometry for Land Administration. In *Proceedings of 10th Joint International 3D GeoInfo Conference*, Oct. 2015, Kuala Lumpur, Malaysia.

Dimopoulou, E., Tsiliakou, E., Kosti, V., Floros, G. and Labropoulos, T. [2014]. Investigating Integration Possibilities between 3D Modeling Techniques. In *Proceedings of 9th International 3D GeoInfo Conference*, Nov. 2014, Dubai. United Arab Emirates.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abstract

"Smart cities" is a relatively new scientific field, applied to an increasing number of application fields. This evolution though, urges data collection and integration, hence major issues arise that need to be tackled. One of the most important challenges is the heterogeneity of collected data, especially if those data derive from different standards and vary in terms of geometry, topology and semantics. Another key challenge is the efficient analysis and visualization of spatial data, which due to the complexity of the physical reality in modern world, 2D GIS struggles to cope with. So, in order to facilitate data analysis and enhance the role of smart cities, the 3rd dimension needs to be implemented. Within this context, standards such as the CityGML and the Industry Foundation Classes (IFC) although fulfill this necessity, they present major differences in their schemas, thus rendering their integration a challenging task. On one hand, CityGML is an open standard that stores and represents information of the entities that can be addressed in a modern 3D city model, while on the other hand IFC describes in maximum detail the construction of a building from an architectural point of view. The aim of this thesis is to investigate the integration possibilities of the aforementioned standards, starting from generating the IFC model and ending with generating a CityGML LoD 4 model, able to preserve its semantic information and be further extended with multiple attributes and properties.

The 1st step of the methodology is the development of the prototype models in BIM, which represent real-world objects. The modelling procedure is presented and analyzed with respect to the key differences that can be noticed between IFC and CityGML in terms of geometry and semantics. Within this context, information that are critical for the correct mapping of semantics are extruded and utilized in the stage of conversion and enrichment. By generating the IFC model there is an opportunity to investigate common errors that might be included in a model such as overlapping surfaces and develop a conversion algorithm that is able to tackle them efficiently.

Secondly, follows the conversion of IFC to CityGML LoD 4 model by implementing Extract Transformation Load (ETL) process. The entities of the IFC model are extracted and manipulated separately. The process is divided in two stages: geometric correction and semantic mapping. With regard to the geometric correction, it is further sub-divided in geometry processing inside FME Workbench and geometry processing in Trimble SketchUp. Semantic mapping occurs inside FME Workbench and complies with the CityGML principles. The CityGML LoD 4 model is generated and evaluated both geometrically and semantically. Then, the preservation of semantics is investigated. The type of semantics that are taken into consideration in this thesis are: (i) general semantic information that exists in every IFC model, (ii) semantic information with respect to the texture and material of each boundary surface that can be implemented for energy management purposes and (iii) semantics that contain attributes and properties with respect to the legal and

cadastral aspect of a 3D model. The aforementioned semantic types can be located in multiple CityGML features. More specifically, the material surface refers to the boundary surfaces of the model, the generic semantics refer to components and boundary surfaces of the model and legal information refer to the interior "free space" of the model. The last step of the developed methodology involves the transfer of the preserved semantics to the CityGML model. This is feasible either via (i) Generic objects and attributes or (ii) CityGML ADEs. Both methods are investigated and the results are clearly presented.

Lastly, an evaluation of the overall process takes place, in response to the research questions. Additionally, conclusions and general remarks regarding the advantages and disadvantages of the presented methodology are presented. The complexity of the process allows for future research work included in 3D modelling, data conversion and model extension. Concluding remarks for both standards are briefly presented in the final part of this thesis.

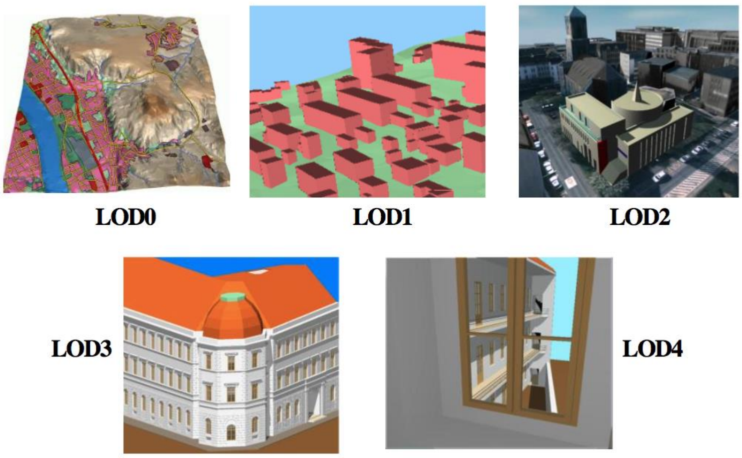
Περίληψη

Σε μία εποχή που η συλλογή πληροφορίας έχει καταστεί ιδιαίτερα προσβάσιμη, είναι σημαντικό να ερευνηθούν τα εργαλεία με τα οποία μπορεί να αξιοποιηθεί, με σκοπό τον ολοκληρωμένο σχεδιασμό για την ανάπτυξη μίας περιοχής. Η συγκεκριμένη μεταπτυχιακή εργασία έχει ως στόχο να διερευνήσει τη διαλειτουργικότητα συγκεκριμένων εργαλείων και προτύπων Γεωγραφικών Συστημάτων Πληροφοριών που είναι σε θέση να δεχτούν και να διαχειριστούν την υπάρχουσα πληροφορία και να δημιουργήσουν ένα τρισδιάστατο μοντέλο πόλης. Αναπτύσσεται μία μεθοδολογία που επιχειρεί να αντιμετωπίσει τις ιδιαιτερότητες μεταξύ των ανοιχτών προτύπων CityGML και Industry Foundation Classes (IFC). Το CityGML αποτελεί ένα ανοιχτό πρότυπο αποθήκευσης και διαχείρισης 3D μοντέλων πόλεων [OGC 12-019, 2012], ενώ το IFC είναι ένα ανοιχτό πρότυπο που περιέχει πληροφορία για τον κύκλο ζωής ενός κτηρίου [buildingSMART, 2007] και υλοποιείται μέσω της διαδικασίας Building Information Modelling (BIM). Τα βήματα της εφαρμογής μελέτης περιλαμβάνουν τη δημιουργία ενός πολύπλοκου 3D IFC μοντέλου, τη μετατροπή του σε CityGML LoD 4, την έρευνα για τη διατήρηση της αρχικής πληροφορίας και τη σημασιολογική επέκταση του μοντέλου με πληροφορία που μπορεί να αξιοποιηθεί σε διαφορετικούς τομείς εφαρμογών.

CityGML & IFC

Το CityGML είναι ένα μοντέλο σημασιολογικής πληροφορίας, για την απεικόνιση τρισδιάστατων αντικειμένων, τα οποία είναι δυνατόν να διαμοιράζονται μεταξύ των διαφορετικών εφαρμογών [OGC 12-019, 2012]. Η συγκεκριμένη αυτή δυνατότητα, είναι ιδιαίτερα χρήσιμη όσον αφορά τη σχέση κόστους-οφέλους της δημιουργίας ενός τρισδιάστατου μοντέλου, μιας και επιτρέπει την πώληση των ίδιων δεδομένων σε αντιπροσώπους διαφορετικών πεδίων εφαρμογών. Ενδεικτικά πεδία εφαρμογών, περιλαμβάνουν, τον σχεδιασμό πόλεων, την αρχιτεκτονική των κτηρίων, τουριστικές και ψυχαγωγικές δραστηριότητες, περιβαλλοντικές προσομοιώσεις, διαχείριση αξιών γης, και πλοήγηση πεζών και οδηγών. Το CityGML έχει σχεδιαστεί ως ένα μοντέλο ανοιχτού πακέτου δεδομένων, βασισμένο στη μορφή αρχείου XML, για την αποθήκευση και μεταφορά των εικονικών τρισδιάστατων μοντέλων πόλεων. Ορίζει τις κλάσεις και τις σχέσεις για τα πιο συνηθισμένα τοπογραφικά αντικείμενα σε μία πόλη με σεβασμό στις γεωμετρικές, τοπολογικές και σημασιολογικές ιδιότητές τους. Ο ορισμός της πόλης, δεν περιλαμβάνει αποκλειστικά τις δομικές κατασκευές όπως κτήρια, αλλά και τη βλάστηση, τις υδάτινες επιφάνειες, κ.ά. Επίσης, περιλαμβάνονται, οι ιεραρχικές δομές μεταξύ των θεματικών κλάσεων, σχέσεις μεταξύ των αντικειμένων και οι χωρικές ιδιότητες τους. Το CityGML εφαρμόζεται τόσο σε περιοχές πολλών τετραγωνικών μέτρων όσο και σε μικρότερες και είναι σε θέση να αναπαριστά το έδαφος και τα αντικείμενα πάνω σε αυτό, σε διαφορετικά επίπεδα πληροφορίας ταυτόχρονα.

Το CityGML υποστηρίζει πέντε διαφορετικά επίπεδα πληροφορίας(LoD) τα οποία διευκολύνουν την αποτελεσματική οπτικοποίηση και την βέλτιστη ανάλυση των δεδομένων (Εικόνα 1). Σε ένα αρχείο CityGML, το ίδιο αντικείμενο μπορεί να απεικονίζεται σε διαφορετικά επίπεδα πληροφορίας ταυτόχρονα, ενεργοποιώντας με αυτόν τον τρόπο τη δυνατότητα ανάλυσης και οπτικοποίησης του αντικειμένου με έμφαση στις διαφορετικές βαθμίδες της οπτικής ανάλυσης. Επιπλέον, δύο διαφορετικά CityGML αρχεία που περιλαμβάνουν το ίδιο αντικείμενο σε διαφορετικά επίπεδα πληροφορίας, είναι δυνατό να συνδυαστούν σε ένα κοινό μοντέλο. Παρόλα αυτά, είναι ευθύνη του χρήστη να εξασφαλίσει πως τα δύο αντικείμενα με διαφορετικό επίπεδο πληροφορίας, απεικονίζουν το ίδιο αντικείμενο στον πραγματικό κόσμο. Το χαμηλότερο επίπεδο πληροφορίας LoD 0 είναι ένα Ψηφιακό Μοντέλο Εδάφους δύο διαστάσεων, πάνω από το οποίο μπορεί να τοποθετηθεί μία αεροφωτογραφία ή ένας χάρτης. Τα κτήρια είναι δυνατόν να απεικονίζονται σε LoD 0 μέσω των εμβαδών τους ή με πολύγωνα των διαστάσεων των σκεπών τους. Το LoD 1 απεικονίζει τα κτήρια πρισματικά με επίπεδες σκεπές. Εν αντιθέσει, ένα κτήριο στο LoD 2, εμφανίζει τις διαφορές μεταξύ των σκεπών και την εξωτερική οπτική πληροφορία των κτηρίων. Το LoD 3 απεικονίζει αρχιτεκτονικά μοντέλα με έντονες λεπτομέρειες στους τοίχους και τις σκεπές και συχνά περιλαμβάνει παράθυρα και πόρτες. Το LoD 4 συμπληρώνει ένα LoD 3 μοντέλο, προσθέτοντας εσωτερικές κατασκευές στα κτήρια. Για παράδειγμα, τα κτήρια στο LoD 4 απαρτίζονται από δωμάτια, εσωτερικές πόρτες, εσωτερικές σκάλες και έπιπλα [OGC 12-019, 2012, σελ. 11].



Εικόνα 1: Επίπεδα πληροφορίας (LoD) στο CityGML [Πηγή: OGC 12-019, 2012]

Η διαδικασία BIM είναι μία 3D διαδικασία μοντελοποίησης η οποία περιγράφει τις γεωμετρικές και σημασιολογικές ιδιότητες ενός κτηρίου και ουσιαστικά παρακολουθεί και περιγράφει τον κύκλο ζωής του κτηρίου. Μπορεί επομένως να οριστεί σαν την ψηφιακή αναπαράσταση των λειτουργικών χαρακτηριστικών ενός κτηρίου και του ευρύτερου περιβάλλοντός του [Isikdag & Zlatanova, 2009]. Σήμερα, η διαδικασία BIM αποτελεί ένα πολύ σημαντικό εργαλείο για την κατανομή της πληροφορίας κατά τη λήψη αποφάσεων στη δημιουργία και πορεία ενός κτηρίου. Επίσης, η χρήση της διαδικασίας BIM καθιστά δυνατή τη συνεργασία διαφορετικών ειδικοτήτων μηχανικών καθόλα τα στάδια του κύκλου ζωής του κτηρίου, δημιουργώντας έτσι μία βάση για την ανανέωση της πληροφορίας του κτηρίου με σκοπό την όσο πιο δυνατόν άμεση προσαρμογή του στις νέες απαιτήσεις του εκάστοτε σχεδιασμού (πρότζεκτ). Τα BIM μοντέλα μπορούν να δημιουργηθούν από πολιτικούς μηχανικούς ή αρχιτέκτονες κατά τη φάση σχεδιασμού η δόμησης ενός κτηρίου.

Οι Howell & Batcheler [2005] διατύπωσαν τα πλεονεκτήματα της διαδικασίας BIM ως εξής:

- Γεωμετρική ακρίβεια του μοντέλου
- Δυνατότητα δημιουργίας αντικειμένων διαφορετικών ειδικοτήτων σε ένα κοινό μοντέλο
- Δυνατότητα εύκολης αναβάθμισης των δομικών στοιχείων ενός μοντέλου (πόρτες, παράθυρα), διατηρώντας το με αυτόν τον τρόπο σύγχρονο στις αλλαγές που δέχεται το πραγματικό κτήριο
- Η συγκέντρωση της πληροφορίας σε ένα αρχείο BIM δίνει τη δυνατότητα για την εύκολη προσθήκη ενδεχόμενης μελλοντικής πληροφορίας, καθιστώντας το μοντέλο ιδιαίτερα εύχρηστο.

Το πιο ευρέως διαδεδομένο σημασιολογικό μοντέλο το οποίο εφαρμόζει τη διαδικασία BIM είναι το πρότυπο Industry Foundation Classes (IFC). Το πρότυπο IFC είναι ένα μοντέλο ανοιχτού κώδικα το οποίο έχει αναπτυχθεί από τον οργανισμό buildingSMART και βασίζεται στην γλώσσα EXPRESS ως μέλος του: STandard for the Exchange of Product model data (STEP) standard (ISO 103030) [buildingSMART, 2013].

Το πρότυπο IFC χρησιμοποιείται για να περιγράφει, ανταλλάζει, διαμοιράζει και ορίζει πως πρέπει η πληροφορία να αποθηκεύεται και να διαχειρίζεται κατά τον κύκλο ζωής ενός κτηρίου [El-Mekawy et al., 2012]. Αποτελεί το διεθνές πρότυπο για την BIM μοντελοποίηση και χρησιμοποιείται για να δημιουργεί το μοντέλο μίας εγκατάστασης που θα περιέχει όλη την πληροφορία και τις σχέσεις μεταξύ των δομικών της στοιχείων. Οι 3 βασικές κατηγορίες γεωμετρίας για το IFC 2X3 είναι οι ακόλουθες: b-rep, swept volumes και CSG και τα επίπεδα λεπτομέρειας απεικόνισης ενός κτηρίου κυμαίνονται από LOD 100 μέχρι LOD 500.

Εξέλιξη της ερευνητικής δραστηριότητας μέχρι σήμερα

Η μέχρι σήμερα έρευνα γύρω από τη διερεύνηση της διαλειτουργικότητας των δύο προτύπων εστιάζει στην επίλυση των σημαντικών γεωμετρικών διαφορών που παρατηρούνται μεταξύ τους. Αναδεικνύεται όμως η ανάγκη και για την διατήρηση της σημασιολογικής πληροφορίας, η οποία δεν μεταφέρεται κατά την μετατροπή του μοντέλου. Η συγκεκριμένη εργασία έχει ως σκοπό να προσεγγίσει τα παρακάτω ερευνητικά πεδία:

1. Δημιουργία μοντέλου στο ανώτερο επίπεδο λεπτομέρειας (CityGML LoD 4).

2. Διατήρηση της σημασιολογικής πληροφορίας που περιέχεται σε ένα IFC μοντέλο.

3. Μεταφορά της σημασιολογικής πληροφορίας στο τελικώς παραγόμενο μοντέλο, ώστε να μπορεί να αξιοποιηθεί σε διαφορετικά πεδία εφαρμογών.

Προκειμένου να επιτευχθούν τα ανωτέρω ζητήματα, αξιοποιείται η διαδικασία Extract Transformation Load (ETL), η οποία επιτρέπει την διάσπαση του IFC μοντέλου στις επιμέρους οντότητές τους και την διακριτή διαχείριση και μετατροπή της κάθε μίας. Επίσης, το συγκεκριμένο εργαλείο, επιτρέπει την αποθήκευση και διατήρηση της πληροφορίας καθόλα τα στάδια της μετατροπής. Τέλος, είναι δυνατή η διόρθωση λαθών που επηρεάζουν το τελικώς παραγόμενο μοντέλο, τόσο σε γεωμετρικό όσο και σε σημασιολογικό επίπεδο

Στόχοι της μεταπτυχιακής εργασίας

Το βασικό ερευνητικό ερώτημα που καλείται να απαντήσει η συγκεκριμένη εργασία είναι:

«Πώς η προτεινόμενη μεθοδολογία διαχειρίζεται τη μετατροπή της γεωμετρίας και της σημασιολογικής πληροφορίας από το πρότυπο IFC, έτσι ώστε να δημιουργήσει ένα συμβατό μοντέλο με το πρότυπο CityGML σε επίπεδο λεπτομέρειας LoD 4 και σε ποιο βαθμό διατηρείται και αξιοποιείται η υπάρχουσα σημασιολογική πληροφορία;»

Προκειμένου το παραπάνω ερώτημα να γίνει πιο κατανοητό και να διευκολύνει την τελική αξιολόγησή της εργασίας, μπορεί να διασπαστεί σε επιμέρους ερωτήματα:

1. Ποιες ιδιαιτερότητες παρουσιάζονται κατά τη μοντελοποίηση μέσω Building Information Modelling (BIM) σε σχέση με τη γεωμετρία και τη σημασιολογική πληροφορία στο CityGML;

2. Κατά τη διαδικασία της μετατροπής, ποια μεθοδολογική προσέγγιση ακολουθείται σχετικά με τη διαχείριση της γεωμετρίας και της σημασιολογικής πληροφορίας;

3. Κατά πόσον ο αλγόριθμός που δημιουργείται είναι κατάλληλος για ένα άλλο κτήριο και ποια χειροκίνητη προσαρμογή χρειάζεται προκειμένου να καταστεί κατάλληλος για τη μετατροπή του νέου κτηρίου;

4. Με ποιους τρόπους μπορεί να επεκταθεί σημασιολογικά το CityGML μοντέλο και πως προστίθεται η πληροφορία σε περιβάλλον BIM;

Ο σκοπός της συγκεκριμένης μεταπτυχιακής εργασίας είναι η διερεύνηση μίας μεθοδολογίας η οποία περιλαμβάνει την μελέτη και ανάπτυξη συγκεκριμένων εργαλείων με σκοπό την παραγωγή σημασιολογικά εμπλουτισμένων τρισδιάστατων μοντέλων που μπορούν να εισαχθούν στο περιβάλλον μίας έξυπνης πόλης. Η μέθοδος που αναπτύσσεται έχει ως σκοπό να μετατρέψει ένα IFC μοντέλο σε CityGML Level of Detail (LoD) 4. Ένα μοντέλο CityGML LoD 4, περιλαμβάνει το μέγιστο της πληροφορίας που υποστηρίζεται από το συγκεκριμένο πρότυπο. Παρόλα αυτά, η σημασιολογική πληροφορία στο IFC είναι σημαντικά περισσότερη σε σχέση με το CityGML. Σε αυτό το πλαίσιο, διατηρούνται τα σημασιολογικά στοιχεία που περιγράφουν γενικευμένες ιδιότητες του IFC, καθώς και η πληροφορία που περιγράφει την επιφάνεια και το υλικό κατασκευής των κτηρίων καθώς και τις νομικές και κτηματολογικές ιδιότητες ενός μοντέλου. Η συγκεκριμένη εργασία ερευνά όλα τα στάδια για την τελική παραγωγή ενός CityGML μοντέλου. Πιο συγκεκριμένα, ξεκινάει από το στάδιο της 3D μοντελοποίησης μέσω BIM και δημιουργούνται μοντέλα που αναπαριστούν κτήρια του πραγματικού κόσμου. Το επόμενο στάδιο που αφορά την μετατροπή γίνεται αξιοποιώντας τη διαδικασία Extract Transformation Load (ETL) και διαχωρίζεται στην διόρθωση της γεωμετρίας και στην σημασιολογική αντιστοίχιση των οντοτήτων των δύο προτύπων. Τέλος, ερευνάται κατά πόσον διατηρείται η αρχική πληροφορία και αν είναι δυνατόν το παραγόμενο μοντέλο να εμπλουτιστεί με τη συγκεκριμένη πληροφορία.

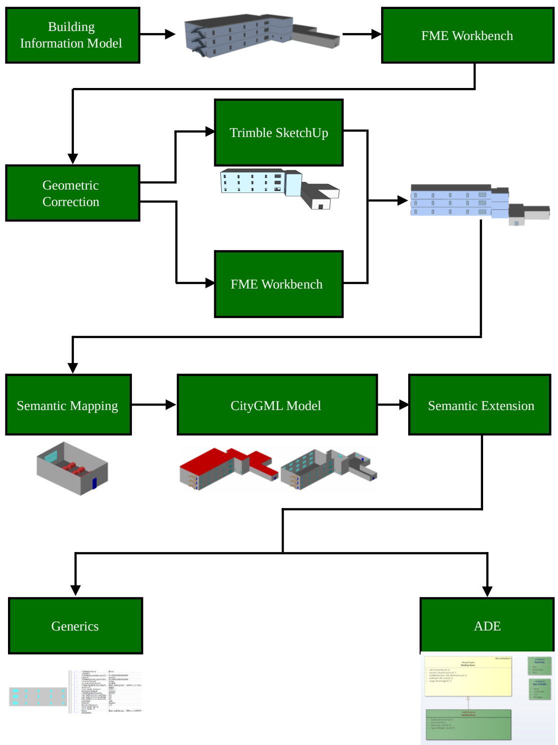
Οι τομείς έρευνας που δεν εξετάζονται σε αυτή την εργασία είναι οι εξής: αρχικά, η μελέτη γίνεται αποκλειστικά για ένα κτήριο μιας και δεν λαμβάνεται υπόψιν η μορφολογία της περιοχής, καθώς και συστατικά στοιχεία μίας πόλης όπως είναι το οδικό δίκτυο, γέφυρες, φανάρια, βλάστηση. Επίσης, η μετάβαση από ένα μοντέλο LoD 4 σε μικρότερο LoD δεν αντιμετωπίζεται σε αυτήν την εργασία. Ακόμα, πρέπει να σημειωθεί πως το συγκεκριμένο εργαλείο λειτουργεί για ένα μοντέλο IFC. Σε περίπτωση που υπάρχουν περισσότερα από ένα κτήρια, πρέπει να προσαρμοστεί ανάλογα, ή να διασπαστεί το συνολικό IFC μοντέλο σε επιμέρους τμήματα και να μετατραπεί το κάθε κτήριο ξεχωριστά. Τέλος, τα παραγόμενα μοντέλα περιλαμβάνουν σημασιολογική πληροφορία, η οποία μπορεί να εμπλουτιστεί έτσι ώστε να χρησιμοποιηθούν για συγκεκριμένες εφαρμογές.

Δομή της εργασίας

Στο κεφάλαιο 2, γίνεται μία παρουσίαση της έξυπνης πόλης, των δομικών της στοιχείων και αναδεικνύεται η ανάγκη για την εφαρμογή της 3^{ης} διάστασης (3D) μέσω εφαρμογών σε τομείς έρευνας όπως η διαχείριση ενέργειας, η αξιοποίηση της ηλιακής ακτινοβολίας και η δημιουργία ενός 3D Κτηματολογίου. Στο κεφάλαιο 3, παρουσιάζονται τα πρότυπα της συγκεκριμένης μελέτης, το IFC [buildingSMART, 2007] και το CityGML [OGC 12-019, 2012], τα χαρακτηριστικά τους, καθώς και πληροφορία για τον τρόπο διαχείρισης της γεωμετρίας και της σημασιολογίας στο καθένα. Κατόπιν, με μία εφαρμογή μελετάται η δυνατότητα επικοινωνίας μεταξύ των δύο προτύπων. Οι ιδιαιτερότητες και τα προβλήματα που εντοπίζονται εστιάζουν στην επίλυση των γεωμετρικών διαφορών μεταξύ των δύο προτύπων. Στο κεφάλαιο 4, γίνεται μία λεπτομερής ανάλυση της έρευνας που έχει προηγηθεί, κατηγοριοποιούνται και καταγράφονται τα πλεονεκτήματα και μειονεκτήματα της κάθε μεθόδου και εντοπίζονται τα κενά, μερικά εκ των οποίων καλείται απαντήσει η συγκεκριμένη εργασία. Στο κεφάλαιο 5, παρουσιάζεται η εφαρμογή, η οποία αρχικά παρουσιάζει τις περιοχές μελέτης που είναι τα κτήρια των Ηλεκτρολόγων Μηχανικών & Μηχανικών Υπολογιστών του Εθνικού Μετσόβιου Πολυτεχνείου, καθώς και ένα κτήριο στο Δήμο Χαλανδρίου. Και τα δύο μοντέλα σχεδιάζονται και απεικονίζονται ψηφιακά σε τρισδιάστατη μορφή με τη μέθοδο μοντελοποίησης BIM, με βάση τα αρχιτεκτονικά τους σχέδια. Κατόπιν, ερευνώνται οι δυνατότητες μετάβασης μεταξύ των δύο προτύπων με μία διαδικασία μετατροπής της γεωμετρικής και σημασιολογικής τους πληροφορίας Στη συνέχεια, πραγματοποιείται η επέκταση του μοντέλου με τις παρεχόμενες δυνατότητες του CityGML. Στο κεφάλαιο 6, πραγματοποιείται η αξιολόγηση της συγκεκριμένης εργασίας με βάση τα ερωτήματα που έχουν τεθεί, διατυπώνονται τελικά συμπεράσματα και παρουσιάζονται προτάσεις για μελλοντική έρευνα.

Μεθοδολογική προσέγγιση

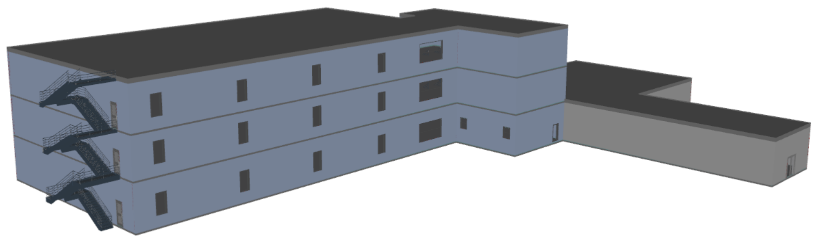
Η μεθοδολογία της διαδικασίας έχει ως σκοπό να διερευνήσει τα προβλήματα που εντοπίζονται μεταξύ των δύο προτύπων σε γεωμετρικό και σημασιολογικό επίπεδο. Για αυτό το λόγο, αρχικά δημιουργείται το μοντέλο μέσω της διαδικασίας BIM και εξάγεται στο πρότυπο IFC 2X3. Στη συνέχεια, εισάγεται στο FME Workbench και εκτελείται η μετατροπή του σε μορφή CityGML, όπου σε πρώτη φάση πραγματοποιείται η γεωμετρική διόρθωση του μοντέλου και εν συνεχεία η σημασιολογική αντιστοίχιση μεταξύ των οντοτήτων του IFC και του CityGML. Τέλος, διερευνάται η διατήρηση της σημασιολογικής πληροφορίας και οι δυνατότητες επέκτασης του παραγόμενου CityGML μοντέλου μέσω των δύο μεθόδων που προτείνει το πρότυπο του CityGML. Το διάγραμμα ροής της διαδικασίας παρουσιάζεται στην εικόνα 2.



Εικόνα 2: Διάγραμμα ροής της διαδικασίας

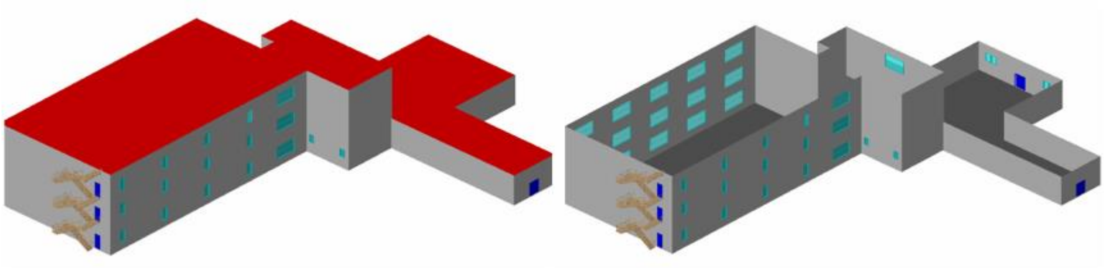
Εφαρμογή

Η εφαρμογή της συγκεκριμένης εργασίας μπορεί να διαχωρισθεί σε 3 φάσεις: μοντελοποίηση, μετατροπή και επέκταση. Στη φάση της μοντελοποίησης, το πρώτο βήμα είναι η γεωαναφορά των κτηρίων. Για το σκοπό αυτό, με τη χρήση γεωαναφερμένων ορθοφωτογραφιών ψηφιοποιούνται τα 2Δ όρια των κτηρίων σε περιβάλλον AutoCAD και στη συνέχεια εισάγονται στο λογισμικό Autodesk Revit. Το Γεωγραφικό Σύστημα Αναφοράς των μοντέλων είναι το Ελληνικό γεωδαιτικό Σύστημα Αναφοράς 1987. Το επόμενο βήμα είναι η δημιουργία των όψεων, έτσι ώστε να μπορούν να οριστούν τα επίπεδα που θα αποτελούν τα όρια των επιφανειών. Για παράδειγμα, ένας εξωτερικός τοίχος έχει ως κάτω όριο το επίπεδο: Δάπεδο και ως πάνω όριο το επίπεδο: 1ος όροφος. Ακολούθως, δημιουργείται γεωμετρικά το μοντέλο με βάση τα αρχιτεκτονικά σχέδια. Τέλος, εμπλουτίζεται με αντικείμενα όπως για παράδειγμα έπιπλα, εσωτερικές και εξωτερικές σκάλες, καθώς και με σημασιολογική πληροφορία κτηματολογικού και ενεργειακού τύπου με τη χρήση της λειτουργίας Schedules που παρέχεται από το πρόγραμμα και γίνεται εξαγωγή του μοντέλου σε μορφή IFC 2X3 (Εικόνα 3).

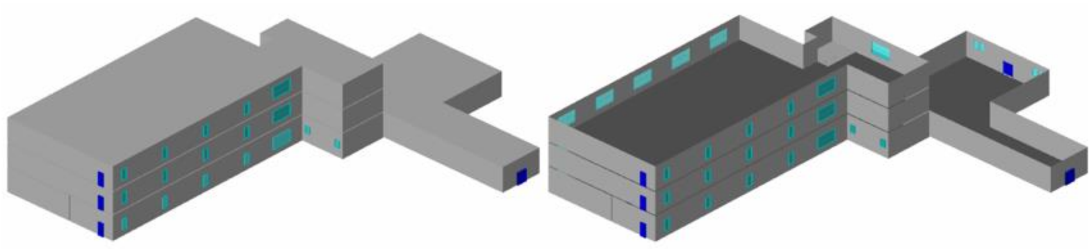


Εικόνα 3: Παραγόμενο IFC 2X3 μοντέλο

Κατά τη φάση της μετατροπής, το μοντέλο εισάγεται στο λογισμικό FME Workbench, το οποίο αξιοποιεί τη διαδικασία Extract Transformation Load (ETL) και ξεκινάει η μετατροπή του μοντέλου. Το 1ο στάδιο είναι η γεωμετρική διόρθωση, έτσι ώστε η νέα γεωμετρία να είναι συμβατή με το πρότυπο του CityGML. Η γεωμετρική διόρθωση του μοντέλου πραγματοποιείται σε δύο επιμέρους φάσεις. Κατά την 1η φάση, γίνεται η εξαγωγή των γεωμετριών των τοίχων, της οροφής και του δαπέδου σε μορφή .skp, η οποία υποστηρίζεται από το πρόγραμμα Trimble SketchUp. Ο λόγος της παραπάνω ενέργειας είναι το γεγονός πως οι υφιστάμενες λειτουργίες του FME Workbench, δεν είναι σε θέση να αντιμετωπίσουν πλήρως αποτελεσματικά τις σύνθετες γεωμετρίες των συγκεκριμένων μοντέλων. Μόλις ολοκληρωθεί η διόρθωση στο trimble SketchUp, το μοντέλο επανεισάγεται στο FME Workbench. Κατά τη 2η φάση, γίνεται η διαχείριση της γεωμετρίας των υπόλοιπων οντοτήτων του μοντέλου, δηλαδή τις πόρτες, τα παράθυρα, τα έπιπλα, τα δωμάτια και τις εξωτερικές και εσωτερικές εγκαταστάσεις (σκάλες, κλπ.), η οποία πραγματοποιείται με επιτυχία στο περιβάλλον του Feature Manipulation Engine (FME) Workbench. Το $2^{ο}$ στάδιο αφορά τη σημασιολογική αντιστοίχιση των οντοτήτων του IFC με το πρότυπο του CitygGML. Σε αυτό το σημείο, αξίζει να αναφερθεί πως η σημασιολογική πληροφορία που υπήρχε στις επιφάνειες των τοίχων, οροφής και δαπέδου, δεν υποστηρίζεται από το Trimble SketchUp. Για αυτό το λόγο, εγγράφεται ξεχωριστά σε ένα αρχείο .csv και στη συνέχεια, αφού το μοντέλο έχει διορθωθεί, επανεισάγεται στο περιβάλλον του FME Workbench και αντιστοιχίζεται με την αποθηκευμένη σημασιολογική πληροφορίας. Με τη χρήση των κατάλληλων μετατροπέων (transformers) η σημασιολογική αντιστοίχιση πραγματοποιείται με επιτυχία εντός του περιβάλλοντος του FME Workbench και παράγεται το τελικό μοντέλο σε CityGML LoD 3 και 4 (Εικόνες 4 & 5).

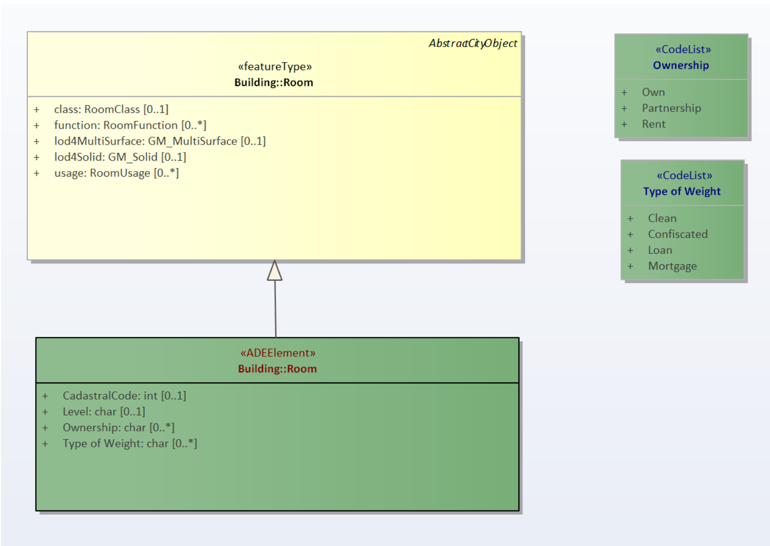


Εικόνα 4: CityGML μοντέλο σε LoD 3



Εικόνα 5: CityGML μοντέλο σε LoD 4

Το τελευταίο στάδιο είναι η σημασιολογική επέκταση του μοντέλου. Αρχικά, διερευνάται η διατήρηση της σημασιολογικής πληροφορίας του μοντέλου, εξετάζοντας τις οντότητες ξεχωριστά. Διαπιστώνεται πως η πληροφορία έχει παραμείνει ανέπαφη κατά τη μετατροπή και είναι σε θέση να εμπλουτίσει το παραγόμενο μοντέλο. Η επέκταση του μοντέλου γίνεται με τους δύο τρόπους που υποστηρίζει και προτείνει το πρότυπο CityGML: (i) με τη δημιουργία Generics attributes και (ii) με τη δημιουργία Application Domain Extension (ADE). Όσον αφορά την $1^{η}$ μέθοδο, τα δύο μοντέλα εμπλουτίζονται με διαφορετικού είδους πληροφορία. Το $1^{ο}$ μοντέλο, το κτήριο των Ηλεκτρολόγων μηχανικών, δέχεται τη γενική σημασιολογική πληροφορία που περιέχει ένα αρχείο IFC κατά τη δημιουργία του και περιλαμβάνει χαρακτηριστικά σχετικά με τις ιδιότητες των επιφανειών και των αντικειμένων (είδος αντικειμένου, εξωτερική/εσωτερική χρήση, θερμοδιαπερότητα, μονάδες μέτρησης, κλπ.). Εμπλουτίζεται επιπλέον με σημασιολογική πληροφορία η οποία αφορά το υλικό κατασκευής ενός αντικειμένου καθώς και την υφή της κάθε επιφάνειας, ιδιότητες απαραίτητες για την αξιοποίηση του μοντέλου σε ενεργειακές εφαρμογές. Το 2° μοντέλο, το κτήριο στο Χαλάνδρι, εμπλουτίζεται ακολουθώντας την ίδια μέθοδο με νομική και κτηματολογική πληροφορία. Πιο συγκεκριμένα, εισάγονται ιδιότητες όπως ο Κωδικός Αριθμός Εθνικού Κτηματολογίου (ΚΑΕΚ), η χρήση γης του κτηρίου, ενδεχόμενες δουλείες και βάρη καθώς και ο τύπος της ιδιοκτησίας. Πρόκειται για έναν τομέα στον οποίο τα 3D μοντέλα έχουν πολύ σημαντική χρησιμότητα και εφαρμογή και τον οποίο δεν καλύπτει στην υπάρχουσα κατάσταση το πρότυπο του CityGML. Σε αυτό το πλαίσιο, εξετάζεται και η 2η μέθοδος που προτείνει το CityGML. Η δημιουργία ενός ADE συνίσταται προκειμένου να αντιμετωπίσει συνολικά ένα ζήτημα, για αυτό το λόγο εφαρμόζεται μόνο στο 2° μοντέλο. Δημιουργείται επομένως, ένα ADE, το οποίο θα μεταφέρει την παραπάνω κτηματολογική πληροφορία στο CityGML μοντέλο. Το προτεινόμενο ADE βρίσκεται υπό ανάπτυξη μιας και είναι αναγκαίο να περιλαμβάνει επιπλέον πληροφορία προκειμένου να αντιμετωπίσει την πολυπλοκότητα των νομικών και φυσικών οντοτήτων του πραγματικού κόσμου (Εικόνα 6).



Εικόνα 6: Σημασιολογική επέκταση μέσω ADE

Όσον αφορά την αξιολόγηση της συγκεκριμένης εργασίας μπορεί να πραγματοποιηθεί με βάση τα 4 ερωτήματα που τέθηκαν αρχικά. Σχετικά με το 1° ερώτημα, σημαντικές διαφοροποιήσεις παρατηρούνται κατά τη δημιουργία των οροφών του κάθε ορόφου. Στο IFC χαρακτηρίζονται ως floors, αντίθετα στο CityGML διασπώνται σε ceilings και floors. Πρέπει επομένως να ληφθεί υπόψιν αυτή η ιδιαιτερότητα κατά τη σημασιολογική μετατροπή, κάτι στο οποίο πλεονεκτεί η συγκεκριμένη μέθοδος έναντι σε αυτοματοποιημένες διαδικασίες οι οποίες ενδέχεται να μην πετυχαίνουν πάντα την ακριβή σημασιολογική μετατροπή. Επίσης, συχνά μία οντότητα στο IFC (π.χ. σκάλες) ενδέχεται να περιλαμβάνει παραπάνω από μία διαφορετικές οντότητες (π.χ. slabs και railings). Στο CityGML όμως, όλες αυτές οι λειτουργίες απεικονίζονται ως building installations, επομένως πρέπει να δομούνται σημασιολογικά ανάλογα. Τέλος, ανάλογα με το σκοπό εφαρμογής του κάθε κτηρίου, είναι δυνατή η διαφορετική γεωμετρική και σημασιολογική μοντελοποίηση, ένα φαινόμενο το οποίο η ευελιξία της συγκεκριμένης μεθόδου είναι σε θέση να αντιμετωπίσει. Σχετικά με το 2ο ερώτημα, είναι γεγονός πως η γεωμετρική διόρθωση του μοντέλου είναι πολύπλοκη διαδικασία και αναγκάζει τον χρήστη να είναι εξοικειωμένος με αρκετά διαφορετικά λογισμικά. Παρόλα αυτά, η διαδικασία της διόρθωσης δεν είναι ιδιαίτερα χρονοβόρα και έχει το πλεονέκτημα πως είναι σε θέση να διορθωθούν γεωμετρίες οι οποίες λόγω ενδεχόμενων λαθών στο μοντέλο να παράγουν επιφάνειες ή αντικείμενα που χάνουν γεωμετρική πληροφορία. Σχετικά με τη σημασιολογία, με την χρήση των κατάλληλων αλγορίθμων, είναι σε θέση να διατηρείται μέχρι και το στάδιο πριν την εγγραφή σε CityGML. Επίσης, είναι δυνατή η εξαγωγή της σημασιολογικής πληροφορίας σε μορφή .csv, γεγονός το οποίο επιτρέπει την διαχείριση και επεξεργασία της για την αντιμετώπιση ενδεχόμενων σφαλμάτων κατά τη διαδικασία της μοντελοποίησης. Σχετικά με το 3ο ερώτημα, η προτεινόμενη μεθοδολογία είναι σε θέση να μετατρέψει οποιοδήποτε κτήριο. Παρόλα αυτά, δεν είναι αυτοματοποιημένη διαδικασία, μιας και σε ενδεχόμενη αλλαγή του μοντέλου, ο χρήστης πρέπει να παρέμβει σε συγκεκριμένα σημεία, ώστε να διαχειριστεί σωστά την μετατροπή. Τέλος, σχετικά με το 4ο ερώτημα, ο σημασιολογικός εμπλουτισμός του μοντέλου είναι δυνατός με τη συγκεκριμένη μεθοδολογία. Η πληροφορία διατηρείται και μεταφέρεται με επιτυχία. Παρόλα αυτά, δεν μπορεί να εξαχθεί συνολικό συμπέρασμα για όλες τις εφαρμογές που έχει ένα BIM μοντέλο, αλλά διαφαίνεται αισιόδοξη προοπτική για τη δημιουργία μοντέλων για ενεργειακούς και κτηματολογικούς σκοπούς.

Σαν γενικό συμπέρασμα προκύπτει πως η προτεινόμενη διαδικασία είναι σε θέση να παράγει LoD 4 μοντέλα που είναι συμβατά με το πρότυπο του CityGML. Επίσης, κατά τη μετατροπή είναι σε θέση να αντιμετωπίζει γεωμετρικά και σημασιολογικά σφάλματα τα οποία δεν αντιμετωπίζονται πάντοτε από αυτοματοποιημένες μεθόδους που έχουν αναπτυχθεί έως σήμερα, για την εξαγωγή σε LoD 3. Τέλος, είναι σε θέση να διατηρεί και να μεταφέρει σημασιολογική πληροφορία, η οποία δομείται στο στάδιο της μοντελοποίησης. Στα αρνητικά της διαδικασίας είναι πως αποτελεί μία μετατροπή η οποία χρειάζεται χειροκίνητη παρέμβαση σε συγκεκριμένα σημεία, κάτι που αυξάνει το χρόνο μετατροπής. Επίσης, παρατηρούνται ζητήματα σχετικά με τη διαχείριση της γεωμετρίας σε επίπεδο LoD 4, όσον αφορά τα κτήρια τα οποία μοιράζονται κοινές επιφάνειες. Σε αυτή την περίπτωση, πρέπει ο εσωτερικός τοίχος ενός κτηρίου να αποτελεί το εξωτερικό τοίχο του άλλου κτηρίου και αντίστροφα. Λόγω του είδους των γεωμετριών στο IFC και στο CityGML, το συγκεκριμένο θέμα είναι υπό έρευνα μιας και μέχρι σήμερα η συγκεκριμένη μεθοδολογία ανήκει στις λίγες εκείνες που δημιουργούν μοντέλα LoD 4.

Μελλοντική έρευνα

Όσον αφορά προτάσεις για μελλοντική έρευνα, μπορούν να κατηγοριοποιηθούν πάλι με βάση τα στάδια τις μεθοδολογίας. Για τη μοντελοποίηση, είναι σημαντικό να ερευνηθεί η δημιουργία μοντέλων με σκοπό την εφαρμογή τους σε συγκεκριμένο τομέα, έτσι ώστε να εμπλουτιστούν με την ανάλογη σημασιολογική πληροφορία. Για τη μετατροπή είναι σημαντικό να αυτοματοποιηθεί η διαδικασία, το οποίο μπορεί να συμβεί με τη χρήση προγραμματισμού μέσα από το περιβάλλον του FME Workbench. Επίσης, ζητήματα σχετικά με την τοπολογία σε LoD 4 είναι σημαντικό να διερευνηθούν. Τέλος, προτείνεται να διερευνηθεί η η δημιουργία μοντέλων χαμηλότερων LoD, από μοντέλα σε υψηλότερο LoD. Όσον αφορά τη σημασιολογική επέκταση των μοντέλων, η διατήρηση της πληροφορία ανοίγει ένα νέο κεφάλαιο στην επικοινωνία μεταξύ των δύο προτύπων. Σε αυτό το πλαίσιο, προτείνεται η διερεύνηση για τη δημιουργία μοντέλων που θα αντιμετωπίζουν συνολικά κτηματολογικά και νομικά ζητήματα. Φυσικά, ανάλογα με το σκοπό χρήσης του κάθε μοντέλου, η διερεύνηση μπορεί να επεκταθεί σε ποικίλους τομείς προσφέροντας ουσιαστικά συμπεράσματα σχετικά με τη διατήρηση της πληροφορίας σε διαφορετικά πεδία εφαρμογών.

Abbreviation Terms

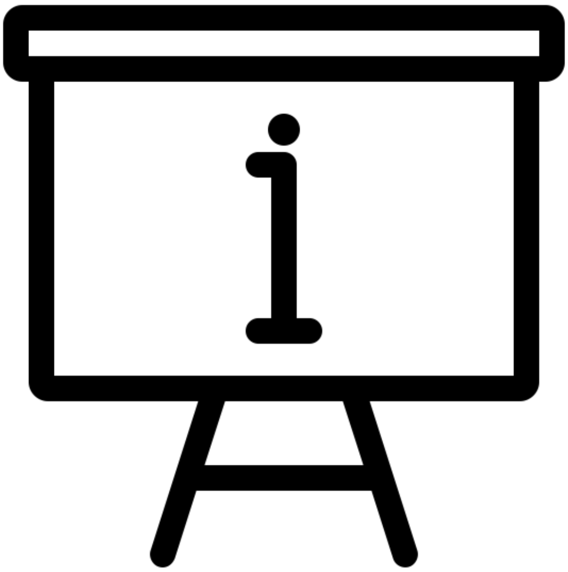
ADE	Application Domain Extension
AEC	Architecture, Engineering & Construction
B-rep	Boundary-representation
BIM	Building Information Modelling
CAD	Computer-Aided Design
CityGML	CityGeographyMarkupLanguage
CSG	Constructive Solid Geometry
DSM	Digital Surface Model
GML	Geogrpahy Markup Language
ETL	Extract Transformation Load
FME	Feature Manipulation Engine
GIS	Geographical Information Systems
GPS	Global Positioning Systems
ISO	International Organization for Standardization
IoT	Internet of Things
IFC	Industry Foundation Classes
LoD	Level of Detail
LOD	Level of Development
OGC	Open Geospatial Consortium
RFID	Radio Frequency Identification
STEP	STandard for the Exchange of Product model data.
UBM	Unified Building Model

UML Unified Model Language

XML Extensible Markup Language

2D Two Dimensions

3D Three Dimensions



Chapter 1

1 Introduction

Our era is characterized by an enormous amount of available data that needs to be properly processed in order to optimize its efficiency. Thus, it is critical to investigate the tools that are able to utilize the encrypted information in petabytes of data, with regard to an integrated approach towards urban development and sustainability. The prospective master thesis aims to investigate the communication of two standards, Industry Foundation Classes (IFC) and CityGML. Both of them support 3D models that represent objects of the real-world and are open data models that can be enriched with additional information in order to be utilized in 3D city modelling.

The rapid urban growth in association with the population expansion that is projected to increase by 1 billion during the upcoming 15 years [United Nations, 2015] and the internal and external migration that is noted globally, affects vigorously the modern cities. Therefore, urban areas are forced to put up with a constantly increasing number of people, an occurrence that leads to the escalation of demands in dwellings, nourishment and energy consumption among others. The consequences of those demands deteriorate the global climate change, affect intensely the priorities of the modern cities and worsen the overall quality of residents' life. In order to address that phenomenon, the advancement of technology serves an important role. More specifically, technology offers the capability of collecting huge amounts of data which include information that can be utilized to improve our standard of living, productivity, environmental protection and project management among others. This capability derives from deploying proper tools such as informatics, 3D modelling, modern techniques of data mining and Geographical Information Systems (GIS). The consistency of technological evolution renders urban planning in every level (domestic, international, global) of paramount importance. Within this context, GIS is able to process that information, analyze it with regard to a certain issue that needs to be tackled and manufacture a product that transfers those services to the user (i.e. Global Positioning Systems). Furthermore, GIS elaborates an issue far more comprehensively and holistically than static maps, due to the facts of in depth analysis as well as interactive visualization of conclusions, that provide a much more vivid and detailed experience to the user. In combination with the available free data GIS is vital for pinpointing where the real problem is and its surrounding context, analyze the proposed solutions and highlight the optimal solution for each scenario in a dynamic environment [Tao, 2013].

The sustainability of a modern city can be affected by economic, environmental, social and technologic/technical parameters. Within this context, Geoinformatics can analyze patterns and trends that take place in a city in order to extract the required feedback to deal with, or even better predict future situations. For example, monitoring and analyzing the activities of a specific target group, provides valuable information for a specific area in terms of land use and land use change detection, connectivity with its transportation options, walkability and even criminality. The rapid urban growth has led not only to an increase in constructions, but also to an increase in the production of construction waste. A regular attempt is occurring from the government and the private sector for the optimization of a project's construction stages and the reduction in construction waste. The implementation of GIS is critical in many levels. Firstly, it allows real time vehicle monitoring and designation of the optimal routes in terms of distance, traffic congestion and time, thus reducing significantly the costs of transport. Also, another important characteristic of GIS is monitoring the surrounding area that is affected by a specific project, in terms of noise and air pollution. Furthermore, the connection of geographical information with large databases is feasible, concerning the regular maintenance and constant upgrade of the information that derive from a project in a dynamic environment.

The various GIS application fields, highlight the necessity for the collection of big data, by using (i) traditional survey methods or (ii) technology advancements including drones, Internet of Things (IoT), Big Data Analysis and Cloud Computing, with promising potential. Big data enables a city to receive big amounts of data from various sources, while IoT enhances the ability of an object to "listen, observe and communicate", all at the same time [Rathore, 2013]. One of the most important challenges nowadays is the implementation of IoT for the generation and proper function of a smart city. The concept of a smart city has derived as an assemblage of ideas about how descriptive and geographic information can be integrated in order to enhance the efficiency, ameliorate the competitiveness and upgrade the sustainability of a smart city [Batty et al., 2012]. From that point of view, the hypothesis can be made, that in an environment of free information, the residents of the city may utilize that information in order to promote innovation and creativity aiming to provide sufficient solution that tackle holistically various issues that arise in a city. One of the major characteristics of a smart city, is its capacity to receive the proper information in the proper time and in the proper device, in order to make a decision with ease that will benefit the affected residents accurately and efficiently.

Nevertheless, despite the importance of collecting data with the aforementioned methods, it is also mandatory to possess the required tools in order to utilize this amount of information and fully exploit its value. Furthermore, analysis and visualization of big data require an environment with more than two dimensions, which also supports the rise in the complexity of structures and buildings in a city which calls for a regular and accurate recording of their legal properties, a field that is unable to be fulfilled by the current two-dimensional cadastre or registration system. Also, the visualization of complex 3D models, gives the opportunity for a more comprehensive understanding of the 3D structures and their spatial relationship with the surrounding environment. The necessity of the modern world, to depict with greater detail the real entities and phenomena of a city, leads to the implementation of the 3rd dimension in the environment of Geoinformatics. This is heavily highlighted in 3D city models that are implemented for urban and regional planning, environmental protection and energy management, estimation of land values, taxation purposes and monitoring the life-cycle of projects.

In general, a 3D city model aims to combine spatial information with the natural and built environment. However, 3D city models are characterized of complexity in terms of their geometry, while in order to be fully efficient and not just for visualization purposes, a semantic basis is essential to describe their geometric and topological characteristics. Within this context, there are various tools that serve those demands and are, among others, 3D modelling software packages, open source standards that utilize 3D GIS and IFC and platforms that enable the visualization of a 3D model including its semantics. However, in order to generate a 3D model for analysis and not just for visualization purposes, there are various difficulties that need to be tackled, such as the communication between the different standards. Furthermore, questions arise with regard to the effectiveness of integrating semantic enrichment in 3D modelling. More specifically, a modern city encloses uncountable entities and their semantic characteristics need to be included in a 3D city model. CityGML standard aims to fulfill that purpose and connect 3D GIS with the generation of 3D models that are geometrically, semantically and topologically concrete [OGC 12-019, 2012]. A major characteristic of CityGML is the fact that includes many entities that compose a city, such as bridges, tunnels, transportation networks, vegetation, etc. It could be stated that CityGML does not focus solely on the building structure, even if current versions provide more detail for buildings, but it also focuses on the general concept of a city. For that reason and for the research purposes of the current thesis, the IFC standard is also investigated [buildingSMART, 2007] which in contrast with CityGML focuses on describing how the information should be structured, stored and managed during the life-cycle of a building [El-Mekawy, 2012]. So, on one hand CityGML aims to describe a whole city and on the other hand IFC delves into the structure of a building. The communication between those standards is of paramount importance and this formulates the basis on which this thesis is developed.

1.1 Research Questions

The current thesis aims to investigate and propose an integrated methodology which firstly generates two IFC models by implementing Building Information Modelling (BIM). Then, the conversion of the IFC models to valid CityGML Level of Detail (LoD) 4 models is presented and the evaluation of the models in terms of semantics and geometries is highlighted. Lastly, the enrichment of the generated model from a semantics perspective is investigated. With this in mind, the main research question addressed in this thesis is:

"How does the proposed methodology handle the conversion from IFC to CityGML LoD 4 models and to what extent the enrichment of the generated model is feasible in terms of semantic properties?"

The aforementioned question provides a wide perspective of the challenges this thesis aims to address. In order to provide some insight and facilitate its evaluation, the research problem is further formed in the following key - questions:

1. What issues may occur and what are the characteristics of the process when designing a model with BIM in order to match the geometries and semantics of the CityGML standard during the conversion process?

2. During the conversion, how are the different geometries and semantics between the two standards handled?

3. What is the level of suitability of the generated algorithm in case different building need to be converted? What are the requirements and manual intervention –if required- in order to render it usable for another model?

4. How can a CityGML Model be extended in terms of semantics and whether the proposed methodology is capable of doing so or not. Also, how is the semantic modelling in BIM differentiated according to the intended use of the generated model?

With respect to the aforementioned research questions, the current master thesis is developed and evaluated. The case study and the conclusions specifically address these questions and aim to form a ground for further research.

1.2 Scope

The purpose of the thesis is to formulate a framework that enables the generation of geometrically correct and semantically enriched 3D models that could be implemented in the environment of a 3D smart city. The proposed methodology aims to facilitate the conversion of IFC models to CityGML LoD 4 models. The IFC models are generated via BIM, not from external sources or existing libraries and therefore, the modelling procedure from scratch is presented including, not only the geometric representation but is enriched with semantic information in order to examine in detail the challenges that occur. A CityGML LoD 4 model contains the maximum amount of information that is supported by the CityGML standard, thus a successful geometric conversion including the interior spaces of a building is a challenging issue. Additionally, the semantic information in IFC is considerably richer than in CityGML. Within this context, it is also investigated how to preserve the additional information during the conversion to a CityGML model and afterwards, how to transfer these information to the generated CityGML model. In order to evaluate the advantages and the limitations of the developed methodology, to each IFC model semantic information is assigned corresponding to different application fields. As a starting point the phase of 3D modelling is considered. The result of the 1st phase is IFC models that represent buildings of the real world. During the 2nd phase, the conversion of the models utilizes Extract Transformation Load (ETL) process and the flexibility of the developed algorithm allows the conversion of multiple buildings that may have dissimilarities in terms of their geometry and semantics. Moreover, the proposed framework is an integrated research approach towards the communication between the two standards, since it does not focus solely on the conversion, but also on the generation of the IFC models, as well as the processing and enrichment of the generated CityGML models. Lastly, the semantic enrichment of CityGML models from IFC sources is examined with properties and attributes that are not supported by the CityGML standard.

Nevertheless, there are certain issues that are outside the scope of this thesis. First of all, the study is conducted solely for specific buildings, thus the surrounding environment as well as the terrain morphology are not taken into account. Furthermore, the IFC models are enriched with semantic information, but further investigation needs to be made in order to be implemented for specific application fields. There are demonstrated as examples in order to investigate how IFC handles semantics and how those semantics can be successfully transferred to CityGML. Additionally, the generalization of a fully detailed CityGML model, at a lower LoD requires a generous amount of manual intervention in the algorithm and constitutes an interesting field for further research, not included in the current thesis. Finally, it should be noted that the proposed algorithm converts one IFC model at a time. In case that there more than one buildings that are not connected with each other in the model, the algorithm should be adjusted accordingly, or the IFC model should be decomposed in unique buildings and convert each one separately.

1.3 Outline

Chapter 2 presents the structural elements of a smart city alongside its characteristics. The necessity of implementing the 3rd dimension in visualization and analysis is pinpointed with the use of relevant examples from various application fields. The goal of this chapter is to bridge the concept of smart cities with 3D GIS. In chapter 3, the theoretical background of the methodological approach is presented. The two standards (IFC & CityGML) that are implemented for the purposes of this thesis are presented and analyzed in terms of how they store and process geometry and semantics. In order to further illustrate the differences and challenges between those two standards, a conversion of a generic IFC building to a CityGML LoD 3 building is demonstrated and explicitly analyzed. The goal of the 3rd chapter is on one hand to describe briefly the two standards and on the other hand to provide an example of the challenges that must be addressed during a conversion. The findings of the conversion have constituted a basis for the development of the main algorithm that will be presented in chapter 5. Chapter 4 aims to analyze in detail the state of the art in 3D data integration and pinpoint advantages and limitations of the developed methodologies so far. The result of such analysis is utilized to develop a methodology that could contribute in the field of 3D data integration by addressing specific limitations between the communication of the two standards. Chapter 5 presents the case study of the thesis in which the three phases of the methodology are explained in detail. More specifically, the modelling procedure of two real world buildings in BIM is presented, focusing not only on the geometric representation but also on the implementation of semantics. Then, the conversion algorithm of IFC to CityGML takes place and the results are visualized and evaluated both geometrically and semantically. Lastly, the implementation of additional semantic information to the generated CityGML is examined. Finally, chapter 6 summarizes the key findings of the thesis and evaluates the developed methodology based on the research questions that are set in this chapter. Also, future areas of research fields and recommendations for the two standards are proposed. In order to facilitate the transition between the chapters of this thesis, a brief conclusion in the end of each one is provided, summarizing the most important findings so far and forming the ground for the research activity that follows.

Chapter 2

2 Role of Smart Cities & GIS

Smart cities constitute a concept that up to today has several meanings. Nam & Pardo [2011] define a smart city by taking into consideration its technological, social and institutional dimensions that are further subdivided into categories such as digital, integrated and learning city. A smart city can be implemented in various application fields. For example, it can be utilized as a government tool to provide access to open data to the residents of a city as an attempt to enhance innovation and creativity. Moreover, it can be used to boost the economy of a city and promote various products with e-commerce. Furthermore, a smart city assists the environmental protection, is able to regulate energy demand and facilitates daily transportation especially during peak hours. It can also provide a valuable insight regarding the weather conditions of an area in order to inform the potential affected citizens before a specific incident. In general, a smart city has a significant role in improving aspects of everyday life such as healthcare, green energy and education [Nam & Pardo, 2011]. Another definition according to Caragliu, Del Bo and Nijkamp [2011] is that a smart city emerges as a synthesis of technological infrastructure, digital communication and social identity of a specified area is defined through 6 dimensions: (i) smart economy, (ii) smart environment, (iii) smart transportation, (iv) smart citizens, (v) smart way of living and (vi) smart government and is mainly based on three pillars: economic development, environmental protection and social equity and a sustainable development can only be achieved if every pillar is taken into consideration. A smart city operates as a tool that aims to improve the competitiveness of a city in a way which ensures that the quality of the city's residents is improved as well [Batty et al., 2007]. More specifically, a smart city that focuses solely on economic development is not so smart. It should always consider the social and environmental dimension. To fulfil that purpose, it is essential for the development of a new system that will be able to receive the whole amount of information that is available in a city, store and process it. The following procedures are indicative of the characteristics that the new system should possess [Batty et al., 2007]:

- Data collection from multiple sources.
- Management of data streams.
- Integration of multiple data formats in a cohesive database.
- Data conversion.
- State of the art methods of data collection.
- Management of the generated models.
- Evaluation tools for the generated model.
- Services of processing, analysis and visualization.
- Generation of simulation and forecasting models.

From the Geoinformatics' perspective, a smart city is a mix of a digital city and technologies such Internet of Things and Cloud Computing. A digital city provides a spatial background and encloses the amount of information that ensures a stable and effective function of the city. It aims to organize the received information in a geolocated system of reference, which renders feasible the visualization of natural and social interactions that occur in a city environment. Furthermore, a digital city, as an accurate replica of the real world, includes all that social, economic, environmental and technological information that is related with the physical environment of a city [Li, 2013]. More specifically, a digital city consists of 2 Dimension (2D) maps, 3D city models, spatiotemporal 4D databases and certain points of interest. Based on the advances in GIS, the techniques of generating a digital city are [Li, 2013]:

- Sensors for the collection of terrestrial and airborne data.
- 3D/4D Modelling.
- Multiresolution, multiscale, and multidimensional visualizations of geospatial data.
- Spatial analysis.

The ultimate purpose of a digital city is, with the assistance of the aforementioned technologies, to provide the right data to the right person at the right moment in time. The spatial background is the fundamental framework of the digital cities. Within this framework, every kind of information can be modelled kai synthesize the basis of a smart city that will have the capabilities of monitoring, managing, controlling and analyzing [Li, 2013].

2.1 Big data & Cloud Computing

The rapid evolution of smart cities has generated the need of receiving more and more amount of data. Therefore, data of such volumes, well known as big data are combined with technologies such as IoT and Cloud Computing. The concept of big data is characterized from volume, speed during the transition and variety of data formats [Gani et al., 2016; Khan et al., 2014]. They offer a unique opportunity for a city to mine important information from a relevant amount of data that have been collected from various sources. Figure 1 illustrates the connection among smart technologies, big data and cloud computing. More specifically, numerous “smart applications” exchange information by deploying integrated sensors and devices that are connected with cloud computing platforms in order to generate large amount of unstructured data. Those data are collected and stored in a cloud by utilizing distributed fault tolerant databases such as Not Only SQL, in order to improve a specific kind of service or application [Borgia, 2014].

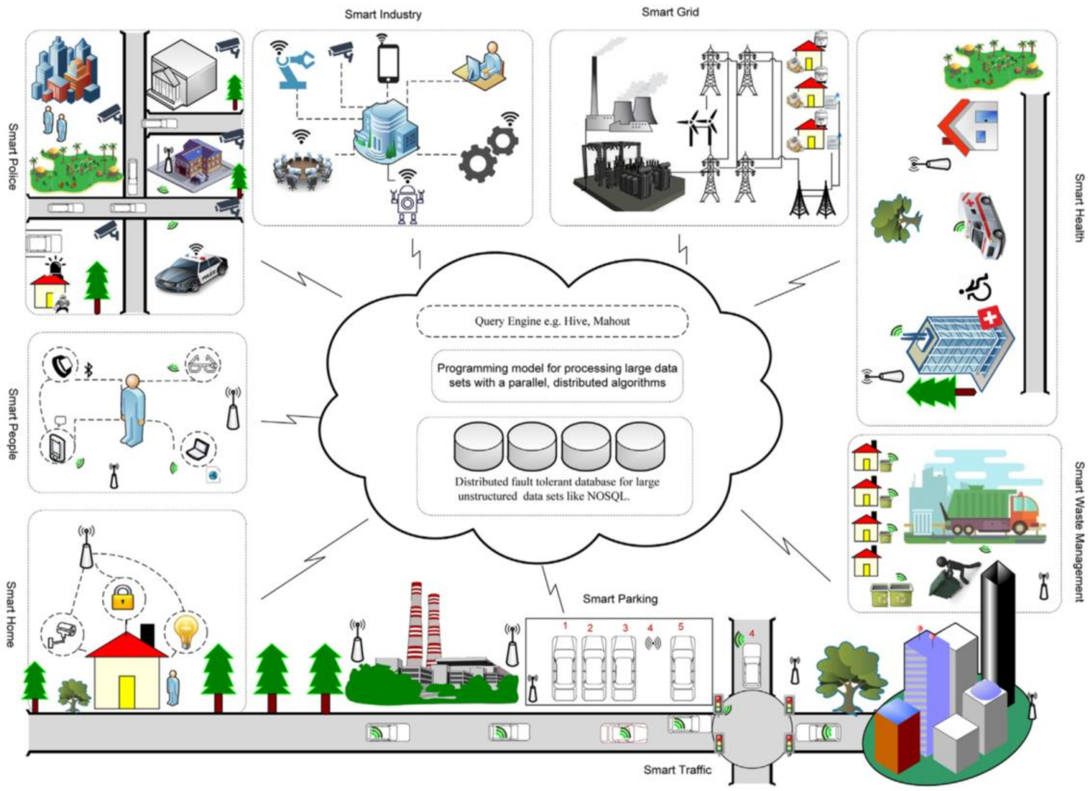


Figure 1: Smart City, Big Data & Cloud Computing [Source: Hashem et al., 2016]

Nowadays, a considerable amount of data derives from various sources, such as smartphones, computers, sensors, cameras, GPS tools, social networking sites, commercial transactions and video games. With the notion that the generated data are constantly multiplied, the efficient storing and processing are important challenges for the traditional data mining and analysis platforms. Also, in order for big data to improve the services of smart cities, certain tools and methods of sufficient data analysis are required. One of the most promising technologies with significant potential to enhance the role of smart cities is big data analytics [Al Nuaimi et al., 2015]. Within this context, big data analytics are able to extract valuable information from the data streams produced by the aforementioned devices [Yaqoob et al., 2016].

The implementation of big data in a smart city has several advantages but also contains certain challenges, such as the capability of large computational and storage facilities to process the data streams that are generated in the environment of a smart city [Hashem et al., 2016]. A potential route of addressing that challenge is the utilization of cloud computing services. Cloud computing [Mell and Grance, 2011] is applied to describe a variety of computational models that include numerous computers or clusters, connected via real-time communication network and offer services such as the extraction of big social network data from smartphones' applications [Chang et al., 2010; Chang et al., 2013].

2.1.1 Big data Applications

Big data are stored, processed and mined in smart cities to produce information that aims to improve the offered smart services. Furthermore, big data can assist urban planners to make a decision about a potential extension in services, resources or areas of a city. Indicative application fields of big data are presented below [Hashem et al., 2016]:

Smart Grid

In a smart grid environment, a large amount of data is generated from multiple sources, such as the regular energy demands of the residents and the data of daily consumption that are collected by smart sensors [Lai and McCulloch, 2015]. An efficient utilization of the big data collected from the aforementioned sources, can facilitate the decision-making regard to the real needs of the users, as well as the future energy demands of a city.

Smart Healthcare

The rapid evolution of the global population has enabled major changes in the field of prevention and treatment of numerous diseases and many decisions behind those changes have come up due to the increase in data availability. By implementing proper analysis tools, doctors are able to collect and analyze the medical data of a patient, highlight patterns and prevent the deterioration of a medical situation, resulting in saving hundreds of lives. The amount and type of collected information can be enhanced by deploying intelligent gadgets connected with the patient's home or clinic, in order to track his/her behavior and understand more accurately the medical records [Roy, Pallapa and Das, 2007].

Smart transportation

Patterns that derive from traffic data assist in the improvement of transportation networks and reduce traffic congestion during peak hours, by proposing alternative routes towards a destination. Additionally, those patterns can reduce the amount of accidents by analyzing the feedback of certain happenings with regard to speed limits and causes of accidents. Also, transportation data are able to upgrade cargo transits [Ju et al., 2013]. Finally, they provide certain environmental benefits, such as noise monitoring in an area, as well as air pollution.

Smart governance

Big data analytics can be a useful tool for the government as well, since the actions and measures that need to be implemented, could be well designed to address holistically an issue of interest in order to improve the everyday life of the citizens. In accordance with information regarding the environmental status of specific areas, or medical records, or traffic congestion records, the future policies will be able to face the problem directly and accurately.

2.2 Internet of Things

A significant number of objects is connected every day to the Internet, constituting the technology Internet of Things. IoT is applied in numerous fields such as transportation, healthcare and every-day chores. One of the most intriguing challenges is how IoT can be utilized to serve the concept of a smart city, since it provides the interlink between the different devices that are connected to the Internet.

2.2.1 Implementing IoT

Li [2013] illustrated an application of IoT that pinpoints its value. Firstly, by establishing sensors in various places it is possible to extract and analyze numerous data formats. The ultimate goal is to generate "smart cities, parking, weather, hydration systems, transportation, environmental protection and surveillance systems". The main framework of a smart city that is based on IoT is demonstrated in figure 2 and can be further analyzed in the following phases [Li, 2013]:

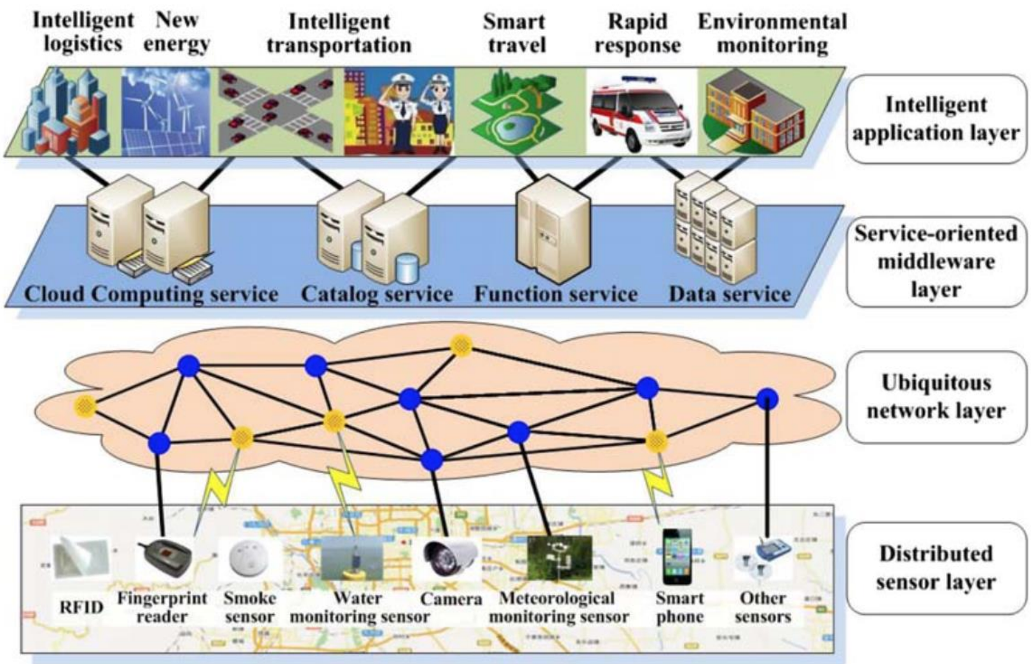


Figure 2: Smart City & IoT [Source: Li, 2013]

- The distributed sensor layer includes the sensors deployed for data collection in real time. Such sensors are smartphones, laptops, cameras and fire sensors.

- The ubiquitous network layer allows the transfer of collected data and information to the service oriented middleware layer by utilizing the Internet network.

- The service-oriented middleware layer is responsible for data processing and analysis, with the assistance of cloud computing and data mining.

- The intelligent application layer is responsible for transferring the required data to the appropriate user by providing an open access platform that all users can receive and manage information.

"Generally, the Internet of Things can be defined as follows: adopting radio frequency identification (RFID), infrared sensors, GPS, and information sensing devices (e.g. cameras and scanners) connecting any items or things that can be connected via the Internet based on agreed protocols of information exchange and communication" [Li, 2013].

A smart house is able to provide multiple utilities for the residents. The implementation of sensors enables the collection of data that afterwards are being uploaded in order to monitor signs of temperature, air pollution, noise or the fire risk hazard of the property. Thus, the reaction of the proper services such as the fire department, or the energy company can be immediate and tackle these issues immediately. Also, monitoring air pollution and noise provides great benefits for the residents since they will be aware in case an index bypasses a certain safety threshold.

A smart parking is able to count the vehicles that arrive from different parking zones. That way, a parking can be planned by considering the number of vehicles in a designated area, or by locating certain blocks that require an additional parking lot, facilitating that way the everyday life of the citizens. Apart from that, this system is prompted to reduce environmental pollution by decreasing the amount of time spent in a car, but also by lowering the time an individual spends looking for park instead of participating in a more productive activity.

Information regarding water composition and weather conditions can also improve the functionality of a smart city by providing weather data such as temperature, humidity, rain, pressure, visibility and water levels which are collected via deployed sensors in proper locations. For example, in real world, most floods are occurred due to rain, while some others due to snow melting. Therefore, by utilizing calculating sensors not only the forecast of such events is feasible, but also an estimation of the water supply for future demand.

2.3 Examples of «smart cities»

In this section, three examples are presented in order to demonstrate how smart cities and IoT technologies relate with each other harmonically [Li, 2013]:

Stockholm

Stockholm recently implemented smart management and applications in order to tackle environmental and transportation issues. More specifically, the vehicles that operated within the city to collect waste followed routes that encountered serious issues such as traffic congestion and air pollution. Therefore, a significant amount of data was collected with regard to the waste collection points in accordance with the initial transportation routes. As soon as the analysis was completed, a fleet of waste collection vehicles with reviewed routes was suggested as an alternative satisfying solution [Shahrokni et al., 2014].

Helsinki

The development of Helsinki as a smart city emerged from the availability and quality of free data. Those data are accessible from the private sector, academic or research institutions and the government. By 2013, more than 1030 databases were functional and covered a considerable number of urban phenomena such as transportation, economics, unemployment and well-being. An example of the aforementioned statement is the "Helsinki region Infoshare Project", which as a platform of open data is giving the opportunity to the citizens to participate and express their opinions with regard to everyday problems [Caragliu et al., 2011; Manville et al., 2014].

Copenhagen

Nowadays, Copenhagen is implementing a range of new and innovative solutions in the fields of transportation, waste management, heating and alternative energy sources, in order to be the carbon-neutral capital by 2025. Copenhagen has built an extensive cycling network and aims to further expand it with facilities such as a smooth transition from a bicycle to the public transit, actions that in order to be effective and efficient require a generous amount of information in order to upgrade cycling infrastructures with regard to the collaboration of the current transportation network [Manville et al., 2014].

2.4 Challenges of smart cities

As mentioned in previous sections, the concept of smart city is in an increasing state of development. Such a development though, heavily boosts the demands of collecting and integrating information. Therefore, major issues arise that is mandatory to be tackled. They can be issues of any kind such as financial or social, but for the purposes of this thesis, the technological concerns and more specifically concerns regarding the fields of planning, data collection and integration and GIS technologies will be examined [Hashem et al., 2016].

Planning

An important arising challenge in the field of planning is the generation of a unified system that will receive big data and will be able to store and process them. The designation of such system will enhance the planner's work and decision making with regard to future spatial interventions, improving that way the quality of life of the affected citizens [Hashem et al., 2016].

Data integration

One of the most important challenges is the heterogeneity of data. The role of a smart city is to receive and store a big amount of data from multiple sources that produce different data formats. Although, steps have been made towards that direction, the quality of those remains an important consideration, especially if those data derive from unique standards and differ in terms of geometry, topology and semantics [Hashem et al., 2016].

Cost of acquiring smart city

Another tricky issue for a smart city is the cost of data collection that is translated either in financial terms or cost in time, speed and efficiency. With the notion that a smart city demands the integration of multiple data formats, their collection might be proven significantly expensive, because of limitations in natural or physical resources [Hollands, 2015]. Within this context, open standard frameworks and technologies are in position to facilitate those challenges and provide valuable tools to enhance the role of a smart city. Furthermore, various open standards will improve the integration and exchange of data between different devices, applications and services.

GIS-based visualization

GIS is broadly used to map and analyze spatial data. For that reason, it is considered a valuable tool in urban and environmental planning, traffic monitoring, land use and land cover change detection. An effective visualization of a specific issue is critical for a smart city since GIS can bridge the gap between the analysis and visualization in a smart city, constituting the procedure much more user-friendly and interactive. The information that will be mined from the model will be manageable according to the user's preferences. The creation of effective and functional devices and applications that will be based upon the aforementioned technology form an interesting area of research around smart cities [Li, 2013]. Nevertheless, we feel that the 3rd dimension should be included in the building process of such platforms.

2.5 But, why 3D?

The need of the modern world to better comprehend and enhance the perception of the real entities and phenomena has led to the description of our environment in a higher dimensionality. The generation of complex 3D models allows for a more sophisticated understanding of the objects and their spatial interactions with their surrounding environment. This is evident especially in 3D city modeling applications, in areas such as smart city planning or environmental simulation. 3D city models are characterized by complexity, while a semantic basis is required to complement their geometric and topological aspects. In recent years, the integration of semantics into 3D city models has been widely accepted [Zhu et al., 2011]. The type and amount of information that can be implemented rises drastically, a condition that promotes the necessity of generating semantically enriched 3D models and highlights the demand for collecting massively huge data which is handled either by (i) the collection of big data, (ii) by the knowledge via Internet of Things (IoT). That collected amount of data needs to be properly stored, edited and visualized, issues that GIS science is able to deal with. The massive amount of free data that are available globally, has enhanced the capabilities of addressing critical issues in an integrated and functional way. Hence, GIS is vital for addressing spatial issues and their surrounding context, analyze the proposed solutions and highlight the optimal solution for each scenario in a dynamic environment [Tao et al., 2013]. That way, a prominent utilization of a 3D model seems mandatory. Semantic 3D city models [Chaturvedi, 2016] join the spatial information with the physical entities in cities and allow an interaction via spatio-semantic queries. They also provide a description of the physical and built environment [Kolbe, 2009]. Semantics have gradually attracted international scientific interest due to their ability of storing data that describe relations between different object parts and their environment [Diakité et al., 2014]. Therefore, semantic based modeling has grown very popular internationally, incorporating a variety of applications of different scientific fields including energy applications, urban planning, indoor navigation, noise propagation simulation and mapping, disaster management and homeland security, cultural heritage, water management, environmental and real-time simulations [Gröger and Plümer, 2012]. Semantic modeling is also promising for depicting relations between legal and physical space which is required to 3D Cadastre applications, where formal definition of 3D space and its containing elements is still an abstract concept, while volumetric parcels are not conceivable in reality but are established via connections to physical objects [Aien et al., 2013]. 3D models' semantic enrichment allows for direct correlation between legal and physical property, improving the accuracy that legal spaces' volumes or locations are defined [Dimopoulou et al., 2014]. More specifically, 3D models are capable of representing entities such as Buildings, Transportation Networks, elements of a real city such as Bridges, Tunnels and City furniture (Traffic signs, Lights), Vegetation and Water Bodies. Those entities can be semantically enriched with a variety of attributes that vivify a virtual 3D model. Furthermore, 3D models can be created, edited and visualized in different scales, from basic shapes up to fully detailed both internally and externally real-looking objects. Another significant advantage is the tracking of their life-cycle and the constant monitoring of the project. Within this context, the role of an object is enhanced by adding specific equipment that depends on the project's purpose (Fig. 3).

"A 3D Model can be implemented to the environment of a 3D Smart City aiming to integrate descriptive and geographic information in order to enhance its efficiency and sustainability" [Batty et al., 2012].

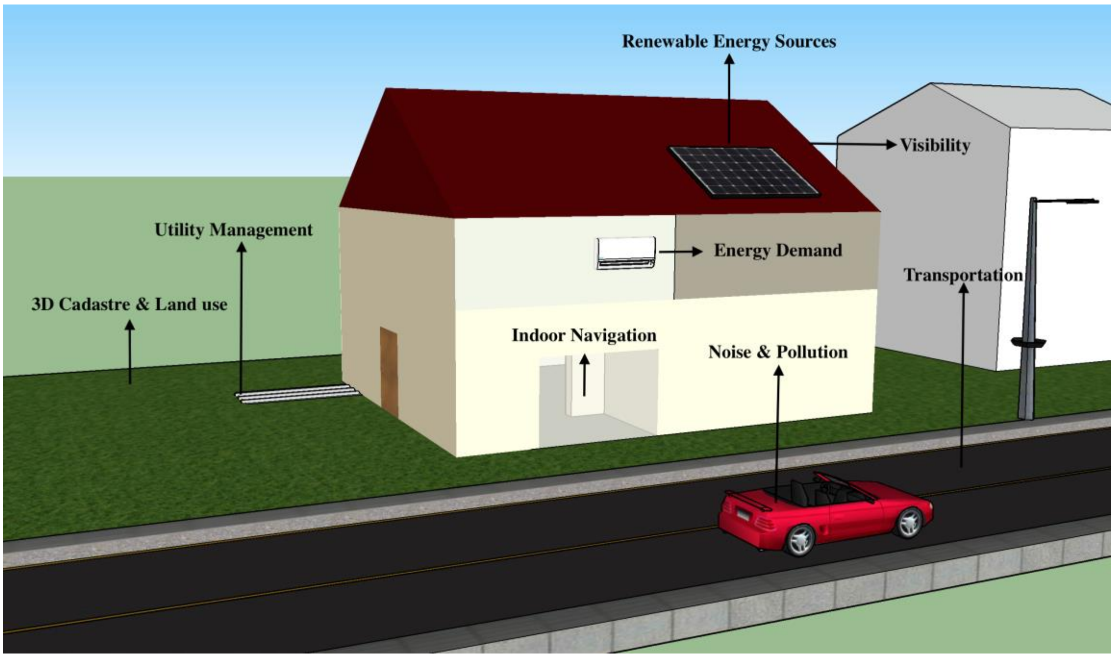


Figure 3: Application fields of 3D Smart cities [Inspired by: Biljecki, 2015]

2.5.1 Applications of 3D Smart Cities

In order to further emphasize the importance of 3rd dimension in a smart city, several examples of 3D models in various application fields are illustrated [Biljecki, 2015]:

Solar Radiation

A field of implementing 3rd dimension that is constantly evolving is the estimation of solar radiation in a building. In accordance with the global effort towards Renewable Energy Sources, a 3D model can become a useful tool to assist that purpose (Fig. 4). In the field of Geoinformatics, this kind of analysis is tackled by implementing Digital Surface Models (DSM). However, the rapid technological evolution with respect to new methods of data collection, present the opportunity of modelling buildings including their structural elements, such as their boundary surfaces. In a 3D model, it is feasible to calculate the amount of heat that each surface receives during the day and therefore estimate the suitability of placing for example photovoltaic systems. Furthermore, 3D models provide information regarding the slope, orientation and area of the roof, data that should be taken into consideration in empirical solar models. Additionally, scientific interested is noted on the capability of recognizing the surface material alongside with its characteristics.

Figure 4: 3D Model & Solar Radiation [Source: Biljecki, 2015]

Energy demand

As mentioned previously, 3D models should be heavily semantized. Examples of such information are –among others- the usage, function, land use, age of construction of a building. By implementing 3rd dimension it is feasible to further process and upgrade its semantic information, since the model is able to portray the effect of terrain morphology, the topology of a building in regard with the surrounding area and possibility of sharing common surfaces. During the last years, noticeable progress is detected in the field of energy management and more specifically, in Germany (Fig. 5) 3D models are applied aiming to combine data relevant with the volume, type and storeys of the buildings in order to estimate energy demand for heating and cooling [Bahu, 2013].

Figure 5: 3D Model & Energy Management [Source: Bahu, 2013]

Smart Building Evacuation & Indoor Navigation

Another important field of deploying 3D model is the field of indoor navigation and building evacuation [Hancke et al., 2012]. Regular evacuation systems activate the alarm in terms of emergency but fail to take into consideration the fact that inside the building might be people that are not aware what is the closest emergency exit or they cannot reach it. By implementing a 3D indoor navigation model, it is possible to visualize the best route to escape safely the building, thus performing an evacuation in a much more efficient way. Also, the best route will be subject to change depending in the congestion that can be noted in certain exit points with the help of special sensors that will upload the information to the smart evacuation model.

Environmental Monitoring

Environmental monitoring and protection is one of the most important challenges of our time. By utilizing GIS, it is possible to monitor air and water quality, as well as other parameters such as humidity, temperature and carbon dioxide levels aiming not only to locate anomalies in our surrounding environment, but also try to prevent them from happening. Environmental monitoring requires the implementation of sensors to the outer environment and areas that are being usually visited by people such as parks, and lakes. Up to a certain point, 2D GIS is able to handle that kind of necessity. However, 3^{rd} dimension can increase the amount of received information but more importantly improve its credibility and accuracy, because it is capable of locating and visualizing the levels of pollution or noise in more than a planar altitude.

Noise estimation

The previous conclusion is presented in figure 6. 3D Data are able to create models that illustrate how much are the citizens affected by noise pollution and how to confine it by establishing noise barriers.

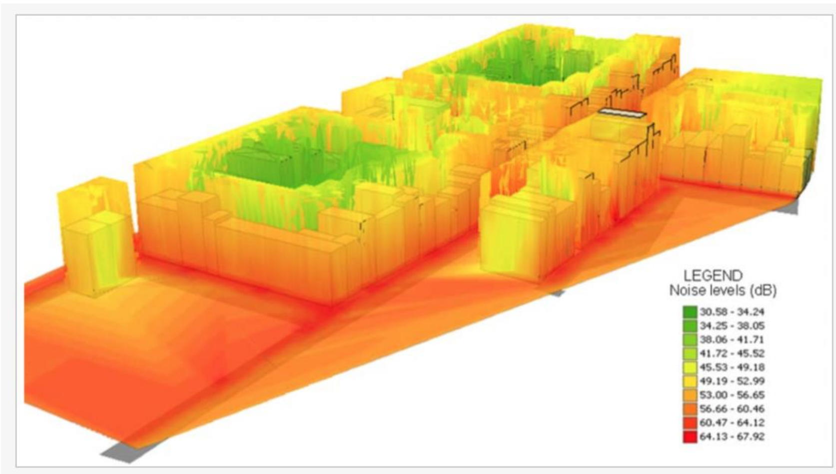


Figure 6: 3D Model & Noise Estimation [Source: Biljecki, 2015]

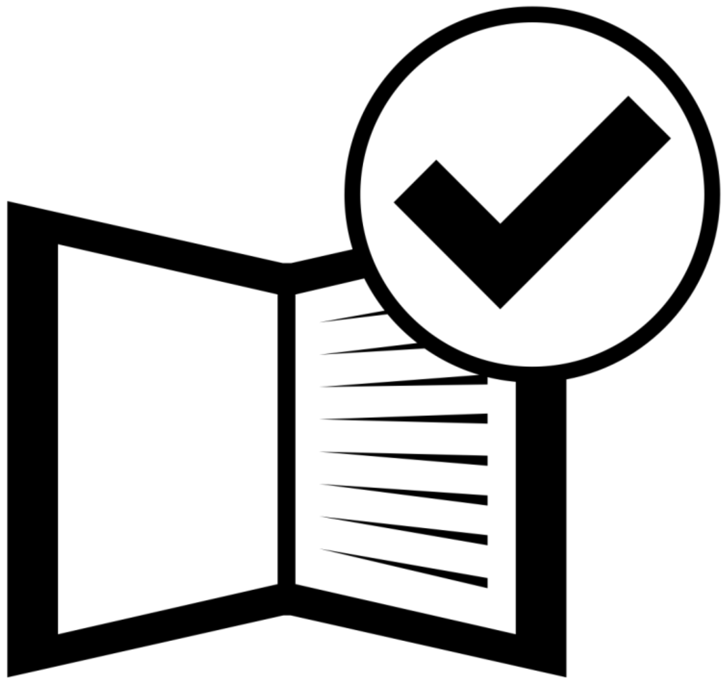
3D Cadastre

Cadastre serves an important role in the development and planning of a country. However, physical reality demonstrates the need of implementing the 3rd dimension, since the complexity of the modern buildings as well as the structures that exist above and beyond the earth surface, cannot be tackled efficiently by a 2D Cadastre. 3D Cadastre is actually a system of establishing rights, restrictions and responsibilities, in which the objects will be represented also with their height. The aim for 3D Cadastre is to constitute a integrated 3D model of physical reality, without alienating its legal aspect. Certain examples that pinpoint the need of 3D Cadastre are [Stöter and Salzmann, 2003]:

- Construction that overlap with each other.
- Underground and over ground infrastructure.
- Location and ownership of cables and pipes (water, electricity, telecommunication, natural gas).
- Apartments (one building with many apartments and different owners).
- Mines and underground activity.
- Monuments of historical value and places of archaeological interest.

2.6 Conclusions

The purpose of this chapter is to illustrate the characteristics of smart cities, as well as their application fields. Several examples have been presented that demonstrate the importance of that concept. Apart from that, the scientific interest is focused in methods of building, managing and upgrading a smart city. Those methods include various technologies, providing an opportunity for different scientific fields to contribute towards that direction. Two of the most important technologies described are cloud computing and IoT, which in combination with big data encapsulate several challenges for researchers. However, the field of investigation of this thesis circles around the necessity of implementing the 3rd dimension in a smart city and more importantly how to tackle the challenges that arise around the subject of data integration. Thus, in the following chapter are presented two of the most popular standards, that implement 3rd dimension and can contribute in the environment of a 3D smart city. Those standards are CityGML and IFC. In a period that the collection of data is characterized by heterogeneity issues, exploring methods of communication between them is necessary, a challenge that aims to be tackled by this thesis. Within this context, each of the standards has different characteristics, advantages and disadvantages as it will be in detail explained. However, in order to establish a 3D smart city, not only the data integration, but also a more holistically approach towards the generation and management of 3D models is required. All in all, this chapter aimed to constitute a basis in order to realize why 3D modelling, data integration and spatial management is essential in order to tackle multiple issues in application fields such as Energy management, 3D Cadastre and Urban Planning.



Chapter 3

3 3D GIS & CityGML

3D city modeling used to focus on visualization of datasets which resulted in cumbersome data bases and technical difficulties in processing. Within this context, challenges and questions raised, concerning the effectiveness of the integration of the semantic aspects in 3D modeling. This semantic enrichment is crucial, due to the structural complexity and the multiplicity of space within the multidimensional urban environment, especially in fields such as land administration in which a range of different RRRs (Rights, Restrictions and Responsibilities) intersect with the corresponding land parcels. This range of land rights, restrictions and responsibilities requires proper 3D registrations complying with each legal structure [Dimopoulou and Elia, 2012]. Additionally, the semantic modeling of cities requires the appropriate qualification of 3D data [Gröger and Plümer, 2012]. Current trends focus on the semantic enrichment of distinctive city objects or 3D geometries which can be decomposed into their structural elements including attributes and their correlations. The semantic modeling approach along with the appliance of 3D geometry and topology of real-world objects is realized by the CityGML open data model [Kolbe, 2009]. However, questions arise about the most effective way to integrate geometries and semantics of different standards or how to efficiently extract semantics from pure geometric models [Zhu et al., 2011], issues which can be tackled by the concept of interoperability. The emergence of novel 3D modeling methodologies and techniques in computer graphics as well as the development of a range of 3D file formats has certainly assisted in this direction. Nevertheless, data integration and interoperability is a great challenge towards the advancement of 3D city modeling.

3.1 CityGML

CityGML is an open data model, based on XML format that aims to store, manage and exchange virtual 3D city models. It is an application schema for the Geography Markup Language version 3.1.1 (GML3), the extendible international standard for spatial data exchange issued by the Open Geospatial Consortium (OGC) and the ISO TC211 [OGC 12-019, 2012, p.9]. CityGML was developed in order to facilitate a thorough and sophisticated analysis of real-world objects alongside their semantic properties and relationships. Its structure allows for the implementation of the same 3D model in multiple application fields, thus rendering it an efficient tool for the sustainable management of 3D city models. A few examples of application fields are city planning, building architecture, environmental modeling and simulation, land use management and evaluation and indoor and outdoor navigation. CityGML defines the thematic classes and relationships for the most common topographical objects in a city with respect to their geometric, topological and semantic properties. The represented features are not limited in the built environment such as buildings, tunnels and bridges but is extended to the natural environment such as vegetation and water surfaces. Also, CityGML defines the hierarchical structure among the thematic classes, as well as the relationships and the spatial properties of the objects.

3.1.1 Characteristics of CityGML

CityGML standard is defined by classes for the most important types of objects that can be found in a 3D city model. It is compiled by the core model and its thematic extensions. The core model describes the structural elements of the CityGML standard; thus, it should be strictly followed by any system that intends to create or edit a CityGML dataset. Based on the core model, every thematic extension aims to cover a specific thematic part of 3D City Models. CityGML introduces the following 13 thematic extensions [OGC 12-019, 2012, p.17]:

- **Appearance:** this thematic extension offers the capability of modifying objects in CityGML.
- **Bridge:** facilitates the representation of thematic and spatial characteristics of bridges and their structural elements.
- **Building:** facilitates the representation of thematic and spatial characteristics of building and their structural elements.
- **CityFurniture:** represents various city objects such as traffic lights, signs, etc.
- **CityObjectGroup:** this thematic extension facilitates the grouping of components in one model.
- **Generics:** provides general extensions to the main CityGML Schema that can be implemented in order to model and manage additional information and attributes that cannot be covered in the rest of the thematic classes.
- **LandUse:** facilitates the representation of the land uses in a 3D City model.
- **Relief:** facilitates the integration of the terrain and its attributes in a 3D City model.
- **Transportation:** represents the transportation network of a city.
- **Tunnel:** facilitates the representation of thematic and spatial characteristics of building and their structural elements.
- **Vegetation:** represents the vegetation and its attributes in a 3D City model.
- **WaterBody:** represents the thematic properties and the 3D geometry of rivers, lakes and other water surfaces.
- **TexturedSurface:** facilitates the visual differentiation of the objects by applying colors and textures on the 3D surfaces.

3.1.2 Multi-scale Modelling

CityGML standard supports 5 different Levels of Detail (LoD) (Fig. 7). The concept of multiple LoDs aims to facilitate an effective visualization and an efficient spatial analysis of the 3D models [OGC 12-019, 2012, p. 11]. An object of a dataset can be represented in multiple LoDs, facilitating the capability of managing the object according to the necessities of the project. Moreover, two different CityGML datasets that contain the same object in different LoDs can be combined and integrated. In that case, the user is responsible to ensure that those objects despite their different LoDs represent accurately the same real-world entity. The lowest LoD is LoD 0 which forms a 2D Digital Terrain Model and can be utilized as a background of an orthophoto or a map. Buildings can be represented in LoD 0 via the area of their surfaces or via polygons of the rooftops. LoD 1 represents a generic shape of 3D buildings. A building in LoD 2 includes information regarding its roof and boundary surfaces. LoD 3 represents architectural models with detailed exterior information in terms of surfaces textures and openings such as doors and windows. LoD 4 completes a LoD 3 model by adding interior structures and spaces for buildings. For example, buildings in LoD 4 are formed from rooms, interior doors, stairs and furniture [OGC 12-019, 2012, p. 11].

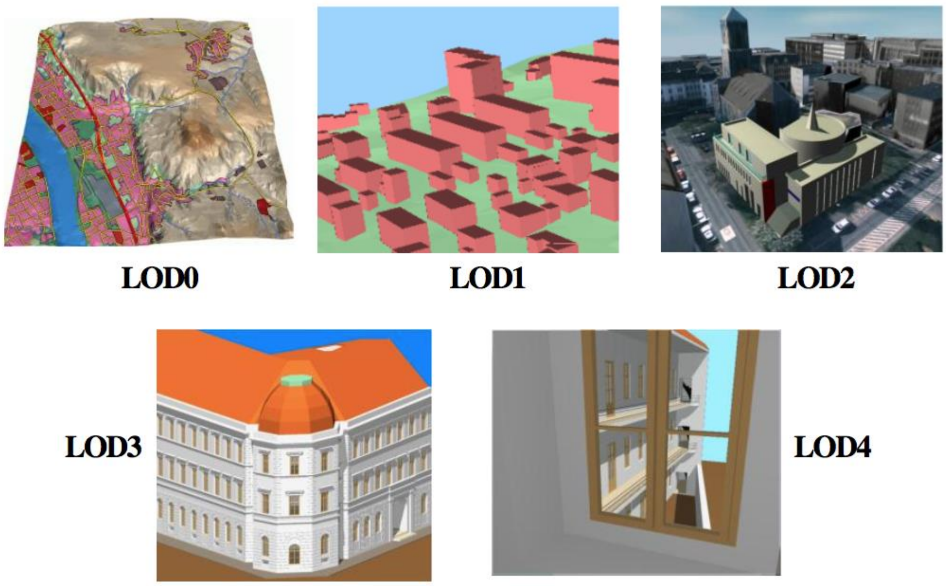


Figure 7: Level of Details in CityGML [Source: OGC 12-019, 2012]

3.1.3 Semantics, Geometry & Topology in CityGML

Modelling the semantic basis and implementing the 3D geometry and topology of the real-world objects is facilitated via the concept of CityGML, which constitutes the standard of 3D semantics. Kolbe [2009] stated that CityGML does not represent only the shape and the graphical appearance of the city models, but delves into the semantic characteristic of the objects. As mentioned, CityGML includes an advanced concept in order to utilize in full the 3rd dimension of the objects, the LoD. The most important aspect of that concept is that LoDs are not referred solely to the geometry, but are furthered in the field of semantics: a higher LoD increases the amount of semantics in a model. One of the most critical design principles of CityGML is the modelling of semantics, geometries and topological properties in a model. In terms of semantics, the real-world objects are represented by features such as buildings, wall surfaces, windows, rooms, bridges, and tunnels. This representation also includes properties and relationships between those features. Therefore, the part of relationships between those features can be analyzed separately in terms of semantic, with the absence of geometry. Nevertheless, on a spatial level, geometry objects are assigned to features representing their spatial location and extent. So, the model is compiled of two hierarchies: semantics and geometry. The advantage of this method is that the model can follow one of the two routes in order to address geometric or thematic queries. Even though that both hierarchies exist separately for the same object, they should also be connected between each other. For example, if the wall of a building has two windows and a door at the semantic level, the geometry that represents the wall should also include the geometry of the windows and doors [OGC 12-019, 2012, p. 12].

The geometric model of CityGML consists of primitives that can be combined in order to create complexes, composite surfaces or aggregates [OGC 12-019, 2012, p.25]. For each one of the four dimensions, there is a relevant geometry: an object with no dimensions is named as Point, an object in one dimension is named as Curve, an object in two dimensions is named as Surface and an object in three dimensions is named as Solid. A solid is formed from surfaces and a surface is formed from curves. In CityGML, a curve is necessarily a straight line and the surfaces are represented by polygons (Fig. 8).

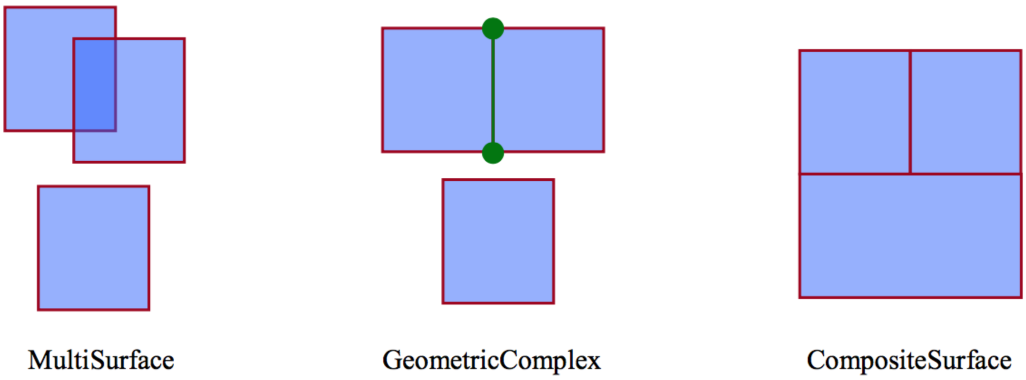


Figure 8: Geometry in CityGML [Source: OGC 12-019, 2012]

CityGML provides explicit structure for topology. A part of space that is already represented by a geometry object should be referenced by the features or the geometries that are related with this geometry object. Practically, topology can be separated in three cases: firstly, two classes that can be spatially defined by the same geometry. Secondly, the geometry can be shared between a class and another geometry. More specifically, a geometry that defines the wall of a building can be represented with two ways: from the solid geometry of the building and the feature Wallsurface. Thirdly, two geometries can refer to the same geometry that consists a boundary for both of them [OGC 12-019, 2012, p. 26].

3.1.4 Core model of CityGML

The core module of CityGML defines the elemental concepts and components of the CityGML standard. It forms the basis of CityGML, thus it is essential if any extension of the schema needs to be implemented. The main purpose of the core module is to provide abstract base classes from which the thematic classes with their extensions derive. The base class of all CityGML objects is the abstract class CityObject which includes several attributes that define a model such as the creation and termination date of the project, or information about the position of the model with regard to the surrounding environment.

The Building model is one of the most detailed thematic extensions of CityGML (Appendix I). It facilitates an explicit representation of the thematic and spatial properties of the buildings and their elemental structures in 5 LoDs. The Building model is specified by the thematic extension Building. In case there are building complexes, they should be grouped as CityObjectGroups. The primary building of the complex can be highlighted by assigning specific values in the attribute "role name". The feature classes Building and BuildingPart inherit all the properties of the AbstractBuilding class. More specifically, they inherit properties such as the class of the building, the function, the usage and the year of construction among others. A LoD 0 building is represented solely from horizontal 3D surfaces. Those surfaces can depict the area of the building and the area of the roof separately. A LoD 1 building consists of a generalized geometric object of the outer shell. This geometric representation is enhanced in LoD 2 by implementing the MultiSurface and MultiCurve geometries which are utilized to model architectural details such as columns. Additionally, in a LoD 2+ Building the outer shell of the building can be semantically differentiated by implementing the classes BoundarySurface and BuildingInstallation. The BoundarySurface class represents a part of the outer shell of the building such as a WallSurface, a RoofSurface, or a GroundSurface among others. The BuildingInstallation class is utilized for elements of the buildings such as chimneys, stairs and balconies; objects that greatly affect the outer shell of the building. The buildingInstallation class inherits the attributes class, function and usage. In a LoD 3 Building model, openings such as doors and windows are represented as thematic objects. In LoD 4, the highest LoD, the interior space of the building is represented which is formed of the class Room. Elements of the interior building such as stairs or immovable objects are represented by the class IntBuildingInstallation [OGC 12-019, 2012, pp. 62-66].

3.1.5 CityGML Boundary Surfaces

The Boundary Surfaces class is the general class of multiple thematic classes that form the outer shell of a building, as well as the visible surfaces of rooms and interior and exterior installations. It is a subclass of the class CityObject, thus inherits all its attributes. From that class, derive some of the most important subclasses of a building: *RoofSurface, WallSurface, GroundSurface,* *OuterCeilingSurface, OuterFloorSurface, ClosureSurface, FloorSurface, InteriorWallSurface and CeilingSurface* [OGC 12-019, 2012, pp. 69-73].

3.1.6 CityGML Room & Room Furniture

If an object belongs to a specific area, such as a desk, then it is connected with the class Room. A CityGML Room can have attributes such as class, function and usage. The attribute class facilitates a categorization of the rooms with respect to their real use, for example personal rooms or shared rooms. The attribute function reveals the original identity of the room such as kitchen or living room, while the attribute usage depicts the current use of the room in case it is different from its original use. The visible surface of a Room is represented geometrically with Solids or MultiSurfaces. Semantically, a Room is composed by boundary surfaces such as *FloorSurface, CeilingSurface InteriorWallSurface* and ClosureSurface. The furniture of a Room, such as chairs and desks can be represented within the CityGML standard with the class Room furniture, which inherits the properties class, function and usage [OGC 12-019, 2012, pp. 74-76].

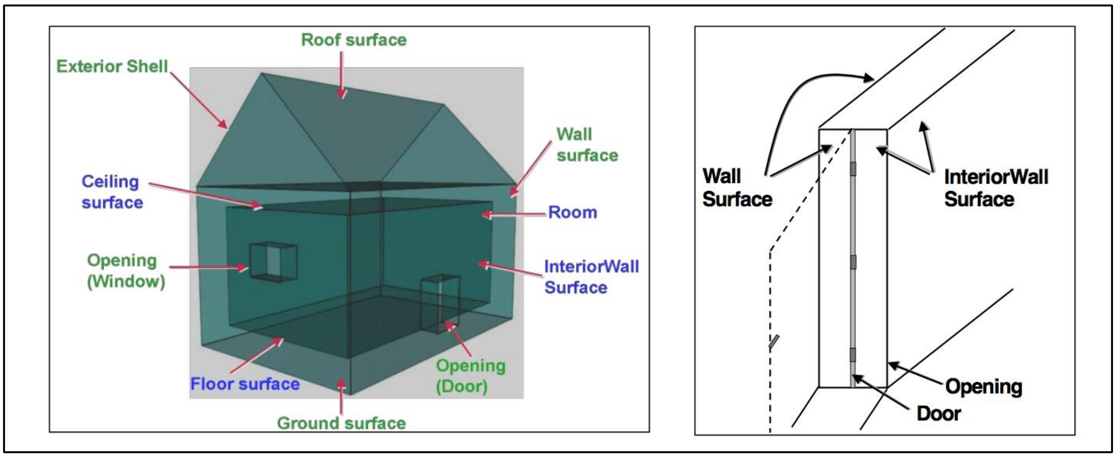


Figure 9: Building representation in CityGML [Source: OGC 12-019, 2012]

3.1.7 Options for enriching a CityGML Model

CityGML standard is a universal topographic information model that aims to provide certain rules and constraints to the real-world objects. However, there are multiple applications that need to implement objects or information that are not supported by the thematic classes of CityGML [OGC 12-019, 2012, pp. 15-16]. In order to tackle that issue, CityGML supports the extension of its geometry and semantics via the following ways:

Generic city objects and attributes

The generic city object concept facilitates the enrichment of a CityGML model thematic classes with additional attributes, properties and values without the requirement to change the basic CityGML XML schema. Additionally, the enrichment in terms of geometry can be achieved via utilizing the thematic extension Generics of CityGML [OGC 12-019, 2012, pp. 15-16]. Even though they provide an extension of the CityGML model, there are several limitations such as the informality of their specification, the limits in data types and the conflicts that may occur between the existing and the additional objects [www.citygml.org].

Applications Domain Extensions (ADE)

The concept of an ADE is to provide an extension to the CityGML schema with regard to a specific application field. A few examples of such additions could be adding various information regarding the properties of a surface, the land value of a building, or define a new object type. The major difference compared to the method of extending a CityGML schema with generic city objects and attributes, is that an ADE is defined via a separate XML schema that must be connected with the main CityGML schema. The advantage of creating an ADE is that the extension can be utilized in specific application fields and recognized globally. CityGML supports the simultaneous implementation of more than one ADE schemas. ADEs can extend any of the CityGML modules, providing an option of adding multiple information to the CityGML model [OGC 12-019, 2012, pp. 15-16]. ADE are widely used in field such as energy modelling, modelling topographic data, indoor modelling and noise modelling [www.citygml.org].

It can be concluded that each method has advantages and disadvantages. On one hand, Generic city objects and attributes provide a quick route to enrich a CityGML dataset but the depth of the type of information that can successfully add to the model is questionable. For example, if a model needs to be enriched with a special city object that is not covered by CityGML, then the generics method could be proven quite valuable. Similarly, if there are specific attributes or properties that need to be added in a model, the generics method can facilitate the extension. However, if the IFC model is able to provide the CityGML model with an amount of data or objects that covers an entire application field, then the Generics method can be proven quite inefficient. On the other hand, ADEs are more complicated and their implementation might be more beneficial if they form a schema that covers holistically a specific application field, while it is doubted if an ADE should be formed to address a generic issue. It should not be neglected though the fact that the extension of the CityGML model will happen by utilizing semantic information of IFC entities. CityGML was not designed to support IFC [Luut and v. Berlo, 2011], therefore the capability of preserving semantic information with either of the two aforementioned methodologies can form the ground for additional future research. Furthermore, it is of particular interest the connection of the semantics and the geometries in IFC in order to be successfully extended in CityGML. Another interesting topic is that CityGML provides limited semantic information to its boundary surfaces. The boundary surfaces inherit the attributes of the _CityObject such as gml:name. While the current state of the boundary surfaces can tackle the lack of additional semantic information, in a fully detailed model it can be proven quite unsuccessful, since the gml:name attribute could be utilized to characterize the orientation of a specific surface in a complex building. IFC surfaces are capable of enriching semantically a CityGML with information that could be implemented in multiple application fields. Another field of investigation is the capability of CityGML to represent the legal aspect of a city model. Up to today, CityGML is successful at modelling and managing the built environment, but lacking in the field of legal land administration [Aien et al., 2015]. BIM provides great capabilities of representing information with regard to the legal aspect of a model [Atazadeh et al., 2017]. They need to, however, be created and stored according to the legal environment as instructed by the cadastre of each country. The legal semantics can also be exported in IFC format; hence it is of particular interest to examine not only the type and the amount of information that can be converted to CityGML, but the limitations that may occur in terms of geometric representation can discourage the successful transition of all legal semantic information. For the purposes of this thesis, we believe that is worth to investigate both methodologies in order to determine the most efficient one in terms of handling the semantic information of a CityGML model. The generated building provides the opportunity of investigating the enrichment of the CityGML boundary surfaces with semantic information that can be utilized for smart energy management systems, determines the extent that a transition of semantics is feasible and the constraints and limitations that may arise in terms of the different geometric structures of the two standards.

3.2 IFC & BIM

Building Information Modelling (BIM) is a 3D modelling procedure that describes the geometric and semantic properties of a building and monitors its life-cycle. A BIM may therefore be defined as a digital representation of the physical and functional characteristics of buildings and their surrounding environment [Isikdag and Zlatanova, 2009]. Nowadays, BIM consists a valuable tool for sharing information and assisting in the decision-making of a building construction. Additionally, utilizing BIM renders feasible the collaboration of multiple engineering fields throughout the life-cycle of the building and creates a dynamic environment that can address the changes that may occur to the project.

"BIM (Building Information Modeling) is an intelligent 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure" [www.autodesk.com].

Howell and Batcheler [2005] have expressed the advantages of BIM:

- Consistency of plans, elevations and section drawings.
- Capability of creating objects of different types in one model.
- Smooth upgrade of the building's structural elements (doors, windows) in order to synchronize the model with the changes that take place in the real-world entity.
- Collecting information in a single BIM file renders the addition of additional information feasible.

BIM is implemented in the current thesis in order to generate the prototype buildings. The following conclusions can be made:

- BIM can contain a plethora of semantic information. Despite the accuracy of the geometric representation, which is expected from a 3D modelling software such as Autodesk Revit, the capability of adding semantics according to the need of the projects renders it a valuable tool for the investigation purposes of this thesis.
- The interoperability with 2D CAD software improves considerably the amount of time needed to generate a model, since by importing 2D drawings it is possible to extrude the model in 3D.
- Multiple visualization methods of the constructed model allow the user to monitor and correct where necessary the modelling process.

BIM complies with the Industry Foundation Classes (IFC) standard. Today, there are several CAD/AEC applications (such as Archicad, AutoCAD and Bentley MicroStation) as well as business analysis applications (such as SAP 2000) that have the abilities to import and export their internal models according to the IFC standard [Isikdag and Zlatanova, 2009]. IFC is a standardized open data model developed by the international organization buildingSMART. The IFC data format is based on the EXPRESS language as a part of the STandard for the Exchange of Product model data (STEP) standard (ISO 103030) for product data exchange [buildingSMART, 2007].

IFC is a data format that is used to describe, exchange, share and define how information should be stored throughout the building industry's life-cycle [El-Mekawy et al., 2012]. It is the international standard for Building Information Modelling (BIM) and is used to create a model of a facility that contains all its information and relationships among its parts and facilitates their sharing among the project members (Appendix II). It can hold data for geometry, quantities, facility management and equipment for various professions. IFC is comprised of a set of schemas and each schema belong to one IFC layer. The content of the schema represents a specific concept of the facility (equipment, geometry, costs). IFC has a full range of geometry classes (solids, surfaces, curves) and a full range of topology classes (shell, point, path). Finally, IFC supports the Level of Development (LoD) from 100 up to 500.

3.2.1 IFC Geometry

The 3 elemental geometry categories of IFC 2X3 are the following:

- B-rep: a solid is represented as a collection of connected surface elements [Donkers, 2013]. Compared to CSG, it is a more flexible method and is used for complex geometry objects such as 'IFCDoor' and 'IFCWindow'.

- Swept volumes: a solid is defined by a 2D surface and a path which is used to extrude the model [Donkers, 2013].

- CSG: it is utilized to generate solids with one or more Boolean operators. An operator of such kind between two geometries generates a new geometry that is formed with the operation of intersect, difference or union [Kolbe and Plümer, 2004].

Compared to IFC which utilizes mostly swept volumes and CSG, CityGML utilizes exclusively b-rep geometry [Donkers, 2013].

3.2.2 IFC LOD

It is a common phenomenon to confuse the term: Level of Detail in CityGML with the term: Level of Development in IFC. In reality, they have completely different meanings and representations. CityGML LoD, which is presented in a previous section, basically describes how much information is contained on the CityGML Model. On the contrary, Level of Development in IFC determines how much can the user rely on the information provided by the current model. The LoDs in IFC are categorized as follows [Bedrick and Vandezande, 2013].

- LOD 100: The model element can be graphically represented, it does not however comply with the LOD 200.

- LOD 200: The model element is represented as a generalized model, with approximate area, location, orientation, volume.

- LOD 300: The model element is represented as a specific model with accurate area, location, orientation, volume.

- LOD 400: The model element is represented as a specific model with accurate area, location, orientation, volume and possessing additionally detailed information for the objects, components and materials.

The LOD has no influence on whether it is possible to convert the model to CityGML, though models with higher LODs are recommended as they contain more accurate information.

3.2.3 IFC Entities & Semantics

Figure 10 represents the most relevant IFC entities with GIS [Nagel and Kolbe, 2007].

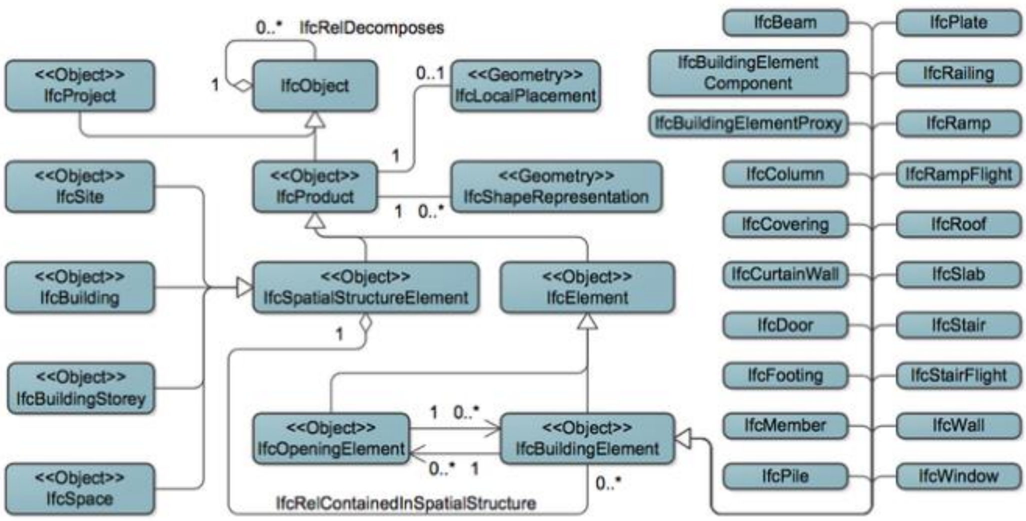


Figure 10: IFC entities [Source: Nagel and Kolbe, 2007]

IFC Door: An element that closes an opening. Its properties are defined by the *IFCPropertySet, while* the geometric representation of *IFCDoor* is given by the *IFCProductDefinitionShape*, allowing multiple geometric representations [www.buildingsmart-tech.org].

IFC Window: An element closing an opening on a wall. Its properties are defined by the *IFCPropertySet, while* the geometric representation of *IFCDoor* is given by the *IFCProductDefinitionShape*, allowing multiple geometric representations [www.buildingsmart-tech.org].

IFC Wall: A construction from a specified material that bounds vertically the model. Its property sets are defined by the *IFCPropertySet and* the use of 'SweptSolid', 'Clipping', and 'Brep' representations is currently being supported [www.buildingsmart-tech.org].

IFC WallStandardCase: It is a subtype of the super type Wall and its properties and geometries are defined by IFC Wall [www.buildingsmart-tech.org].

IFC Slab: A component that encloses a space vertically. Its property sets relating are defined by the *IFCPropertySet* and the use of 'SweptSolid', 'Clipping', 'Brep' and 'MappedRepresentation' representations is supported [www.buildingsmart-tech.org].

IFC Roof: A construction enclosing the building from above. Its property sets *IFCRoof* are defined by the *IFCPropertySet* [www.buildingsmart-tech.org].

IFC Space: Represents the free space of a building bounded actually or theoretically. Its property sets are defined by the *IFCPropertySet,* while the use of a 2D 'FootPrint' representation of type 'Curve2D' or 'GeometricCurveSet' and a 3D 'Body' representation of type 'SweptSolid, 'Clipping' and 'Brep' is currently supported [www.buildingsmart-tech.org].

IFC building: A construction that aims to provide shelter of its occupants. Its property sets are defined by the *IFCPropertySet* and its geometric representation (if the building has an independent geometric representation) is defined using faceted B-Rep capabilities [www.buildingsmart-tech.org].

IFCBuildingElement: An important part of the building from a structural point of view such as floor, roof, wall. Any *IFCBuildingElement* can be represented by one or several geometric representations [www.buildingsmart-tech.org].

IFCBuildingStorey: Represents the storeys of the building**.** Its property sets *IFCBuildingStorey* are defined by the *IFCPropertySet*. Currently, the use of a 2D 'FootPrint' representation of type 'GeometricCurveSet' and a 3D 'Body' representation of type 'Brep' is supported [www.buildingsmart-tech.org].

IFCOpeningElement: Represents the elements that bound an opening. Its property sets are defined by the *IFCPropertySet* [www.buildingsmart-tech.org].

3.3 Communication of IFC & CityGML

The interoperability between IFC and CityGML is considered essential since it could address issues such as cost reduction that is also translated in a time-efficient management of projects, advanced data analysis and a unified view of the details of an area [El-Mekawy, 2010]. Nevertheless, it renders a particularly challenging process due certain parameters. Firstly, it should be taken into account that there is not only one way of 3D modelling, on the contrary more and more software companies develop 3D modelling software tools (Autodesk Revit, Trimble SketchUp, ESRI Cityengine). The aforementioned modelling tools follow different rules during modelling procedures and are often created for different application fields and address different type of users (government, academics, private sector). So naturally, the integration of those systems encrypts major difficulties. By implementing open source standards such as IFC and CityGML, those difficulties can be partly tackled. There are however, important dissimilarities between the structure of those standards that are especially noticeable in their geometric, semantic and topologic properties, forming an intriguing field of research. Nagel and Kolbe [2007] and El-Mekawy et al. [2012] highlighted the most relevant relationships in IFC models that can be applied in geospatial analysis and a part of them is investigated in the specific master thesis. As mentioned previously, the different schemas as well as the handle of geometries and semantics in each standard render the integration quite complex. For example, IFC focuses on the construction of a building and provides structural elements such as Beams, Tiles and Walls. On the contrary, CityGML describes the Buildings as observed and used. Moreover, IFC focuses solely on the building, while CityGML represents a more complex city model that is compiled of LandUse, Transportation Objects, Vegetation and Water Bodies. Finally, unlike CityGML, IFC does not support the multi-scale modelling, since its objects are represented in one Level of Detail [Gröger and Plümer, 2012]. In order to fully highlight the challenges that occur during the conversion between IFC and CityGML, a prototype IFC generic model has been implemented and is converted to a CityGML LoD 3 model, forming the basis for more complicated and semantically enriched conversions.

IFC to CityGML LoD 3 conversion

The methodology proposed is categorized as follows: Firstly, the geometric adjustment of the model takes place, in order to be compatible with the CityGML specification for LoD 3 Buildings. Secondly, semantic information based on the CityGML standard is added and then descriptive information defined by the CityGML standard is implemented. Afterwards, the generated model is validated in Val3Dity and finally, it is evaluated in terms of complexity. The workflow of the process is presented in figure 11.

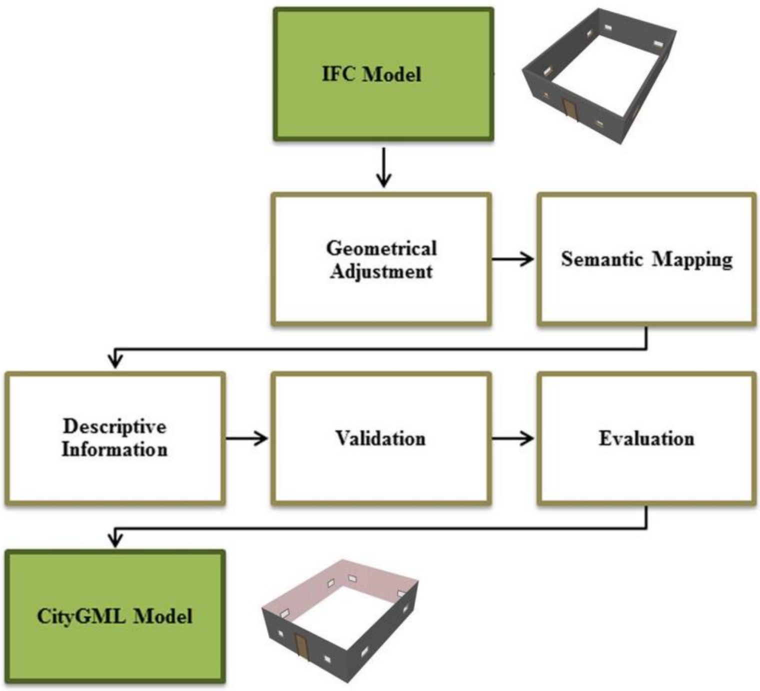


Figure 11: Workflow of the Process

3D Modelling

The building in figure 12 is modelled via BIM in Autodesk Revit 2017 software. It is georeferenced by linking a CAD georeferenced file of the 2D boundaries of the site, based on the Greek Geodetic Reference 1987 coordinate system. As soon as the modelling process and the geolocation of the model were completed, it was exported to IFC Format 2x3. The IFC entities utilized for the conversion were IFC Building, IFC WallStandardCase, IFC Slab, IFC Window and IFC Door. The exported IFC model was visualized in FME Data Inspector and inserted in FME Workbench.

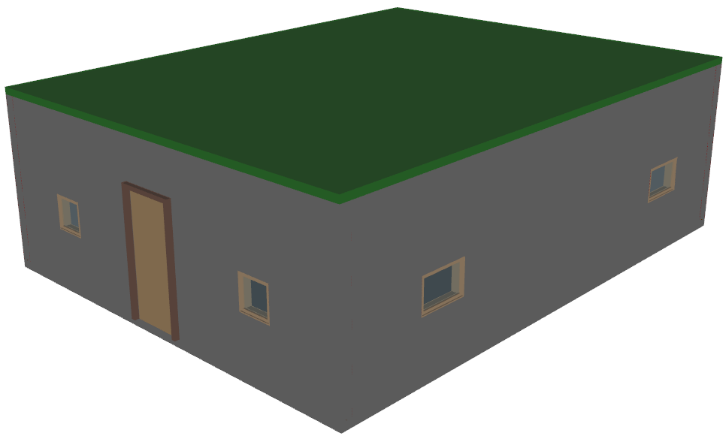


Figure 12: IFC model in FME Data Inspector

Geometric Adjustment of the model

A key characteristic of an IFC model is that each surface appears as a solid in contrast with CityGML LoD 3 specification. So, in order to achieve the geometric adjustment of the model the following process was implemented. The 1st step of the process was to render the IFC geometries compatible with CityGML LoD 3 geometries. More specifically, the interior shell of the building had to be removed. As soon as the exterior shell of the building is extracted, the geometry of the model had to be adjusted, in order to fit the b-rep specification of GML. Therefore, the produced geometries fit the gml:MultiSurface geometry specification of CityGML.

Extraction of geometry: It should be mentioned that each IFC Entity had to be manipulated separately due to the complexity of the schema. The algorithm created for the extraction of the geometry for IFC slab is presented in figure 13.

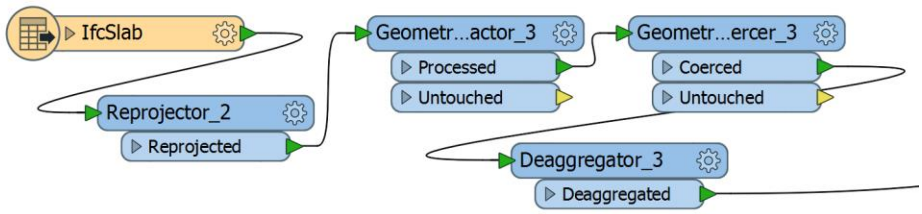


Figure 13: Algorithm for the extraction of slabs

Firstly, with the implementation of the GeometryPartExtractor transformer, the IFC Slabs are extracted (Fig. 14). Then, the GeometryCoercer transformer converts the solid surface to a composite surface in order to be de-aggregated in its structural elements. The algorithm to convert the IFC WallStandardCase follows the same principles with the IFC Slab at this stage of the process.

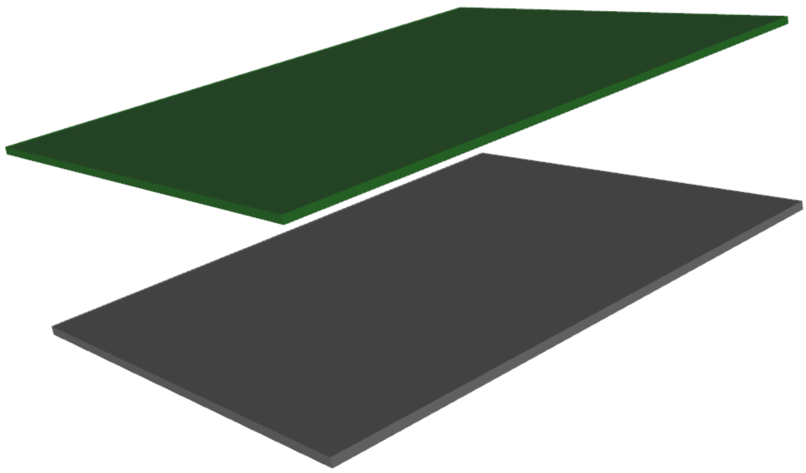


Figure 14: Extraction of slabs

For the IFC Door, the Geometry Extraction is less complicated, since the model consists of only one door. A challenging task is the extraction of the IFC Windows that has to be filtered by attribute characteristics in order to be handled separately on latter stages. Afterwards, the GeometryPart extractor is implemented and the extracted geometry is de-aggregated in order to be converted in a MultiSurface geometry type (Fig. 15).

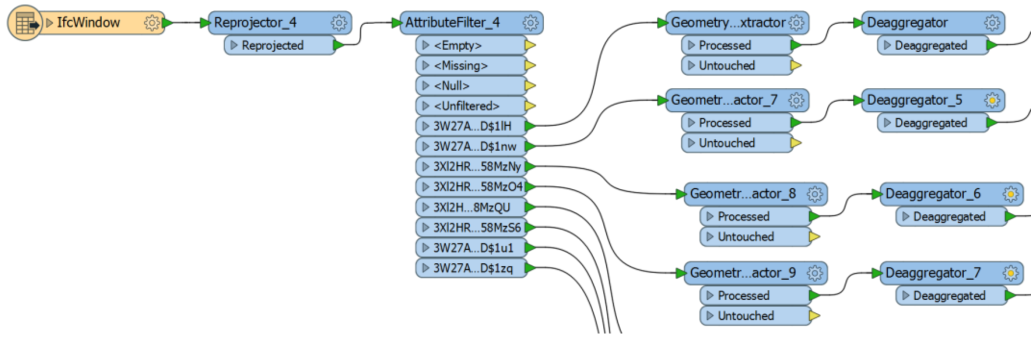


Figure 15: Algorithm for the extraction of windows

Geometry Refinement: After the phase of the extraction, the geometry should be refined to fit the requirements of CityGML. The part of the algorithm responsible for the refinement of the IFC Slab is presented in figure 16. The extracted geometries are inserted in the GeometryCoercer Transformer, which allows the conversion of the geometries in features. The surfaces are converted from Solids to MultiSurfaces. Then, by implementing the AttributeFilter Transformer, the surfaces are categorized based on their attributes to Floor and Roof, which represent the CityGML GroundSurface and RoofSurface respectively. The same algorithm is applied to the IFC WallStandardCase, IFC Window and IFC Door in order to convert the geometries to MultiSurfaces.

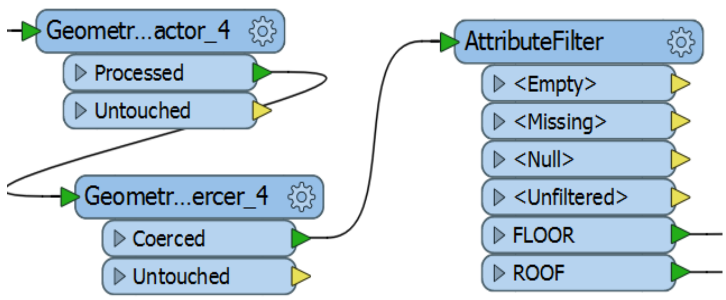


Figure 16: Algorithm for the geometric refinement of the model

Semantic Mapping of the Model and Descriptive information

In order to achieve the semantic mapping of the CityGML, the IFC Building is utilized as input and is converted to CityGML Building. The GeometryRemover transformer is used and then by implementing the AttributeCreator and CityGMLGeometrySetter, the Building is assigned a specific gml_id in order to render its connection with the Boundarysurfaces feasible. The CityGMLGeometrySetter set the Geometry type to LoD3MultiSurface and the feature role to boundedby. It should be noted at this point, that the aforementioned transformer does not accept as valid input geometries that do not meet the b-rep specifications. The AttributeCreator is used to connect the surfaces with the CityGML Building by matching the gml_parent_id of RoofSurface and GroundSurface with the gml_id of the Building. Figure 17 presents the generated CityGML RoofSurface and GroundSurface.

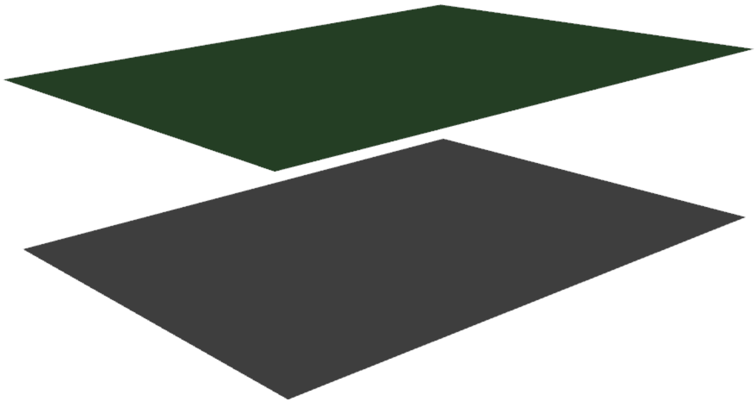


Figure 17: Generated CityGML surfaces

The semantic mapping of the BoundarySurfaces is more complicated because of the fact that the WallSurfaces should be matched with the corresponding Openings. The FeatureMerger transformer ensures that each opening is placed on the appropriate WallSurface. The previously geometrically adjusted surfaces of the Windows serve the role of the Requestor, while the corresponding WallSufaces serve the role of the Supplier. The same algorithm was created for the successful conversion of the Door. The CityGMLGeometrySetter transformers ensure the geometry type of the openings which is LoD3MultiSurface and the feature role Opening. The model is enriched with attributes in accordance with the CityGML standard, such as gml_name, class, function and usage. This is feasible by utilizing the AttributeCreator Transformer as a final stage of the conversion. The generated CityGML model is inserted in the Val3dity software, a validation tool of 3D GML primitives, created by TU Delft in Netherlands (Fig. 18).

```
Reading file: ifc2citygmllod3.xml
Parsing the file...
# of <gml:MultiSurface> found: 15
XLinks found, resolving them...done.
Input file correctly parsed without errors.
Validating 15 MultiSurface
[==================================================] 100%

++++++++++++++++++ SUMMARY ++++++++++++++++++
Primitives validated: MultiSurface
Total # of primitives:      15
# valid:                    15 (100.0%)
# invalid:                   0 (0.0%)
+++++++++++++++++++++++++++++++++++++++++++++
```

Figure 18: Evaluation of the model with Val3Dity

The model is inspected in terms of semantics in FZK Viewer. The output is considered satisfactory, since the semantic hierarchy that is structured by CityGML in LoD 3 is preserved (Fig. 19).

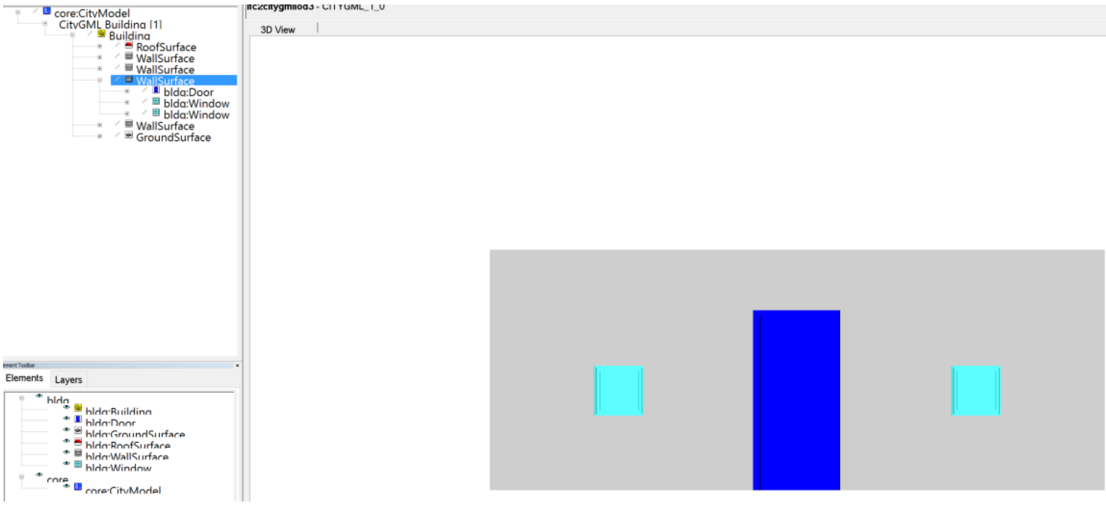


Figure 19: Semantic examination in FZK Viewer

Lastly, the final CityGML model is visualized in FME Data Inspector, as well as in FZK Viewer (Fig. 20).

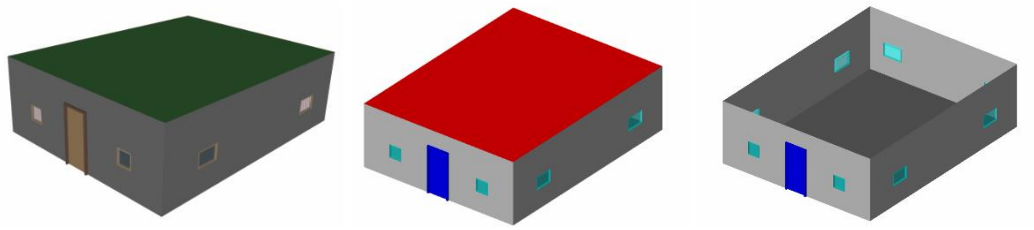


Figure 20: Visualization of the CityGML LoD 3 model in FME and FZK Viewer

3.4 Conclusions

The presented methodology aims to provide the concept that should be followed during the conversion from IFC to CityGML. The geometric conversion of the surfaces is prioritized compared to semantic mapping. There are however several limitations that should be taken into consideration. First of all, the generated CityGML LoD 3 model is a generic model in term of geometry. It consists of BoundarySurfaces and Openings (Windows, Doors), but outer installations are not included. The geometric adjustment of the model is the most challenging task of the conversion algorithm. The implemented software does not support the sophisticated tools that are required for such a conversion and more specifically to convert a solid geometry to b-rep geometry. For this reason, a solution must be investigated in order to convert geometrically complicated buildings. Regarding the semantic mapping, the differences between the IFC and CityGML entities that are addressed during the conversion of slabs should be considered. Also, in case a more complicated model is to be converted, the semantic mapping between more entities needs to be examined. Lastly, the evaluation of the model with validation software tools formulates the basis of a feasible conversion, that needs however to be expanded for more complicated models in terms of geometry and semantics.

Chapter 4

4 State of the Art in 3D Data Integration

GIS and BIM present 3D models from different perspectives: GIS focuses on the spatial relationships between the features of the model that vary in terms of type of objects, while BIM delves into the building process of the model and its structural characteristics. Moreover, the main characteristic of GIS is that the model is geolocated and often it is being approached from a geographic perspective, while BIM facilitates construction projects, thus it is being approached from a building/architectural perspective. There are multiple differences between GIS and BIM, that derive from different kind of users, different application fields, different handling of geometry and semantics, different representations and scaling, different focus on the objects of physical reality and different methods of storage and management [Liu, 2017]. Therefore, it is evident that the integration of GIS and BIM, or more specifically 3D GIS and IFC is of paramount importance, since it can provide unlimited benefits to a majority of users, planners, professionals and ultimately compile a solid tool of data processing and visualization in order to aid towards the goal of generating semantized 3D Smart Cities. The most popular approach for 3D data integration is the unidirectional transformation between IFC and CityGML models, which is argued to remain the only valid method that integrates efficiently BIM with geospatial technology [Isikdag and Zlatanova, 2009]. This chapter, aims to provide an insight regarding the state of the art in the field of 3D data integration. There are multiple options of how to summarize the state of the art such as geometry-semantics, unidirectional-bidirectional and open source-commercial software [Liu, 2017]. Amirebrahimi et al. [2015] proposed that the integration between IFC and CityGML can be classified into three categories: data level, process level and application level. El-Mekawy [2012] categorized IFC and CityGML data integration as follows: (i) unidirectional approaches, (ii) extension of CityGML and (iii) implementation of a new model. Within this context and for the purposes of this thesis, the state of the art is classified based on the aforementioned characteristics of each developed methodology. That way, limitations and advantages of each method can be presented clearly and be directly compared with our proposed methodology. So, the structure is divided as follows: firstly, the theoretical and technical approaches that facilitate a unidirectional or bidirectional methodology are examined. Furthermore, limitations of those frameworks as well as future recommendations are included in order to demonstrate the upcoming topics of scientific research. Secondly, the methodologies that integrate IFC and CityGML data by implementing an Application Domain Extension (ADE) in CityGML are examined. Afterwards, methodologies that require a 3rd party as an integration tool are presented and analyzed.

4.1 Unidirectional methods

Nagel [2007] presented a unidirectional conversion algorithm for the automatic generation of valid CityGML LoD 1 models. In order to do so, the complex IFC model should be in accordance with the simplified geometries of a LoD 1 CityGML model. So, as a 1st step a geometry simplification of the model had to take place. Secondly, by utilizing 2D planar view, the footprints of each floor were separated and then the 3rd dimension for the boundary surfaces was extracted producing the final CityGML model. However, limitations of the method arise especially in the field of generating higher LoDs models and the fact that the proposed methodology was focused on handling differences between the geometries of IFC and CityGML without delving into the field of semantics. With respect to Nagel's findings, Isikdag and Zlatanova [2009] proposed a unidirectional framework for generating CityGML models using BIM. The framework is characterized by two critical steps: the semantic mapping and the geometry simplification of the model. Based on those principles, several examples have been presented, generating CityGML models from LoD 1 up to LoD 4, proving that an IFC model is fully capable in terms of geometric representation and semantics to produce a CityGML model of any detail. However, significant issues raised, that were highlighting dissimilarities of the two standards, such as the weakness of CityGML to address semantically an opening that is not consisted of doors or windows. Also, occasionally the granularity of the model can become a considerable challenge to tackle during the conversion since the levels of representing structural elements is more detailed and sophisticated in IFC compared to CityGML. Nagel, Stadler and Kolbe [2009] proposed reconstruction methods for 3D city modelling in order to enhance the efficiency of BIM which was applied mostly on new constructed projects. The process encloses two stages of reconstruction. During the 1st stage, the 3D model which derives from multiple sources, such as photogrammetry, laser scanning, or manual drawings (CAD) is converted to a CityGML model, based on specific spatio-semantic principles. Depending on the source of the model, in order to handle and refine geometry various sources are proposed. The 2nd stage is the conversion of the CitygGML model to IFC. During this stage, important differences are highlighted in the geometry of the model. While CityGML follows strictly the boundary representation geometry, IFC is more flexible and supports, CSG, sweep volumes and boundary representation. Therefore, the generated geometries are often ambiguous and provide a ground for further research. With regard to unidirectional conversion, El-Mekawy [2012] analyzed the semantic mapping between IFC and CityGML as well as pinpointed the key differences between the two formats. He concluded that despite the fact there are enough IFC classes to serve GIS purposes, there are noticeable differences with the geometric and semantic structure of CityGML. For example, an IFC Building can be separated in storeys and spaces that form a specific storey, while in CityGML, the concept of storeys is not yet supported. Furthermore, the geometric representation of IFC spaces is mostly CSG or sweeping volumes, while in CityGML the boundary representation is followed. Additionally, boundary surfaces such as Walls, in IFC are represented as solids, while in

CityGML are represented as multi surfaces, which generates obstacles during the process of conversion. Within this context, Ellul et al. [2015] investigated a unidirectional conversion from BIM to GIS elaborating further on the differences of the geometries between the two standards and especially on the issues that arise for the conversion of space geometries and boundaries. Donkers [2013] presented an automatic process of converting an IFC model to a LoD 3 CityGML that is evolved in three stages: semantic filtering and mapping, geometric transformations and geometric and semantic refinements. The generated models successfully follow the principles of CityGML. With regard to limitations of the process, the generated models contain only semantic information that is relevant with the CityGML standard, thus the additional IFC semantic properties are discarded. It is also noted the necessity of expanding the conversion not only to CityGML LoD 4 models but also to other city objects such as tunnels, bridges and roads. Geiger [2015] demonstrated the importance of generalizing IFC 3D models, correlating it with the concept of Level of Detail in CityGML. The developed process aims to reduce geometric and semantic redundancy of the model in order to facilitate the extraction of a LoD 1-3 representation without missing critical information. With regard to limitations of the process, it could be mentioned that the tested objects could be more complex, while the need for generating LoD 4 models remains. Furthermore, questions arise with regard to the efficient mapping not only of geometry but also semantics. Zlatanova et al. [2013] stated that one of the limitations of the conversion between IFC and CityGML is the missing semantics that are stored in enriched IFC models.

4.2 Extension of CityGML

Apart from the unidirectional conversion, the integration between IFC and CityGML is also feasible by CityGML with an Application Domain Extension (ADE). Cheng et al. [2013] propose a framework that supports bidirectional translation between IFC and CityGML in different Levels of Detail. In order to facilitate a lossless conversion of geometric and semantic data a CityGML ADE named Semantic City Model (SCM) was developed. Afterwards, a conversion algorithm is utilized by implementing reference ontology and instance-base mapping rule generation [Cheng et al., 2016]. Laat and van Berlo [2011] developed a methodology that aimed to generate CityGML models by utilizing the semantic pluralism of IFC models and assigned each IFC entity to a relevant entity that could be applied in a geospatial environment in order to cover the enrichment of the model with semantic information. CityGML GeoBIM extension allows the semantic enrichment of a CityGML model with IFC data, is developed as an ADE for CityGML and is implemented on BIM server. With regard to the 2nd approach there are clearly significant limitations that need to be considered. First of all, the extension of a CityGML schema in order to process the IFC data results in huge CityGML files that complicate the implementation and management of a 3D city model in multiple application. Secondly, the improvident use of IFC data in a CityGML format can render the file inefficient to use in a smart city and lastly it should always be taken into consideration that the two standards serve different purposes. The communication is important, but it should be targeted in specific application fields.

4.3 3rd party Integration methods

Another approach of 3D data integration is the implementation of a new model that serves a specific purpose. Benner et al. [2005] presented a 3D building model for urban applications. The QUASY system presents many similarities with CityGML but it is more flexible than CityGML due to the application of Quvariants [Liu, 2017], since it is semantically enriched with extensions such as storeys, passages and opening objects. IndoorGML is another framework developed by the IndoorGML Standard Working Group in an OGC GML 3.2 application schema. It facilitates indoor navigation but can also provide valuable insight to the IFC and CityGML. More specifically, the capability of providing indoor data to the aforementioned standards can enhance its role in the integration between IFC and CityGML. El-Mekawy [2012] proposed another framework: Unified Building Model (UBM) for 3D GIS aims to tackle data integration. UBM encapsulates both the geometry and semantic aspects of CityGML and IFC, thus facilitating a smoother communication of the two standards. Aien et al. [2015] proposed a data model that encapsulates both the physical and legal aspects of the environment. The 3DCDM model is developed on the basis of a cadastral system and is extended to support objects from the urban environment. This methodological approach has been utilized in multiple applications as well. Karran et al. [2013] present a BIM-GIS collaboration aiming to assist the integration process of construction supply chain management by implementing a plugin in Revit software. A web based visualization system is developed by Niu et al. [2015] that aims to integrate BIM and GIS in order to monitor the energy performance of a building. This methodological approach can solve efficiently an integration problem, however it is limited to provide a solution from one particular view, for example energy management or construction logistics [Liu, 2017].

4.4 Available data conversion tools

There are numerous conversion tools available that convert IFC to CityGML such as BIMserver, KIT IFCExplorer and Feature Manipulation Engine (FME) by Safe Software [Donkers, 2013]. BIMserver and IFCExplorer are able to convert successfully the IFC Geometry but lack in semantic mapping [Donkers, 2013]. Recently, a semi-automatic process of converting BIM and GIS data was developed by implementing Extract Transformation Load process, which imports the original source of data in a digital workbench environment and allows the manipulation of their features in order to convert them in various data formats [Liu, 2017]. The mapping process during ETL is characterized of flexibility and allows for a fully customized conversion between BIM and GIS [Liu, 2017]. There are however, serious limitations. First of all, it should be noted though, that since ETL process involves a lot of manual data handling of the operator as well as the process is based on his/her interpretation of the model's entities, there is a large room for error. Moreover, the conversion progress requires a significant amount of time and supports the model that has been originally created for. Customization is available and recommended, which is a major advantage of the procedure, however it is not characterized as cost-efficient. A software tool of such purpose is Feature Manipulation Engine (FME) [Safe software, 2017]. An advantage of FME is that supports bidirectional reading and writing between IFC and CityGML, so in theory a bidirectional conversion is feasible. Also, inside the environment of FME, the geometries and semantics retain their original attributes, an issue that arises often in unidirectional methodological approaches [Zlatanova, 2013]. The converters from FME that are available up to today, are not capable of converting IFC models to valid CityGML, even though there is an output in .gml format. Various errors such as the geometric inaccuracy and semantic incoherence of boundary surfaces as structured by CityGML are addressed in the generation of a LoD 2 CityGML model. Additionally, the CityGML output of the conversion in LoD 3 contains thickness in the WallSurfaces, while in LoD 4 both geometries and semantics do not follow the CityGML standard.

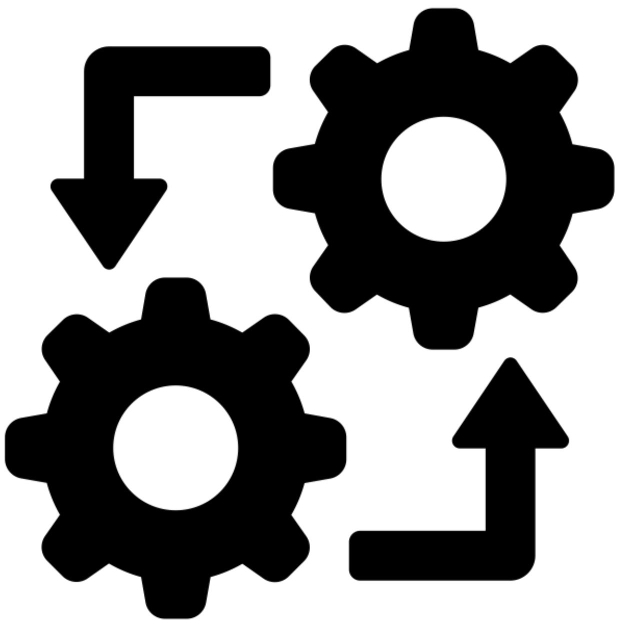
With respect to the aforementioned methodological approaches and available integration tools, the following table summarizes the findings of the presented categorization.

Table 1: Summary of the integration approaches

Integration method	Advantages	Challenges
Unidirectional approach	Successful geometry conversion Time-efficient	Lack of semantic mapping Generation of valid LoD 4 CityGML models Generation of lower LoDs from a LoD 4 model
CityGML Extension	Efficient solution of integrating data in terms of geometry and semantics	Offered solution for a specific application field Wasteful in terms of time and money
3rd party system	Efficient data integration	Offered solution for a specific application field

4.5 Conclusion

The developed methodology can be categorized in the field of unidirectional approaches due to the fact that one of the most important goals of the thesis is to generate a CityGML model in the highest LoD and transfer successfully additional semantic information from IFC sources. The conversion algorithm is intended to be developed by utilizing ETL process via FME software. The reasons enabling the selection of such tools are the following: first of all, the up to date developed conversion algorithms in FME workbench do not generate valid CityGML models, therefore there is plenty of room for improvement and is an intriguing challenge. Secondly, based on previous experience of the author and the paradigm presented in chapter 3, it is highly estimated that the selected tools can preserve and map successfully semantic information. On top of that, the flexibility of the procedure might be able to tackle certain issues that automatic approaches are not always able to deal with and can occasionally mess up the model. Moreover, the bidirectional capabilities of the software render it a valuable tool for future investigation in order to fully understand the communication between the two standards. Within the context of future research, it may be possible to create an algorithm in the FME Workbench that is able to generate simultaneously from one IFC model, different LoDs of CityGML models, contributing significantly in another challenge of the unidirectional approach.



Chapter 5

5 Case Study

5.1 Study area

For the case study two prototype models have been implemented. The 1st model is located in the municipality of Zografou in Athens, Greece. The generated model depicts a building of the School of Electrical Engineering in the campus of National Technical University of Athens, with an area of approximately 2000m². The technical department of the university provided digital and architectural plans of the building, which facilitated the accurate modelling of the building. The building is characterized by great complexity due to its outer façade and rich interior space. Additionally, information with regard to the materials and textures of the surfaces have also been utilized to form a building as close to the reality as possible. Therefore, the specific building is suitable for investigating the integration capabilities between IFC and CityGML, by implementing a conversion algorithm that takes into consideration a significant number of features that exist in both standards (Fig. 21).

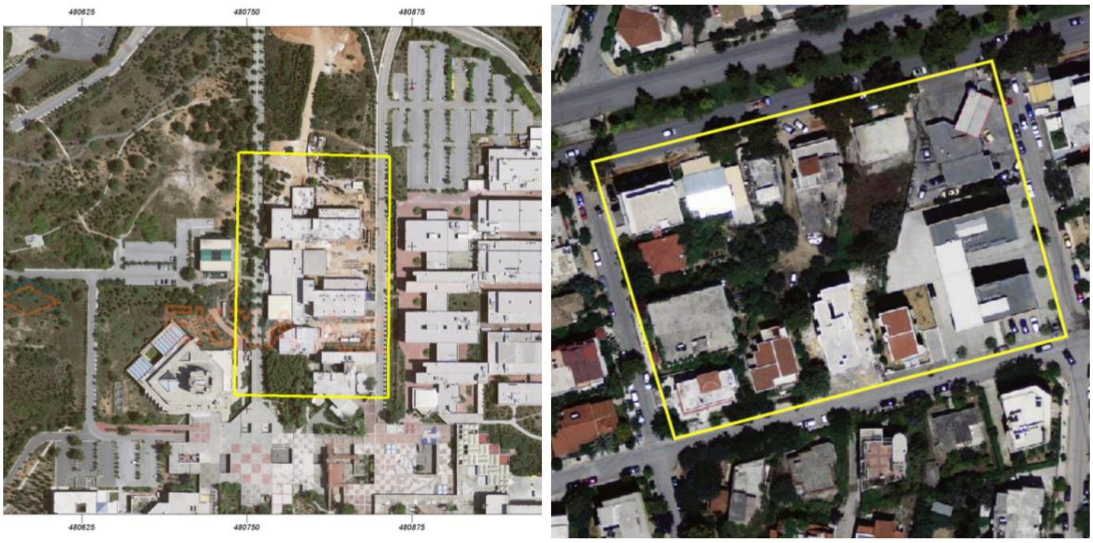


Figure 21: Location of the models

The 2nd model is located in the municipality of Chalandri in Athens, Greece and depicts a building that is being used primarily for commercial purposes. In terms of geometry, although significantly smaller than the 1st model, the complexity of its outer façade can confirm the accuracy of the developed conversion algorithm. Furthermore, it is enriched with cadastral information in order to examine the semantic preservation and transfer during the conversion. The model is based on architectural plans and covers an area of approximately 300m².

5.2 Software & Tools

Within this research work, the various open source and commercial software that have been utilized, can be categorized as follows: with regard to modelling aspect the software that have been implemented are: AutoCAD Civil and AutoCAD Map 2018, Autodesk Revit 2018 and Trimble SketchUp 2017. With regard to spatial processing and analysis the open source software QuantumGIS 2.14 has been utilized. For the conversion of the IFC model, the commercial software Feature Manipulation Engine 2017 has been used, while for the examination and visualization of the generated CityGML models, FZK Viewer and FME Data Inspector have been implemented. Lastly, for the generation of the ADE, Enterprise Architect software has been utilized. An educational license has been received for each commercial software.

5.3 Methodological Approach

The methodology developed in the current thesis aims to provide an insight regarding the geometric and semantic issues that derive between IFC and CityGML in the maximum possible Level of Detail. Firstly, the model is designed in Autodesk Revit following Building Information Modelling. When the modelling process is completed, it is exported to IFC Format 2x3 and then inserted in FME Workbench in order to be further processed. The building's geometry and mapping of the semantics have been separately manipulated between the two standards. With regard to the geometry management, a part of the model is handled inside the workbench, while the rest is inserted and corrected in Trimble SketchUp. The semantic mapping is achieved inside the FME Workbench and attributes and properties of the features in IFC are maintained until the generation of the CityGML model. The generated model consists of CityGML features in Level of Details 3 and 4. As soon as the conversion is complete, an enrichment of the CityGML model with the extra semantic information of the IFC model is investigated via two different approaches as structured by CityGML. Finally, results, key findings as well as recommendations for future research work are thoroughly presented. The workflow of the process is presented in figure 22.

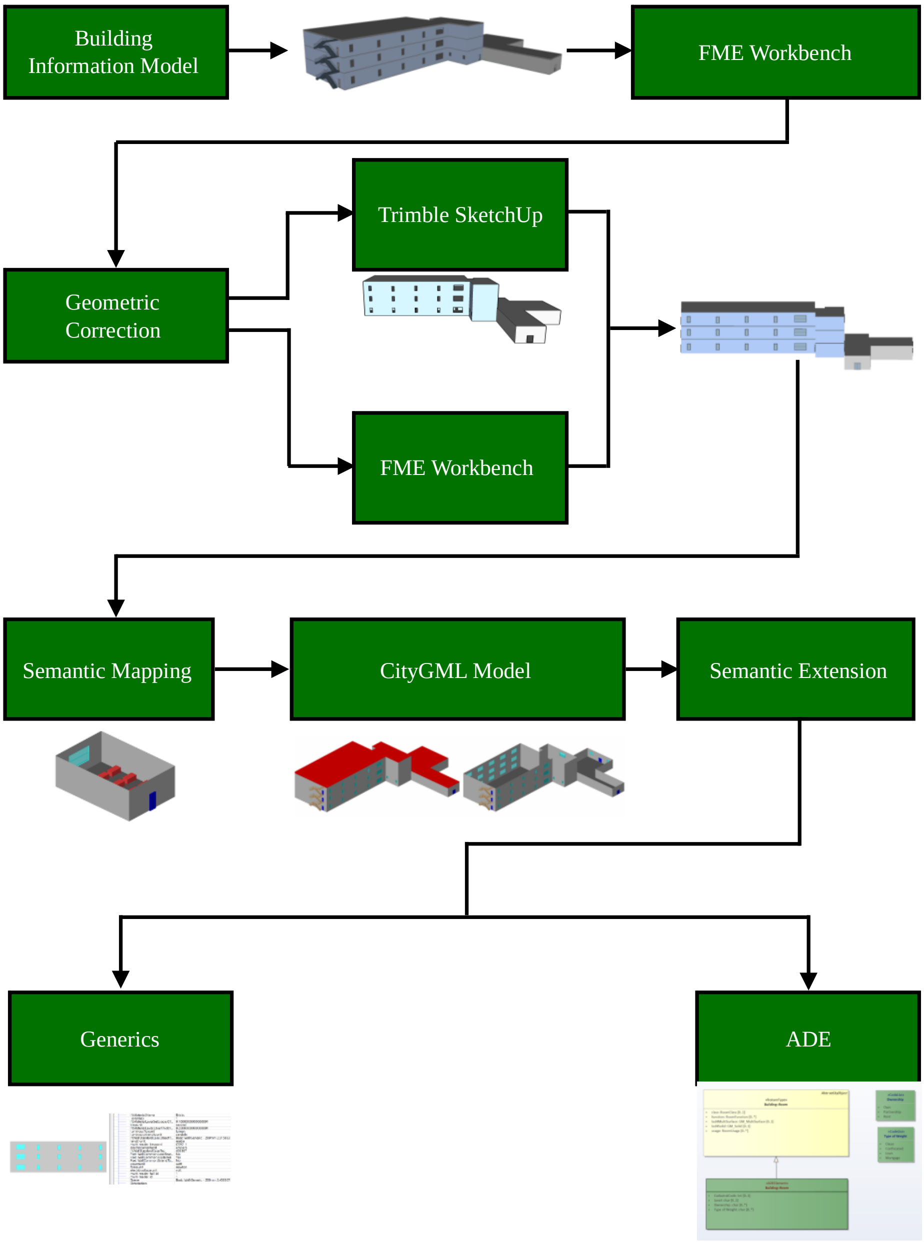


Figure 22: Workflow of the process

5.4 Building Information Modelling process in Revit

The modelling of the building in Autodesk Revit 2018 can be decomposed in 4 critical stages: the geolocation of the model in order to acquire the appropriate coordinates, the setting of the element views' parameters, the creation of geometries, openings and structural elements and the semantic enrichment of the model with information such components and openings, the material of boundary surfaces and the assignment of legal information to the interior spaces of the model.

Georeference of the Model

Autodesk Revit provides the option to link a georeferenced AutoCAD file with the Revit model and acquire its coordinates. In order to do so, it is mandatory to model the physical boundaries of the building in AutoCAD in order to link them with the Revit file. The digital architectural plans provided by the technical department of the NTUA are not referred to coordination system, so the linking between them and the Revit file is not feasible. Therefore, a new AutoCAD drawing should be modelled that will depict the physical boundaries of the building in the proper coordination system. In order to achieve this, firstly a true orthophoto is downloaded from the Hellenic Cadastre website (www.ekxa.gr). The orthophoto is then imported in QGIS 2.14 and georeferenced, by linking known ground points to the relevant points in the orthophoto, and then imported in AutoCAD Map 2018 where the boundaries of the model are digitized. Finally, it is inserted in AutoCAD Civil 2018 and linked with the Revit model. The coordination system of the model is the Greek Grid Reference System '87 (GGRS '87).

Setting element views

An important step of the modelling process is setting the element views. By doing so, the top and bot constraints of each object are immediately defined, therefore the geometric accuracy of the model is preserved. The building consists of a ground floor and two additional floors. The element views are set to match both the ceiling and floor view of each floor in order to facilitate the conversion to a CityGML model. Additionally, interior and outer building installations such as stairs or furniture also need base and top constraints, thus the views have been set accordingly as shown in figure 23.

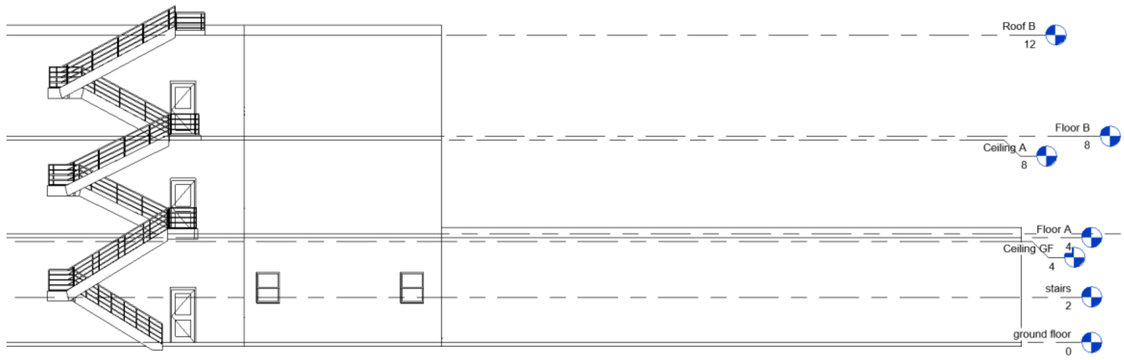


Figure 23: Element views in Autodesk Revit

Generating geometries, openings & components

As soon as the elements view are set, the building is designed based on architectural plans in 2D for greater accuracy and efficiency. As mentioned before, BIM complies with the IFC standard in terms of geometry, semantics and topology. Therefore, the structure of the wall is presented as a solid geometry that although connects with another wall, each geometry maintains its original form as shown in figure 24.

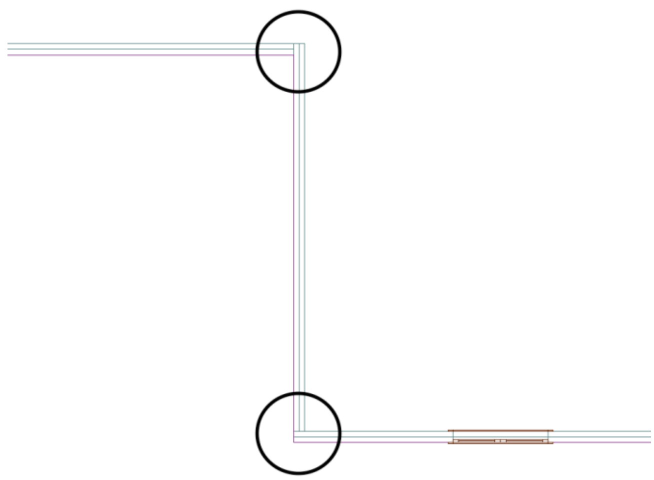


Figure 24: Geometry structure in BIM

The latter constitutes one of the greater differences between the two standards in terms of geometry, especially when the interior wall surface has to be taken into consideration for a generation of a CityGML LoD 4 model. Similarly, surfaces such as floors and roofs require special modelling approach. The boundaries of those surfaces can be attached either with the interior, or the exterior of the wall surfaces, which causes significant geometric issues during the conversion process. Furthermore, due to the fact that roofs and floors are solid geometries as well, the ceiling of the ground floor constitutes the floor surface of the 1st floor.

When the boundary surfaces and interior of the building are modelled, openings and multiple components are to be installed. Autodesk Revit provides a library that allows the selection of the appropriate element depending on the project's needs. For the purposes of this research, the elements installed are various types of doors and windows depending on their usage externally or internally, stairs and rail cases connecting the floors of the building and classroom equipment such as desks and chairs in order not only to vivify a high LoD model, but also investigate the conversion limitations and challenges that may or may not occur during the conversion of IFC to CityGML (Fig. 25).

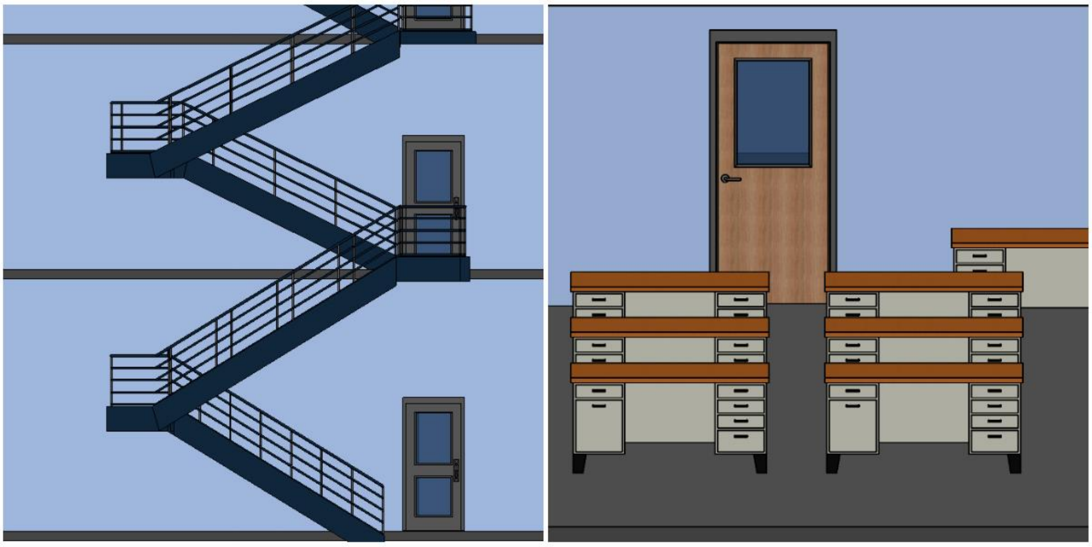


Figure 25: Model enrichment with components in BIM

Semantic enrichment & Properties

A challenging task in 3D data integration between IFC and CityGML is the preservation of semantics. An IFC model is enriched with critical semantic information, even in its most simple form. A building designed in Autodesk Revit is composed of multiple information that currently cannot be stored in CityGML. In order to achieve interoperability option between the two standards and to generate models that are enriched with multiple types of information, the presented methodological approach aims to address the semantic enrichment of a CityGML model. Research and development on IFC standard ensures that an estimated number of 900 classes meets the building industry' s requirements. However, as it has been previously mentioned only a small portion of those data is relevant with GIS applications [Luut and v. Berlo, 2011]. This thesis, aims to provide a method that not only produces a CityGML model, but also preserves - if not all- a significant amount of IFC semantics. So, in order to investigate this amount and types of semantics that can be stored in IFC and properly mapped to CityGML, the models are created from scratch in Autodesk Revit. BIM is heavily utilized in project management among other application fields, therefore the accurate geometric representation of objects and features is often not sufficient. Each and every one of the elements that are included in the model have been semantically enriched up to a certain extent. More specifically, boundary surfaces such as walls, roof and floor are assigned the material which they are made of. Accordingly, openings, such as windows and doors include information with regard to the main and secondary material they are consisted of, their reflectivity, and whether they are external or internal objects of the building. The 2nd model, has been enriched with legal information in order to examine whether the stored semantics can be preserved and successfully transferred to CityGML or not. Autodesk Revit provides the capability of setting specific areas as rooms. Within this context, 4 rooms are created and the semantic enrichment took place by creating corresponding schedules. Inside those schedules, cadastral information has been assigned and more specifically the following columns have been generated: Cadastral Code Number, Ownership Properties, LandUse and TypeofRestriction. These attributes constitute a small part of the key-element legal information included in the Hellenic Cadastre. Additionally, they are not assigned to an object or a surface, but on a semantically enclosed space, thus they satisfy the criterion of examining the semantic conversion that are located in non-geometric elements.

After the last stage is completed, the model is exported to IFC 2x3 coordination view format and visualized in FME Data Inspector (Fig. 26).

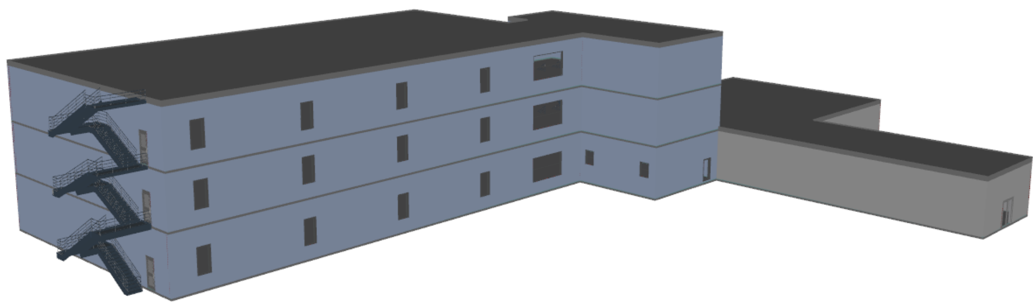


Figure 26: Generated IFC 2X3 model

The modelling procedure unravels important issues that should be considered prior to the conversion of the model in CityGML. First of all, the flexibility of the software, for example in designing roofs and floors can differentiate the same IFC model when created by multiple sources and therefore render the conversion to CityGML more complicated. More specifically, the footprints of a slab that are designed based on the exterior footprints of the wall facilitate a smoother conversion to LoD 3 CityGML, but can complicate the conversion to a LoD 4 CityGML. Another important characteristic is the fact that a component might be consisted from multiple IFC entities, such as a staircase, which can include slabs and railcases. However, in CityGML, these objects are mapped as BuildingInstallations, which limits their efficiency and functionality in various applications, such as indoor navigation and evacuation systems. Moreover, BIM proves capable for adding multiple semantic information to the model, even in its simplest form. In the buildings generated, information that can be used for construction and energy management as well as for cadastral purposes have been attached. This information needs to be examined if maintained throughout the conversion progress, and whether they can be written in CityGML format or not.

5.5 Conversion algorithm between IFC and CityGML

The generated IFC model is imported in FME Workbench to be manipulated and converted to a CityGML LoD 4 model (Appendix III and IV). Inside FME Workbench, it is decomposed to its structural elements that follow the IFC standard and contain geometric and semantic information. The automatic decomposition of the model is of significant importance, since it facilitates the separate manipulation of each entity. The IFC model consists of the following IFC entities, as presented in table 2. They are categorized based on whether they contain solely semantic information or combine geometry and semantics. This table forms a primary distinction of the model's entities towards the semantic mapping that will be implemented on later stages.

Table 2: IFC entities of the generated model

IFC Entity	Geometry & Semantics	Semantics
Building		✓
BuildingStorey		✓
Door	✓	
FurnishingElement	✓	
Member	✓	
OpeningElement		✓
Project		✓
Railing	✓	
Roof		✓
Site		✓
Slab	✓	
Space		✓
Stair		✓
StairFlight	✓	
WallStandardCase	✓	
Window	✓	
PropertySetDefinition		✓

IFC Building: serves a similar role as the _AbstractBuilding in CityGML and contains semantic information.

IFC Door: matches the Door from CityGML and contains both semantic and geometric information.

IFC FurnishingElement: matches the BuildingFurniture from CityGML and contains both semantic and geometric information.

IFC OpeningElement: represents the void created by the existence of an opening such as a door or window.

IFC Railing: alongside with IFC Stairflight and IFC Slab form exterior or interior stairs that match the outer or interior BuildingInstallation in CityGML. IFC Stair supplies the geometry with additional semantic information.

IFC Roof: contains semantic information of the roof surface that should be joined with IFC slab during the conversion.

IFC Site: contains information regarding the surrounding environment.

IFC Slab: matches boundary surfaces in CityGML such as ceiling surfaces, floor surfaces or ground surfaces. Additionally, matches any surface that forms a component and might be considered as a floor or roof. Such an example is the landing slab at the end of a staircase.

IFC Space: serves a similar role with CityGML Room. It can be heavily enriched with semantics that contain multiple type of information about the specific space.

IFC WallStandardCase: matches the WallSurface and InteriorWallSurface in CityGML and contains both geometric and semantic information.

IFC Window: functions similarly with CityGML Window.

IFC PropertySetDefinition: contains semantic information with regard to the properties and attributes of each IFC entity.

Even though the mapping of semantics follows the geometric correctness of the model, it is essential to distinguish "a priori" the geometries and the semantics of IFC and how they should be mapped according to the CityGML standard, because inside the workbench they need to be filtered and stored accordingly.

Geometric compliance with CityGML standard

The geometric compliance can be further separated in two processes. The 1st process includes the adjustment of IFC WallStandardCases and IFC Slabs outside the environment of FME Workbench and more specifically in Trimble SketchUp, while the 2nd process includes the adjustment of the rest of the geometries inside the FME Workbench environment. In order to achieve the required compatibility between the two standards, each IFC feature is manipulated separately.

Process in Trimble SketchUp

As illustrated in previous chapters, a challenging task is the conversion of solid geometries to geometries that comply with the CityGML standard. During the conversion of a generic building to a CityGML LoD 3, the transformers in FME are sufficient to facilitate the conversion. However, when the complexity of the building increases, the current transformers are not capable of generating geometries that comply entirely with the CityGML standard. The main issues concern LoD 4 models and models of multiple LoDs with greater complexity in their boundary surfaces, such as “niches” in the walls. In order to tackle this issue, the IFC WallStandardCase and the IFC Slab have been extracted and via a separate algorithm (Appendix V) have been written in a .skp file, in order to be imported in Trimble SketchUp 2017 (Fig. 27). The coordination system that is set to EPSG: 2100, ensures that remains unaffected during the extraction of the entities. The algorithm firstly implements the GeometryPartExtractor transformer in order to extracts the “Body” geometry of the IFC entities. Then the GeometryCoercer transformer coerces the solids to composites surfaces and the Deaggregator transformer breaks up the composite surfaces into faces. Then, the OverlaySurface transformer detects the overlapping geometries inside the model and a Tester transformer removes the redundant geometry. A unique id is then set to all faces and by implementing the GeometryPropertySetter transformer the unique id is set as the geometry trait: “sketchup_layer_name:” in order to write the model in .skp format.

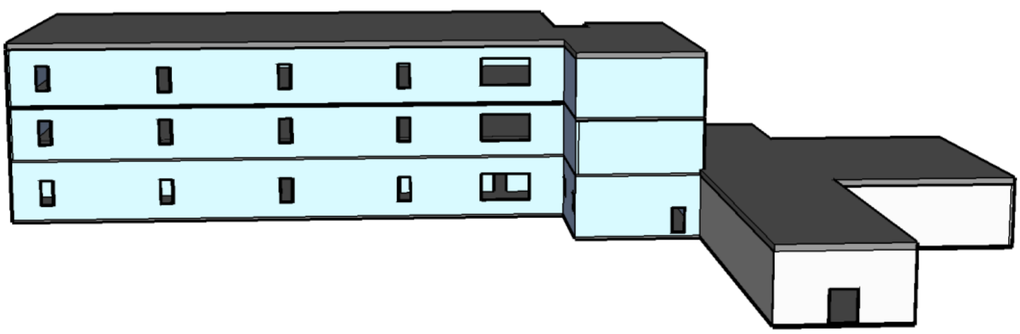


Figure 27: Generated Trimble SketchUp model

It should be noted that the semantic functionality of modelling in Revit and the IFC properties have been maintained, while the methodology will be presented in more detail in the stage of the semantic mapping. As soon as the model is inserted in Trimble SketchUp, the correction of the geometries is performed by utilizing specific tools such as the extrusion of objects and the grouping of components. Trimble SketchUp is mentioned as the modelling tool able to generate valid CityGML models (www.citygml.org). It is a 3D modelling software that includes limited BIM capabilities, but in terms of handling geometry, it presents multiple similarities with CityGML. First of all, objects such as walls, are represented as multisurfaces and not solid geometries. This is a significant advantage, since it facilitates the geometric correction by implementing the erase tool in order to discard the redundant geometries (Fig. 28).

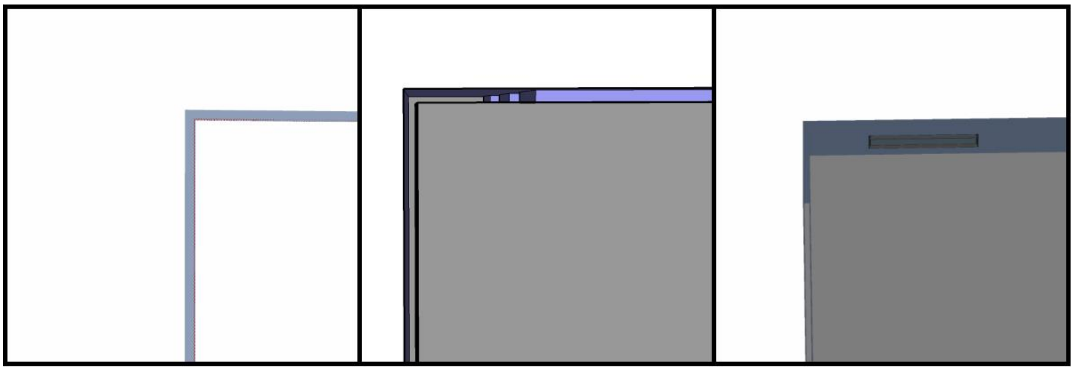


Figure 28: Geometry of wall in IFC, Trimble SketchUp and CityGML respectively from left to right.

Furthermore, it has been documented by previous works [Dimopoulou et al., 2014; Floros et al., 2015], that Trimble SketchUp is able to generate CityGML models via FME Workbench. The functionality of the software, as well as previous experience with the conversion algorithms between .skp and .gml render the conversion efficient. However, a major disadvantage of Trimble SketchUp is that lacks semantic enrichment and functionality, even though it is connected to an online warehouse and is able to import in the model components that can be used in multiple applications. So, in order to address the aforementioned issues, an erase of the redundant geometries is sufficient. An example of such correction is illustrated in figure 29. Additionally, it should not be taken as a fact that an IFC model will always be geometrically correct, since each IFC building may be employed to various application fields, thus the modelling procedure in each case may differ. Also, an IFC model might be unintentionally consisted of minor geometric errors, such as disjointed surfaces or geometric misshapes that do not, however, render the IFC model invalid [Donkers, 2013].

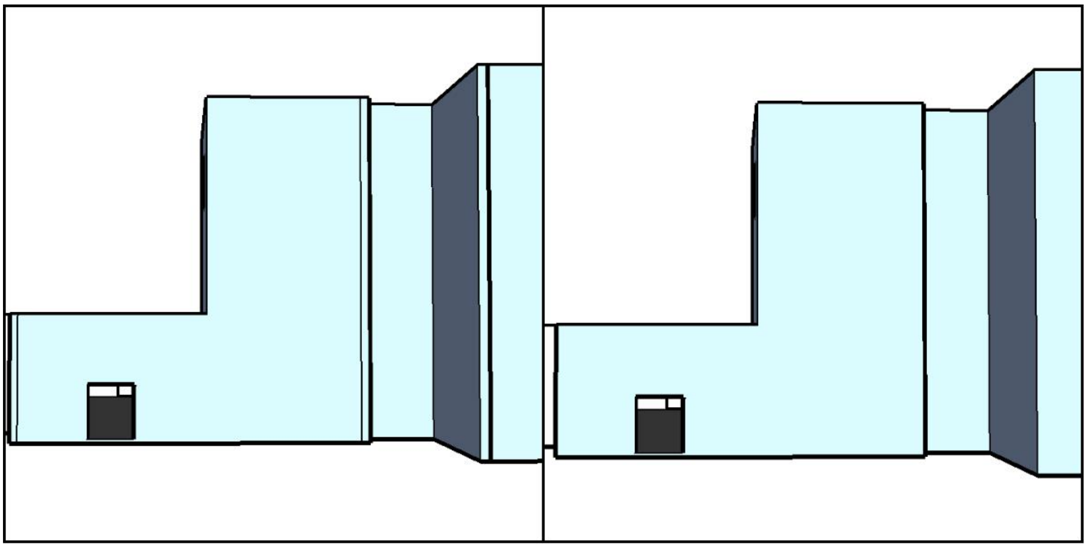


Figure 29: Geometric correction of the model in Trimble SketchUp. Before (left figure) and after (right figure)

Therefore, the extraction of the geometries in Trimble SketchUp is able to overcome and solve such issues in order to ensure geometrically concrete surfaces and objects. This process aims to fix the geometric accuracy of the wall surfaces and the slabs. This issue arises in LoD 4 models, since the roof or the ground surface should be further decomposed in ceiling and floor surfaces respectively. In order to solve it, the roof surface is "moved inside" and the attached wall surface is extruded up to the level of the roof surface (Fig. 30).

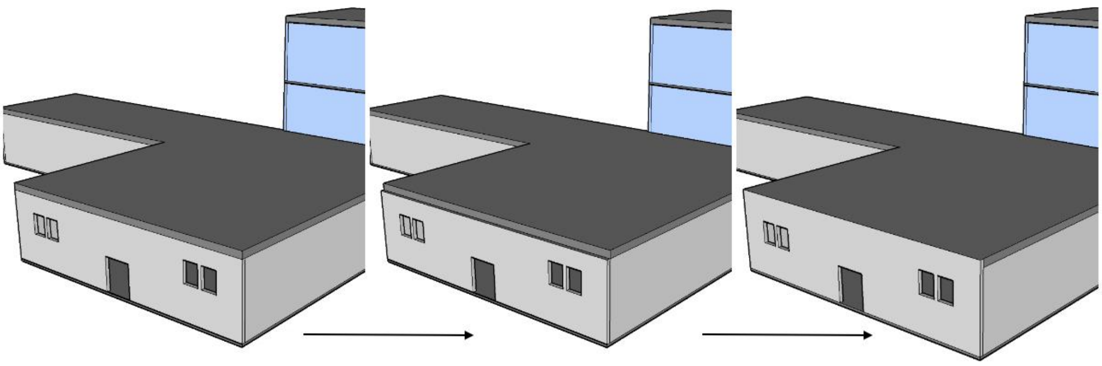


Figure 30: Geometric correction of roof and ground surfaces

Finally, the redundant geometries are erased and the process of correcting the slabs is completed so the model fits the geometry principles of CityGML (Fig. 31).

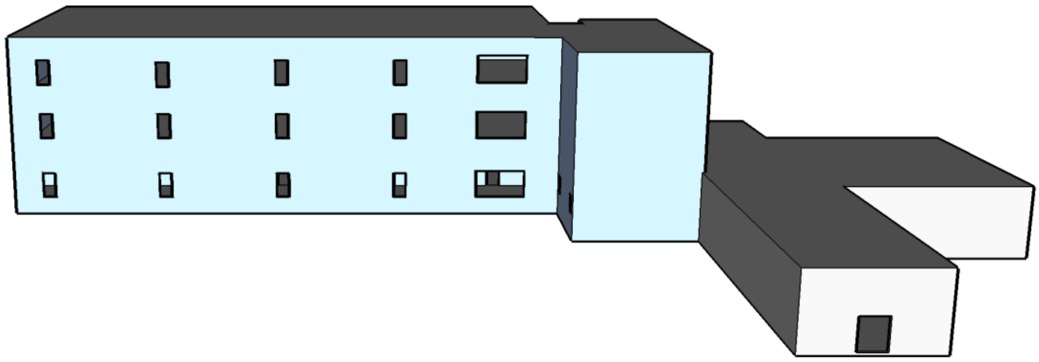


Figure 31: Fixed SketchUp model

Process in FME Workbench

As soon as the geometries are fixed via SketchUp, the model is inserted in FME Workbench as a .skp file and the conversion to CityGML Surfaces takes place. Each entity is manipulated separately, thus the stages of the geometric conversion of each entity must be presented distinctively along with the key findings and issues that arise. It should be noted, that the geometric process refers to the IFC entities that contain both geometry and semantics based on table 2. The rest of the entities will be explicitly analyzed during the stage of the semantic mapping.

IFC WallStandardCase & IFC Slab: The boundary surfaces are already corrected via Trimble SketchUp. Therefore, the critical step in FME is to extract the relevant geometries with respect to the CityGML surface they belong to. More specifically, by implementing the GeometryPartExtractor and filtering with the geometry trait: “sketchup_layer_name” the geometries that form the GroundSurface, the RoofSurface and the WallSurface are separately distinguished and stored. As a final step, the GeometryRefiner transformer is implemented in order to address potential minor geometric errors and the geometries are now available for semantic mapping with the CityGML features.

As mentioned previously, IFC WallStandardCase contains both the exterior and interior WallSurface in terms of CityGML structure. Similarly, IFC Slab can be further categorized in CeilingSurface and FloorSurface. Therefore, the geometric correction in Trimble SketchUp benefits the interior wall surfaces, the ceilings and the floors. By implementing the GeometryPartExtractor transformer, filtering based on the geometry trait: “sketchup_layer_name” and the GeometryRefiner transformer the geometries are converted to fit the CityGML standard and are stored for the semantic mapping as the next step of the process (Fig. 32).

IFC Door & Window: The IFC openings match the openings Door and Window in CityGML. However, in order to comply with the CityGML geometry specification and more specifically with lodXGeometry or lodXMultiSurface they need to be geometrically manipulated. First of all, by implementing the Deaggregator transformer, the components are split in their elemental parts. Afterwards, the geometry trait: “Body” is extracted and by implementing the GeometryCoercer transformer their geometry is converted to composite surface and the GeometryRefiner transformer fixes potential minor geometric errors. The UUID generator transformer creates a unique ID for each object and based on that, the Aggregator transformer joins the disaggregated parts to form the final components. Lastly, they are filtered based on their attributes and are stored until the stage of the semantic mapping.

IFC Furnishing Element: In case the furnishing elements are connected solely to the BuildingFurniture feature in CityGML, the conversion steps of their geometry match the steps of the IFC openings. After the geometric correction, they are filtered and stored separately in order to be assigned to the appropriate rooms.

IFC Stairflight & Railing: These IFC entities should be matched with the interior or the outerbuildinginstallation feature in CityGML. Therefore, the geometry processing starts with the Deaggregator transformer in order to split the objects into their elemental parts. Afterwards, the GeometryPartExtractor transformer distinguishes the interior from the outer building installations. Since an IFC stair may be consisted by IFC slabs, it is important during the conversion, to include them as well. The GeometryCoercer transformer converts the geometry to composite surface, the objects are aggregated based on a unique id attribute and are stored in order to be semantically mapped.

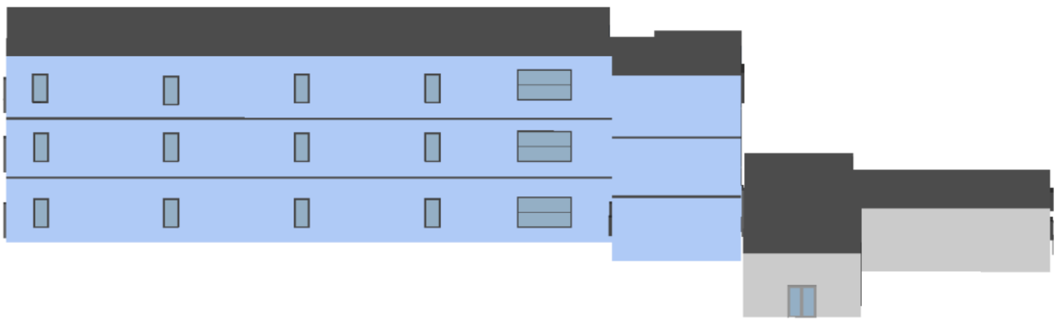


Figure 32: Geometrically fixed model pending semantic mapping

Semantic Mapping

The semantic mapping between the entities of the two standards can be proven quite complicated especially in higher LoDs. On one hand, CityGML can possess semantic properties at three levels of geometry: solid, face and curve/line level. On the other hand, IFC allows the connection of an object with multiple other objects in order to obtain semantic information [Donkers, 2013]. The IFC schema holds around 900 classes and most of them are irrelevant for GIS purposes. Luut and v. Berlo [2011] have presented an approximate number of 60-70 classes that are considered appropriate for GIS applications. Within this context, there are IFC entities that are irrelevant to the CityGML Building, hence they are excluded from the conversion. Furthermore, Luut and v. Berlo [2011] have defined certain entities that are able to be mapped directly in CityGML such as the IFC building, IFC Wall and IFC Door. However, the semantic mapping between the two standards is not always a straightforward process and should be taken into consideration that an IFC entity may contain other IFC entities alongside their semantics (i.e. landing slab in a staircase).

IFC Building provides similarities with the CityGML Building in terms that both serve semantics. CityGML Building is formed by boundarysurfaces, such as walls, ceilings and floors. Therefore, the IFC Building entity is mapped semantically with the CityGML Building. In order to accomplish the aforementioned mapping the AttributeCreator transformer is implemented to convert the IFC_unique_id to gml_id, which is set as an attribute to the CityGML Building with the name "fme_shmmy". Following that, the CityGMLGeometrySetter transformer is applied which sets the feature role as a "CityObjectMember" and the CityGML LoD Name as LoD4MultiSurface.

IFC Space is used to model the interior free space in a Building, similarly as the feature Room in CityGML. The Rooms in CityGML are compiled of CeilingSurfaces, InteriorWallSurfaces, FloorSurfaces and Closuresurfaces. Therefore, the semantic mapping between IFC Space with CityGML Room takes place by utilizing firstly the AttributeCreator transformer. More specifically, each room is assigned a gml id (i.e. fme_Room1) and a gml_parent_id that links the room to the CityGML Building it belongs to, which in our case is "fme_shmmy". Lastly, the CityGML GeometrySetter transformer is applied, which sets the feature role as "Interior room" and the CityGML LoD Name as "Lod4MultiSurface". For the purposes of this thesis, a total of nine (9) rooms has been created.

When the semantic mapping of the Building and the Rooms is completed, the rest of the objects need to be mapped as well. As mentioned above, the IFC WallStandardCase and IFC Slab have been extracted, written and fixed geometrically in Trimble SketchUp. Within this context, a logical argument arises stating what is the purpose of modelling in Revit in the 1st place, instead of modelling in Trimble SketchUp, since the geometries are simpler and the semantics are discarded. However, in our case, all of the semantic information is stored. More specifically, when the IFC entities are converted to .skp file (Appendix V), they are assigned a specific id. Simultaneously, the semantic information that is contained in IFC Slab and WallStandardCase is stored in a separate .csv file. Firstly, the same id that is assigned to all geometries is assigned to each of their properties as well, in order to share a common attribute. Secondly, the BulkAttributeRemover transformer ensures that unnecessary attributes are removed and the final writing in a .csv file takes place. So, as soon as the geometric correction in Trimble SketchUp takes place, the .skp file is imported in FME Workbench. Simultaneously, the .csv file is imported as well and by implementing the FeatureMerger transformer and linking the properties with the corresponding geometries via the aforementioned common id, the result is a model that is geometrically corrected in Trimble SketchUp and preserving the semantic information from BIM (Fig. 33). It should be noted that during the geometric correction, there are certain geometries that are being erased. Even though the surface is discarded from the model, the "sketchup_layer_name" which sets the common id between the semantics and the geometries remain unaffected. Therefore, in those cases the preservation of semantics is prioritized over the geometric correctness.

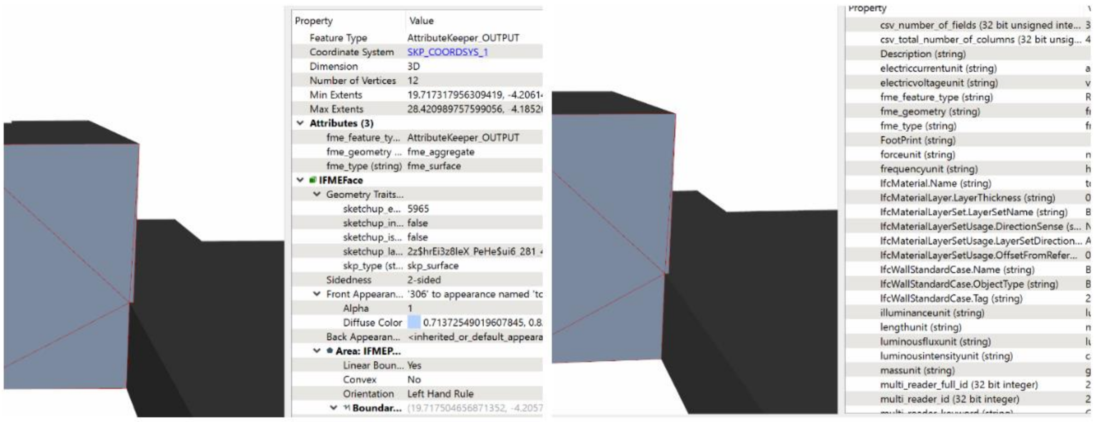


Figure 33: Preservation of semantic properties throughout the process. On the left side, the wall surface inside Trimble SketchUp is missing semantic information. On the right side, it is reinserted in FME Workbench alongside its stored semantic information

In order to map correctly the surfaces to the relevant CityGML feature types, the AttributeFilter transformer is utilized to distinguish its geometry. From that point, the semantic mapping of the process is split in two stages. The 1st stage includes the semantic mapping of the outer façade of the building and more specifically the mapping of the geometries that are detected in a LoD 3 model. Hence, the AttributeCreator transformer links each surface (WallSurface, RoofSurface, GroundSurface) to the relevant CityGML Building, by creating the gml_parent_id and setting the value "fme_shmmy". Afterwards, the CityGMLGeometrySetter is implemented which ensures that the feature role of the objects is set to "bounded by" and the CityGML LoD Name is set to LoD3MultiSurface. The 2nd stage includes the semantic mapping of the interior surfaces. Thus, the AttributeCreator sets as a gml_parent_id the relevant room that each surface belongs to (i.e. fme_room1), in order to connect the rooms with the interior surfaces (CeilingSurface, InteriorWallSurface, FloorSurface and ClosureSurface). Finally, the CityGMLGeometrySetter transformer sets the feature role of the objects as "bounded by", while the CityGML LoD Name as LoD4MultiSurface. At this point, it should be noted that the "IsExternal" semantic property of IFCWallStandardCases is not always accurate [Donkers, 2013]. This is depicted in figure 34, where a part of the wall is exterior, while the rest of it is part of the interior building. The proposed methodology considers such issues and addresses them by mapping the objects to the appropriate CityGML surfaces.

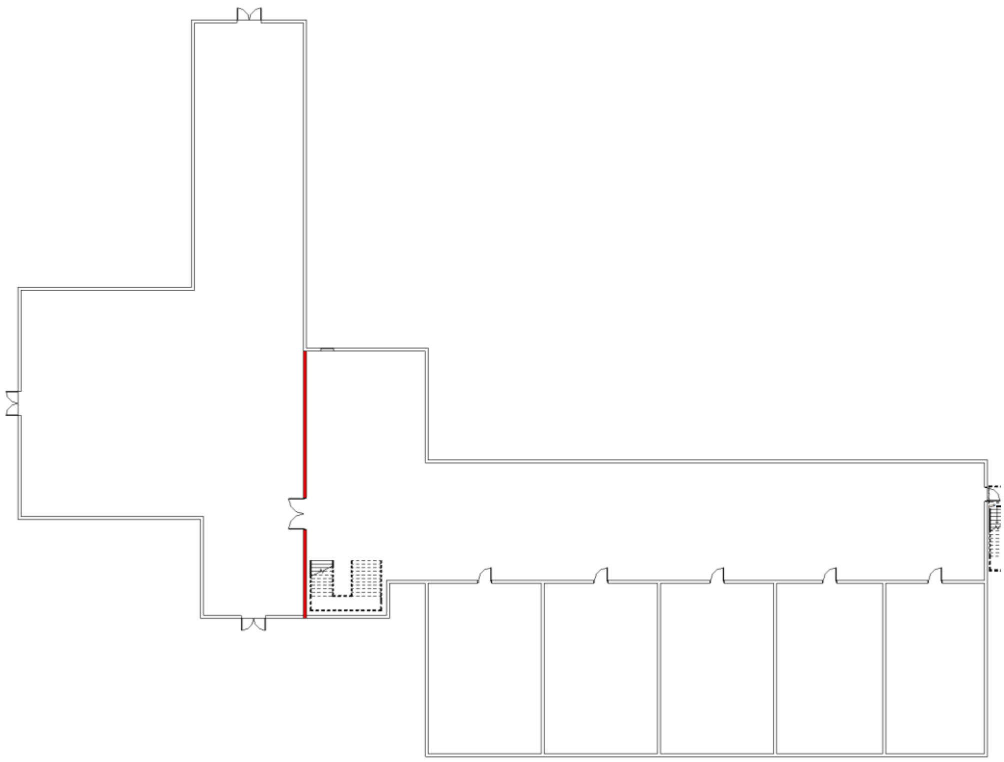


Figure 34: Highlighted (red) part of the wall is considered an exterior wall

Another challenging task is the appropriate mapping of IFC openings, such as windows and doors. According to the CityGML standard, if the surface of the wall contains openings, then this relationship must also be depicted semantically [OGC, 2012, p. 12]. Within this context, the implementation of the FeatureMerger transformer is mandatory. In order to do so, in the AttributeCreator transformer an attribute named "_join" with value "1" is created for both the wall surface and the opening. Then, those two features are merged to be semantically connected, and the result is inserted in the CityGMLGeometrySetter transformer and the feature role is set as "opening" and the CityGML LoD Name of the object is set as "LoD4MultiSurface". However, since the generated CityGML model is LoD 4, the openings must be semantically connected with the interior surfaces as well in order to enables a connection of adjacent rooms. Therefore, each opening is connected semantically with the interior surfaces by implementing the

FeatureMerger transformer and a common attribute, before it is linked with the aforementioned CityGMLGeometrySetter transformer (Fig. 35).

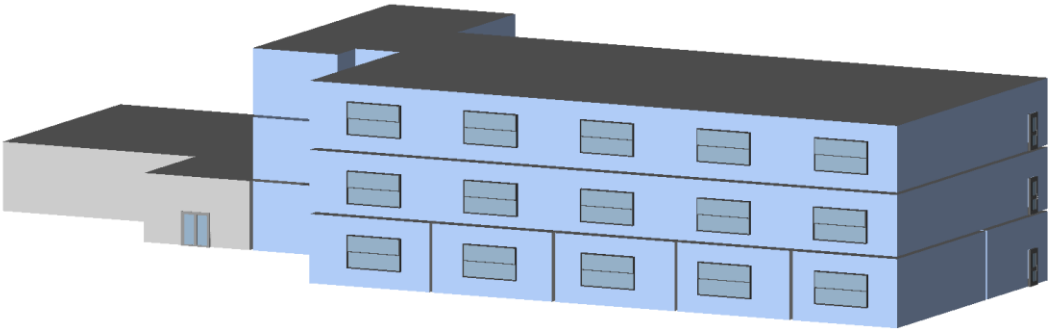


Figure 35: Semantic mapping of openings and boundary surfaces

With regard to the semantic mapping of IFC Furnishing Elements, a connection between the furniture and the room they belong to must be established. This is feasible by the AttributeCreator transformer and setting the gml_parent_id the value of the corresponding room (i.e. fme_Room1). Finally, the CityGMLGeometrySetter transformer sets the feature role as “Roomfurniture” and the CityGML LoD Name of the objects as LoD4MultiSurface.

Lastly, the IFC Stair Flight, Railing and Stair need to be semantically mapped as outer and interior building installations. With regard to the outerBuildingInstallation, in the AttributeCreator transformer the gml_parent_id matches the gml_id of the Building, which is “fme_shmmy”. In CityGML, an interiorinstallation can belong to either the whole building or to a specific room [OGC, 2012, p. 76]. For the purposes of this case study, the interior building installations have set as gml_parent_id the gml_id of the Building. Finally, the CityGMLGeometrySetter transformer sets the feature role as “outerbuildinginstallation” and “intbuildinginstallation” and the CityGML LoD Name of the objects as LoD3MultiSurface and LoD4Multisurface respectively.

Table 3: Semantic mapping between IFC and CityGML

IFC Entity		CityGML Mapping	CityGML LoD Name	Feature Role
Ifc Building		CityGML Building	LoD4MultiSurface	CityObjectMember
Ifc Door		CityGML Door	LoD4MultiSurface	Opening
Ifc FurnishingElement		CityGML BuildingFurniture	LoD4MultiSurface	Building Furniture
Ifc Railing	Outer	CityGML Outerbuildinginstallation	LoD3Geometry	outerbuildinginstallation
	Interior	CityGML Intbuildinginstallation	LoD4Geometry	intbuildinginstallation
Ifc Slab	Roof	CityGML RoofSurface	LoD3MultiSurface	bounded by
	Ground	CityGML GroundSurface	LoD3MultiSurface	bounded by
	Ceiling	CityGML CeilingSurface	LoD4MultiSurface	bounded by
	Floor	CityGML FloorSurface	LoD4MultiSurface	bounded by
	ClosureSurface	CityGML ClosureSurface	LoD4MultiSurface	bounded by
	Landing slab-Outer	CityGML Outerbuildinginstallation	LoD3Geometry	outerbuildinginstallation
	Landing slab-Int	CityGML Intbuildinginstallation	LoD4Geometry	intbuildinginstallation
Ifc Space		CityGML Room	LoD4MultiSurface	interiorRoom
Ifc Stair	Outer	CityGML Outerbuildinginstallation	LoD3Geometry	outerbuildinginstallation
	Interior	CityGML Intbuildinginstallation	LoD4Geometry	intbuildinginstallation
Ifc Stairflight	Outer	CityGML Outerbuildinginstallation	LoD3Geometry	outerbuildinginstallation
	Interior	CityGML Intbuildinginstallation	LoD4Geometry	intbuildinginstallation
Ifc WallStandardCase	Wall Surface	CityGML WallSurface	LoD3MultiSurface	bounded by
	Interior WallSurface	CityGML InteriorWallsurface	LoD4MultiSurface	bounded by
Ifc Window		CityGML Window	LoD4MultiSurface	Opening

5.6 Visualization & Results

CityGML supports multiscale modelling. In a CityGML model, the same object can be modelled and visualized in different LoDs, while maintaining its attributes and characteristics. That way, a deeper analysis and understanding of the objects is facilitated. Additionally, CityGML supports the co-existence of multiple LoDs in the same CityGML dataset. Concretely, an object that complies with multiple LoDs in CityGML can be modelled in the lowest LoD in order to enhance the efficiency of the model [OGC, p. 11, 2012]. Depending on the intended use of the model, the full complexity of the dataset is often not required. During the conversion of the model, the aforementioned function of CityGML has been taken into consideration. The generated model consists of LoD 3 and LoD 4 objects. For example, while the WallSurface could be generated as a LoD 4 Multisurface geometry, it is generated as a LoD 3 Multisurface geometry. The utility of this method is illustrated in figure 36, where the CityGML model is visualized in LoD 3.

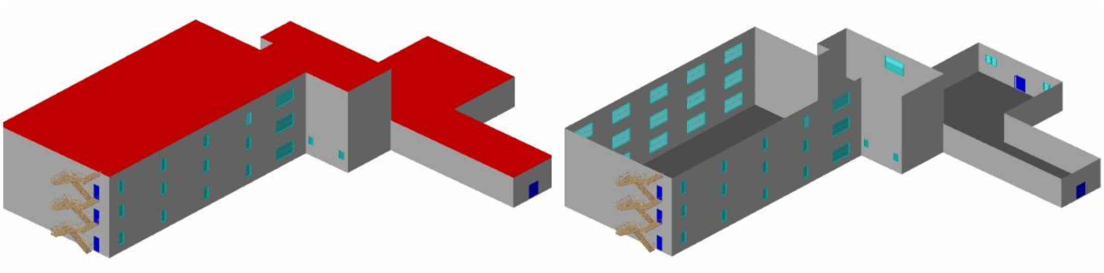


Figure 36: Generated CityGML LoD 3 model

The LoD 3 model generated is evaluated based on the geometric accuracy and the semantics coherence. According to Ledoux [2013] and Donkers [2013], specific criteria have been set to ensure the geometric correctness of the model. Therefore, in order to evaluate the geometry of the model, the GeometryValidator transformer is implemented prior to the final writing in CityGML. Figure 37 presents the selected criteria for the geometries inside FME Workbench.

☑ Contains NaN (Not a Number) or Infinity		Yes
☑ Contains Null Geometry Parts		Yes
☑ Duplicate Consecutive Points	...	Yes
☑ Degenerate or Corrupt Geometries	...	Yes
☑ Self-Intersections in 2D	...	Yes
☑ Non-Planar Surfaces	...	Yes
☑ Invalid Solid Boundaries	...	Yes
☑ Invalid Solid Voids		Yes
☑ Fails OGC Simple		No
☑ Fails OGC Valid	...	No
☑ Missing Texture Coordinates		Yes
☑ Missing Vertex Normals		Yes
☑ Invalid Area Orientation	...	Yes

Figure 37: Geometric validations of the models

Additionally, Val3dity software [http://geovalidation.bk.tudelft.nl] has been employed in order to double check the generated model. The model returns no errors.

With regard to the semantic coherence of the model, based on the principles of CityGML standard that have been presented in previous chapters, results can be drawn by examining the model in FZK Viewer. Figure 38 illustrates the structure of the model. The boundary surfaces such as Walls, Roofs and Ground and the outer building installations are contained inside the CityGML Building, while the openings are semantically connected to the appropriate surfaces.

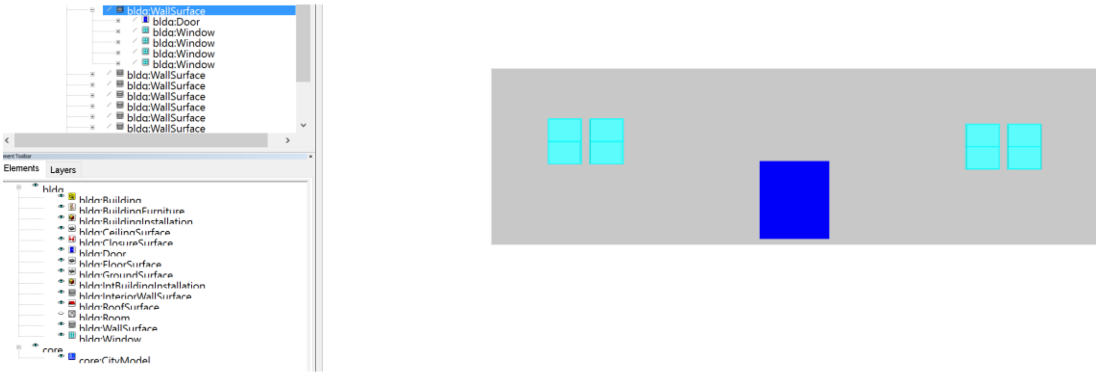


Figure 38: Semantic coherence of the 1st model in FZK Viewer

Next follows the model in LoD 4, as presented in figure 39. The general conclusion is that a CityGML LoD 4 has been created, which complies with the CityGML standard. More specifically, the Rooms are composed of the interior boundary surfaces as instructed by CityGML, while the openings are attached to the interior wall surfaces as well and are depicted as LoD 4 Multisurfaces.

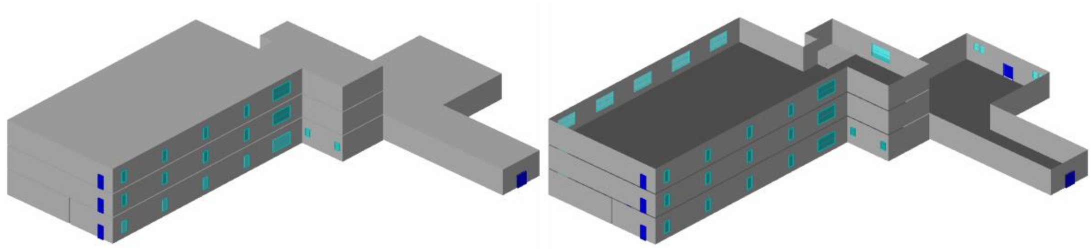


Figure 39: Generated CityGML LoD 4 model

The previous validation with regard to the geometric accuracy of the model is applied in the LoD 4 model as well, since it is included in the same dataset. The GeometryValidator transformer has also been implemented for each LoD 4 object.

With regard to the semantic coherence of the model, it is examined via FZK Viewer (Fig. 40) The interior space of the building has been mapped to form the CityGML Room feature, which is contained by interior boundary surfaces as proposed by CityGML. Additionally, the openings are semantically connected with the relevant interior wall surfaces they belong to.

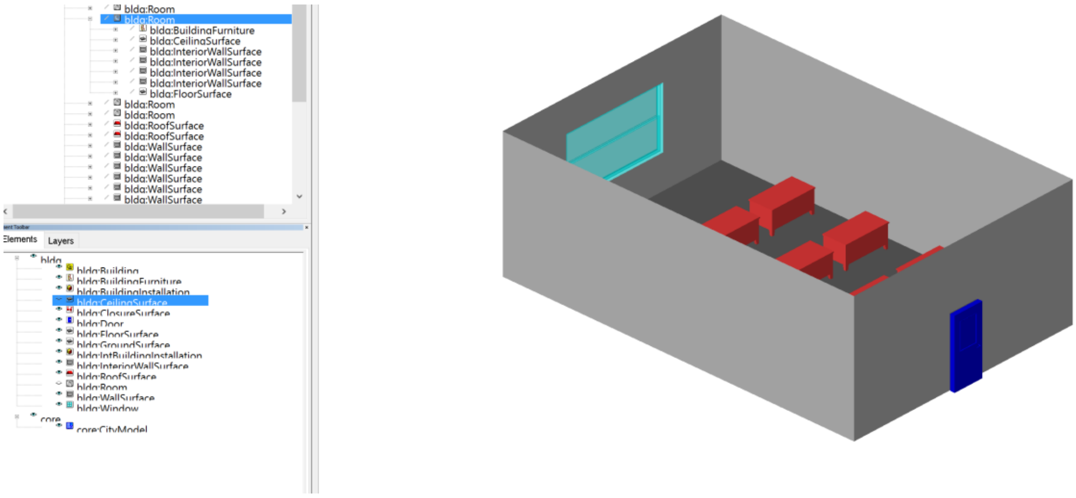


Figure 40: Semantic examination of the CityGML LoD 4 model in FZK Viewer

Similarly, the generated CityGML model of the 2nd building is presented in figure 41. Despite the GeometryValidator transformer, the model has been evaluated with the Val3Dity as well, ensuring its geometric compliance with the CityGML standard.

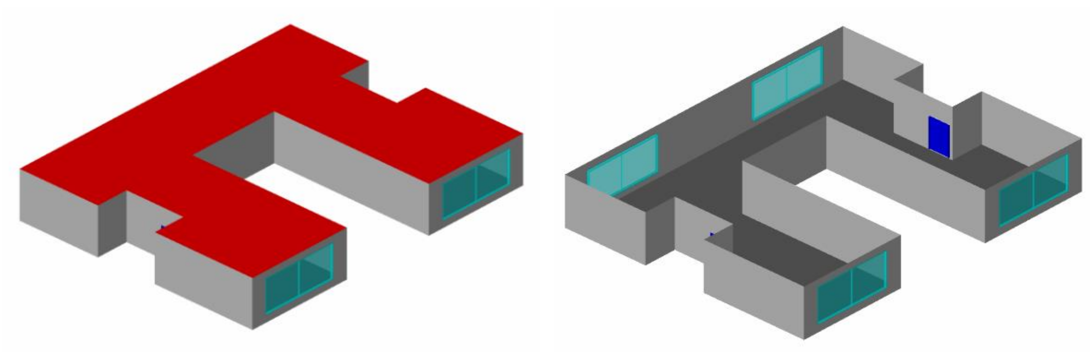


Figure 41: Generated LoD 3 CityGML model

Regarding the semantic coherence of the model, figure 42 illustrates a part of the generated CityGML model within the FZK Viewer. More specifically, the windows and the openings of the model in general, semantically belong to the relevant boundary surfaces.

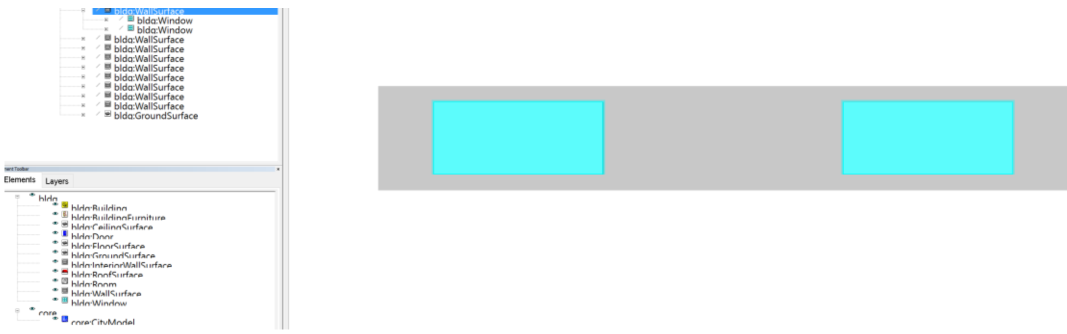


Figure 42: Semantic examination of the 2nd model in FZK Viewer

The LoD 4 CityGML model is presented in figure 43 as well. The interior model consists of Rooms with the appropriate boundary surfaces and the furniture that are placed in the building.

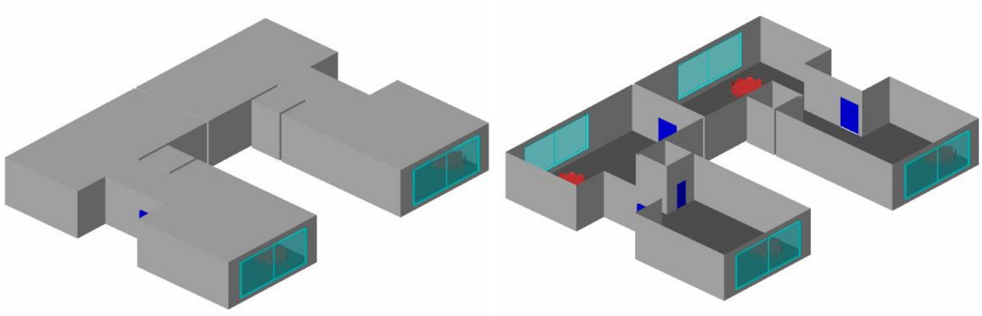


Figure 43: Generated CityGML LoD 4 model

Semantically, the Rooms are composed of InteriorWallsurfaces, CeilingSurfaces and FloorSurfaces. Each interior wall contains the relevant opening as instructed by CityGML (Fig. 44).

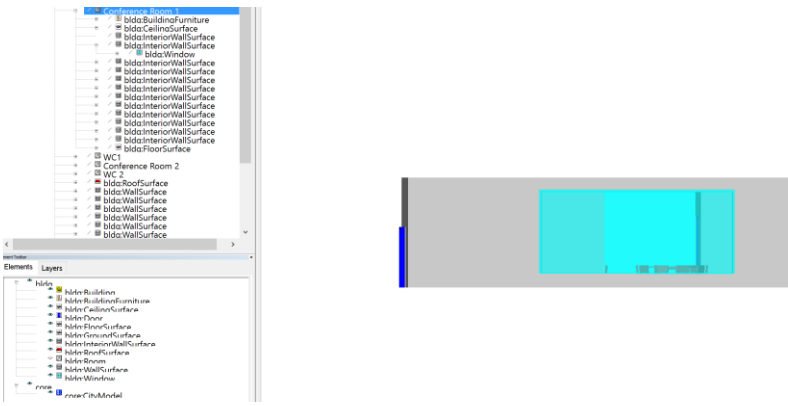


Figure 44: Semantic examination of the 2nd model in FZK Viewer

Each Room has been assigned the attribute gml_name in order to properly identify each space. There are four Rooms and the furniture have been connected with each room by matching the gml_parent_id of the furniture with the gml_id of the appropriate Room (Fig. 45).

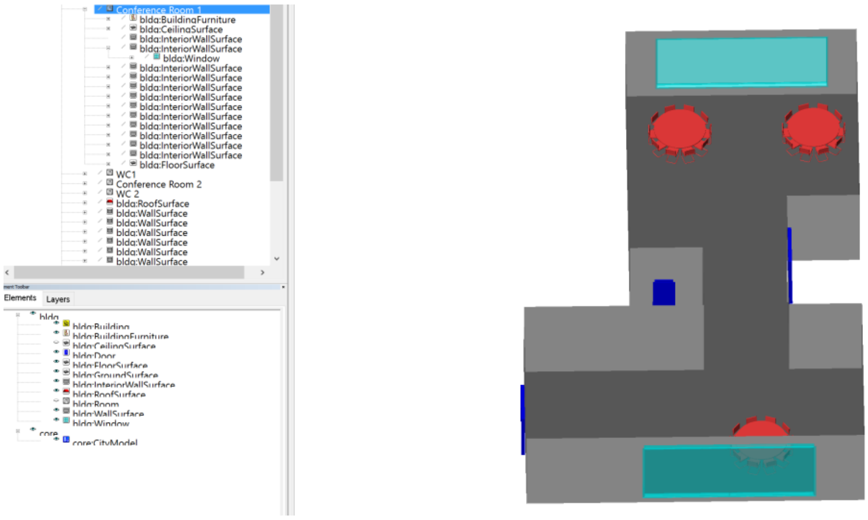


Figure 45: Semantic mapping of CityGML Rooms and Furnitures

5.7 Semantic extension of the model with Generic attributes

According to CityGML, the property element _genericAttribute augments the base class _CityObject. As a result, the subclasses of _CityObject inherit the generic property and can be enriched with multiple attributes in order to represent adequately information that cannot be covered otherwise by the main CityGML schema. However, since extending a model with generic attributes is not always an optimal solution, there are certain conformance requirements that need to be met. Concretely, they must be utilized to describe properties of features that are not covered by any of the thematic classes in CityGML and the existent properties of a feature is not sufficient for the additional information. The aim of this thesis is however, to examine the interoperability between IFC and CityGML semantics during a conversion and not to extend the CityGML model for a specific application purpose. Figure 46 proves that the methodology not only preserves the semantics, but is able to enrich a CityGML model with the maintained information.

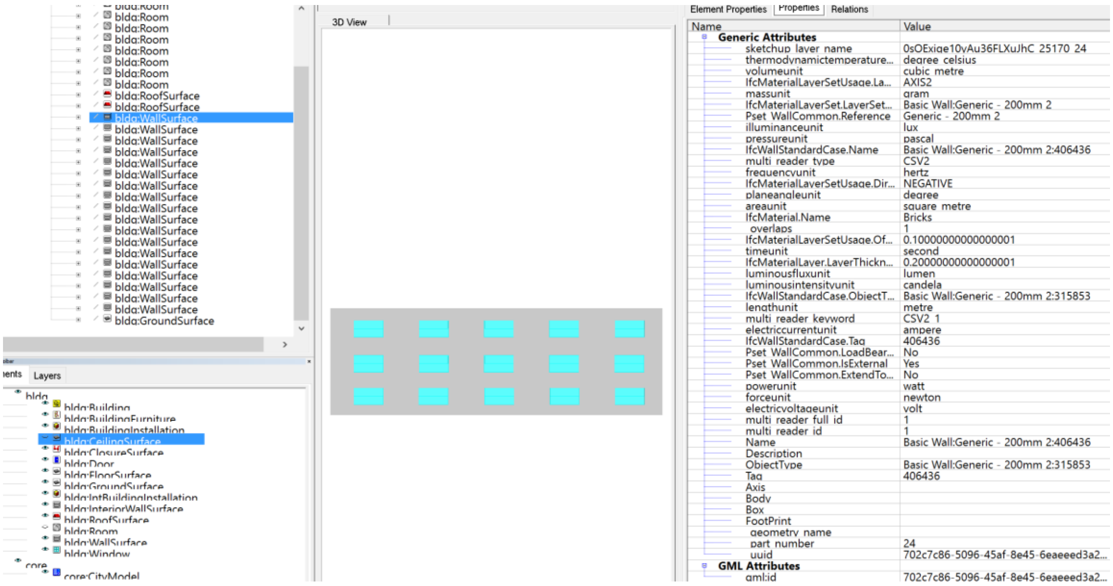


Figure 46: Preservation of semantics in boundary surfaces

In order to achieve this result, two critical issues need to be considered during the conversion:

1. Semantic information must be kept intact throughout the whole process. However, this is not always easy. The geometric parts that are extracted in order to be fixed should be matched afterwards with the relevant semantic information.

2. The semantic extension of the CityGML model is feasible by modifying the CityGML writers inside the FME Workbench. More specifically, each extended CityGML feature type must implement the relevant IFC attribute alongside the data type of the information (i.e. integer, Boolean, string).

As mentioned in Chapter 1, the scope of this thesis is to generate a CityGML model and investigate if the semantics can be preserved and transferred to the generated model. Figure 46 illustrates the fact that even though the semantic enrichment of the model is feasible, a considerable amount of those information is of no particular interest for the Geoinformatics community, such as the units and certain IFC properties.

The 1st model designed in Autodesk Revit is enriched with semantic properties that can be implemented for e.g. energy management purposes. Concretely, the surfaces have been enriched with the material they are made of, a property that is really important in smart energy management applications, as explained in chapter 2. Figure 47 presents the roof of the building that is made of Concrete 20/25. The current attributes of the boundary surfaces in CityGML do not allow the implementation of such information. It could be possibly included in the gml:name but is not valid, since it opposes the specifications set by CityGML standard.

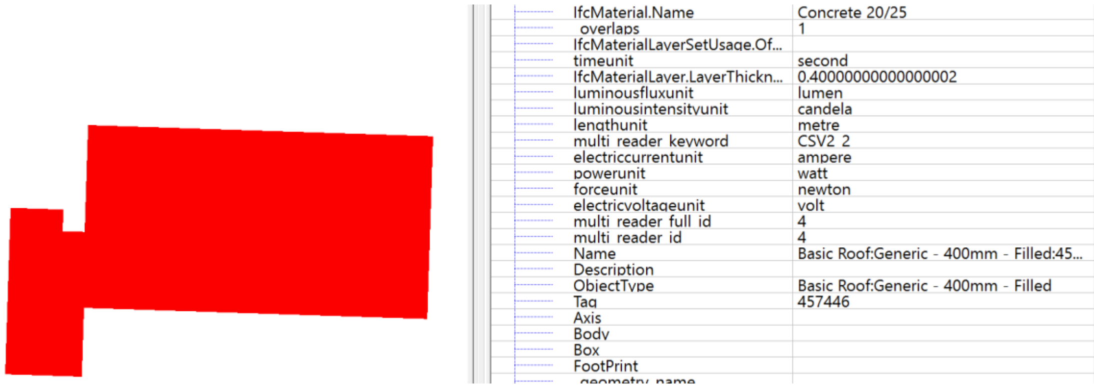


Figure 47: IFC material of slabs transferred to CityGML model

There is additional information that can accompany the material of the surface that can be implemented in BIM and be successfully added to a CityGML model. Figure 48 illustrates a wall surface that is made of bricks. The type of a surface material is one of the most important attributes in a building because IFC is designed for AEC purposes and does not excel in texture visualization [Luut and v. Berlo, 2011]. During the modelling phase, the wall surfaces have been assigned as material a specific type of brick, which is successfully visualized in the environment of Autodesk Revit. However, during the export to IFC format, the texture of the surfaces is lost, hence maintaining this type of information during a conversion to CityGML format is critical, since it cannot be easily restored.

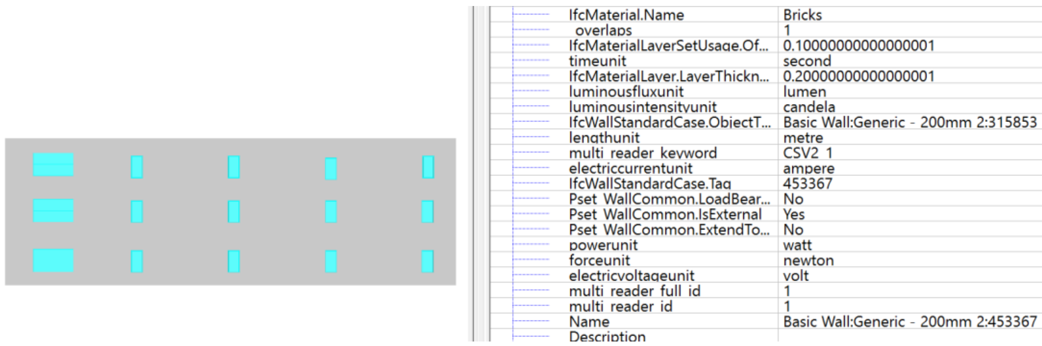


Figure 48: IFC material of walls transferred to CityGML model

However, in complex 3D applications the necessity for increasingly more semantic information can often excess the functionality of the predefined attributes that can be found in a BIM software such as Autodesk Revit. More specifically, the material of a surface and its characteristics such as thermal resistance, can be useful for various applications but they need to be combined with additional information so that the model is effective. An application field that requires a heavily semantized 3D city model is the field of Land Administration and 3D Cadastre. The space with its constituting elements in 3D city models is an abstract concept [Aien et al., 2013] and considerable limitations in representing the legal environment of a city model may occur. Hence, it is important to investigate if a conversion between IFC and CityGML can enrich the latter in terms of legal properties. Within this context, the 2nd model is assigned semantic information that can assist towards that purpose. However, it should be noted that the model does not represent in full detail a building with cadastral information, since it is outside the scope of this thesis. In order to investigate if BIM can enrich a model with legal information and that information can be preserved and enrich a CityGML model, a different approach than the previous model is required. Legal information, such as land uses, property rights and cadastral information cannot be stored on a surface or an object. Therefore, the utility of IFC Space and CityGML Room is mandatory. With that in mind, legal properties have been assigned to the model during its generation in Autodesk Revit software.

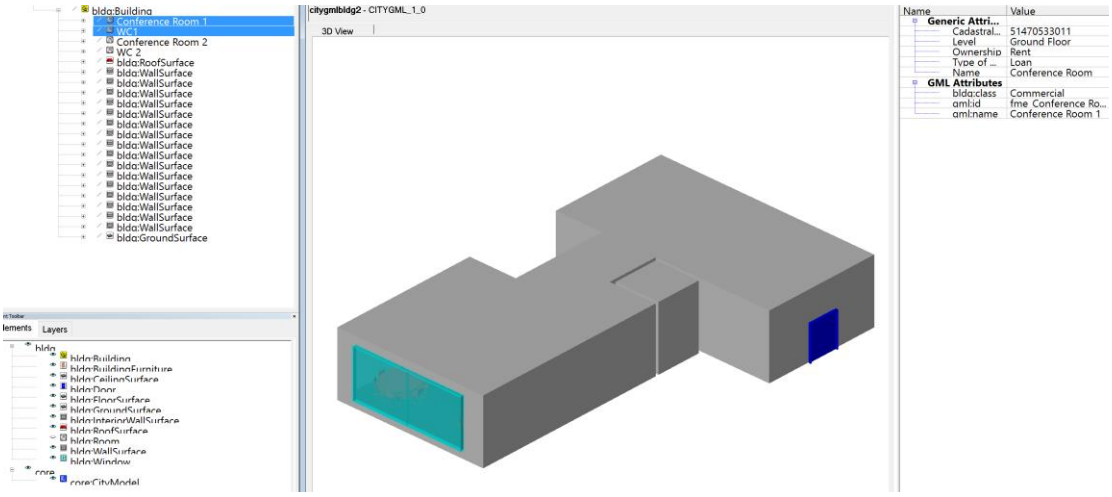


Figure 49: Cadastral properties transferred from IFC to CityGML model (1/2)

Figures 49 and 50 illustrate the semantic extension option of a CityGML model in the field of Cadastre. It should be noted however, that the cadastral information tends to differ considerably from country to country. In Greece for example, an important key-information is the Cadastral Code Number which is assigned to each land parcel/ entity and sets a unique id that is able to identify it. If the id cannot be found or is not created, all cadastral transactions are invalid. It is therefore important to be included and maintained in each building or real-world object. Another important attribute for land administration is the land use of the building. CityGML supports that aspect by implementing the attributes citygml class, usage and function. The citygml_class has been implemented and filled with the value "Commercial", following the standard which mandates that the use of Generic attributes should be implemented in case there are not relevant extensions of the CityGML that can fill that purpose [OGC, 2012, pp.146-148]. The building has been enriched with additional legal information. The Hellenic Cadastre includes information with respect to the restrictions that accompany the property. Figure 50 contains properties which state that the current building is assigned a mortgage. Lastly, an attribute that defines the ownership of the structure has been applied as well. In one case (Fig. 49) the ownership type is set to "rent", while in the other case (Fig. 50) the ownership type is set to "own". It is clear, that those properties are only a small part of the cadastral properties that need to be assigned to a building or a parcel, in order to render CityGML relatively feasible for land administration purposes. However, the results seem encouraging and form the ground for further research.

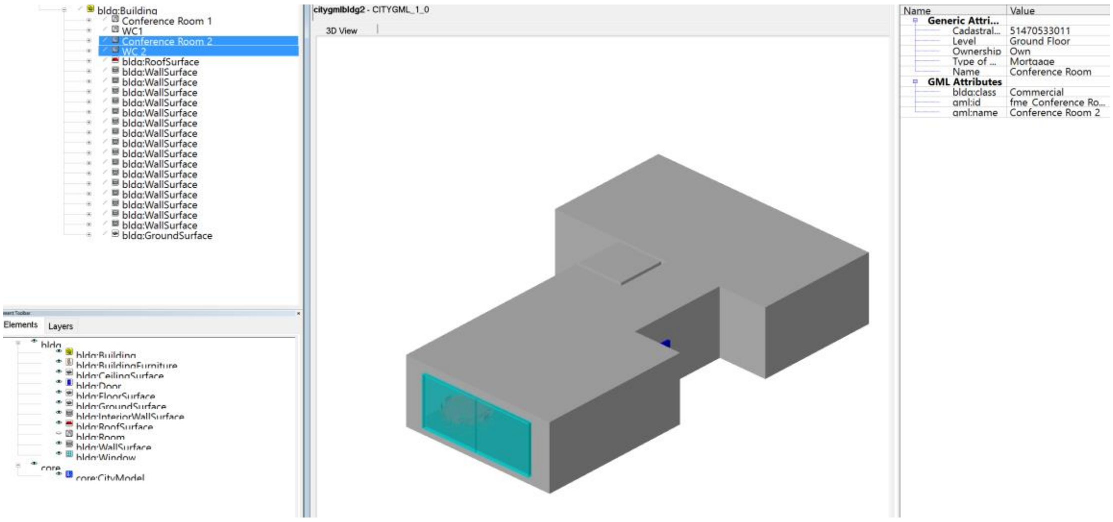


Figure 50: Cadastral properties transferred from IFC to CityGML model (2/2)

5.8 Semantic extension of the model with an ADE

As mentioned previously, ADEs provide certain benefits compared to the extension of the model with Generic objects and attributes. They are developed in order to address specific issues, and within this context, figure 51 illustrates a basic UML diagram of a legal CityGML ADE. The ADEElement: LegalCadastre aims to extend the CityGML feature Room with additional semantic properties and is connected with a Generalization relationship. These properties are:

- CadastralCode: in Greece is 12-digit unique number that identifies the building or the parcel. The data type *integer* has been applied. *Multiplicity* has been set accordingly to 0 or 1 instances, since there is only one number that can be applied.

- Level: it allows to implement the level of the space inside a building. If it's for example the ground floor or the 1st floor. The data type *char* has been implemented and *multiplicity* has been set to 0 or 1 instances.

- Ownership: it describes the type of the ownership relationship. The data type *char* has been applied and *multiplicity* has been set to 0 or more instances. A relevant "Codelist" has been generated which describes the values that can be set in the specific field, as well as their data type.

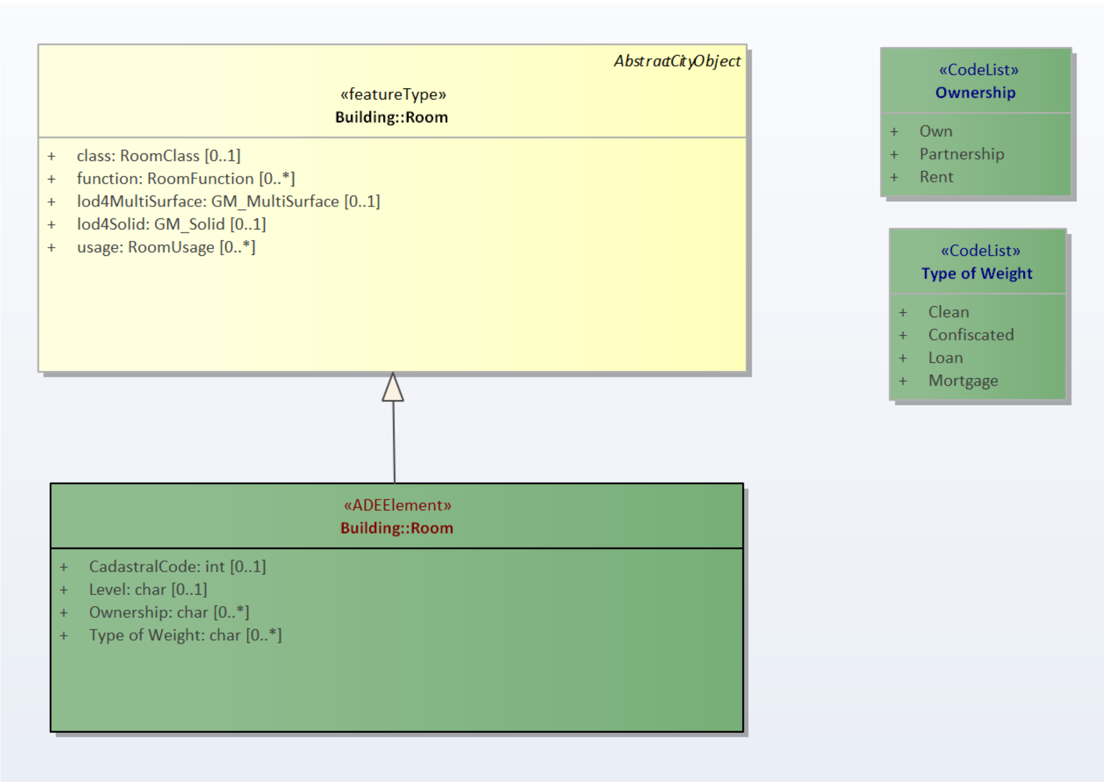


Figure 51: UML diagram of the under-development legal CityGML ADE

- Type of Restriction: describes the kind of restriction that accompanies the property. The data type *char* is applied and *multiplicity* has been set to 0 or more instances. A relevant "Codelist" has been developed in order to set the attributes that can be assigned to the Type of Restriction attribute such as mortgage, loan, clear from weights, or confiscated from a financial institution.

The specific ADE is currently under investigation in order to be enriched with additional legal properties and address holistically the legal aspect of the real world.

Chapter 6

6 Conclusions, Future Work & Recommendations

6.1 Evaluation

The developed conversion methodology can be divided in three phases. The 1st phase is the geometric and semantic modelling of the buildings with BIM and its export to IFC format. The 2nd phase is the conversion of the IFC buildings to CityGML LoD 4 models, which are presented and evaluated. The 3rd phase is the enrichment of the models with semantic information that is originally generated via BIM and maintained throughout the whole process. Within this context, findings and conclusions can be drawn, which further evaluate the whole process. The results presented under the research questions, form the foundations of this thesis, and are presented as follows:

1. When designing a model with BIM, what issues may occur and what are the characteristics of the process, in order to match the geometries and semantics of the CityGML standard during the conversion?

By generating the IFC model via BIM, there are several conclusions that can be drawn. First of all, the vertical surfaces that form the floor and the ceiling of each storey in CityGML, contain different attributes in BIM. More specifically, the solid geometry that is designed as a roof object, is solely a roof of the model. On the contrary, in CityGML the lower part is assigned a CeilingSurface feature while the higher part is assigned a RoofSurface or a FloorSurface feature. The aforementioned example is of particular importance at the stage of semantic filtering and mapping, since a roof surface that is mapped as floor will contain semantic information that correspond to the primary feature. Secondly, the mapping between BIM and IFC should be taken into consideration when converting to CityGML. Concretely, an element in BIM, such as a complex of stairs might be categorized in multiple IFC entities not only semantically, but also geometrically. Such an example is the distinguish of surfaces that are labelled as slabs, while in BIM they are labelled as landing surfaces, which are parts of the stairs. Such an issue should be taken into consideration when converting to CityGML format, otherwise the building installations in CityGML will present “holes” due to the missing elements. Another issue that derives when modelling for CityGML LoD 4 models, is whether the vertical geometries should be modelled according to the exterior or interior wall boundaries. In LoD 3 models it is less complicated since the upper part of the surface is removed. In LoD 4 though, the geometry must comply with the CityGML standard and the slabs should be modelled based on the exterior of the wall boundaries. In case though, the IFC model is structured otherwise, the conversion algorithm is able to handle those changes and produce geometrically valid CityGML models. Additionally, modelling a building in BIM can be quite advantageous, since the flexibility of the software and the IFC standard allows the enrichment of the model with structures and information that can be implemented to CityGML. This conclusion has been demonstrated via the semantic enrichment of the generated CityGML model. Each element in BIM, either it is geometrically defined or not, can be assigned additional attributes and properties. Following the preservation of semantics, a relationship between BIM and CityGML can be proven quite beneficial for multiple application fields.

2. During the conversion, how are the geometries handled and the semantics mapped in order to comply with CityGML specification?

The developed algorithm can become quite complex, especially with buildings of sophisticated geometry that also contain a plethora of semantic properties and information. Therefore, it is essential to categorize the steps of the conversion in order to avoid confusion and possible errors in the generated CityGML model. So, first of all, as soon as the model is imported in FME Workbench a general semantic mapping should take place. The user should be aware of the relationships between IFC and CityGML entities in order to convert the model in the most efficient way in terms of time and accuracy. This distinction is not a required step of the process, it is a conclusion that can be made in order to enhance the functionality of the process. So, the next step of the methodology is the geometric adjustment, which is further split in two different processes as presented in detail in chapter 5. The split is required, since FME Workbench cannot process certain geometries that need to be eliminated in order to generate valid CityGML geometries. The geometric correction inside Trimble SketchUp, even though it is not time-demanding, requires a certain experience with the specific modelling software in order to be aware of how the specific software handles object's geometry. However, even though the model is exported and modified in another modelling software, the preservation of its semantics is totally feasible. Within this context, there are a few conclusions that can be made: firstly, the correction of geometry that takes place in Trimble SketchUp, can include the fix of minor errors that they may not render the model invalid in terms of CityGML, but can affect its representation. A few examples of that kind are presented by Donkers [2013] such as a door that misses multiple surfaces due to the fact that the IFC properties and elements were either damaged or missed elements in the first place. Another example is the fact that IFC solids can overlap. In fact, that can be a common mistake since in BIM all components are placed based on the set elevation views and an unintentional error is possible. The algorithm which exported IFC entities to Trimble SketchUp includes transformers that remove overlapping geometry. And if that is not enough, geometries can be manually handled in the environment of Trimble SketchUp. Another characteristic of the process is the fact that every component of an IFC model can be exported and manipulated in Trimble SketchUp, while preserving its semantic properties. The rest of the IFC entities, are manipulated inside the FME Workbench. The capability of selecting the relevant geometries that combine a CityGML feature lowers the risk of making semantic errors. The 2nd stage of the conversion process is the semantic mapping of the elements. In that case, the mapping of boundary surfaces is a straight forward process. What should be taken into consideration is that openings, elements mapped as building installations, or furniture, should be semantically placed into their corresponding CityGML features. Furthermore, it should be noted that placing the attributes in a separate .csv file enhances the maneuverability of the process. More specifically, in case there are semantic errors in the elements, for example a surface is assigned a wrong material or attribute, it can be fixed. On a further extent, it would be feasible to add information from scratch to an IFC element, but this is outside the scope of the thesis. Moreover, the concept of multiscale modelling is utilized in full. Concretely, the models are consisted of LoD 3 and 4 geometries, facilitating a sophisticated and advanced management of the model via a spatial database environment. Lastly, the methodology preserves the original semantic information and it is up to the user whether to employ them in the generated CityGML model or not.

3. Is the generated algorithm suitable for a different building that needs to be converted and at what level? What are the requirements and the manual intervention –if required- in order to render it usable for another model?

The generated conversion algorithm is pretty flexible when the conversion of multiple IFC models is required. It includes all the essential CityGML feature types and their properties and a successful conversion should follow the steps mentioned in chapter 5. The conversion process though, cannot be characterized as straight-forward in the case that another building is imported. The implementation of a 2nd test model provided valuable insight with regard to the suitability of the developed algorithm. Within this context, the results can be divided based on the defined LoD of the model. A LoD 3 conversion is far more straight-forward than an LoD 4 conversion. To begin with, even if the model contains additional IFC entities, the algorithm is capable of a successful conversion. So, the overall steps regarding the geometry adjustment and semantic mapping remain unchanged. What must be modified however, is the extraction of the appropriate geometries that match the relevant CityGML feature. Afterwards, the implemented transformers are able to process and convert successfully the model. In a LoD 3 conversion, where the interior of the model is discarded, the algorithm does not require significant modifications. In a LoD 4 conversion though, the process is more complicated since the rooms must be properly composed and the additional geometries require methodical adjustments in Trimble SketchUp. With regard to the field of semantic mapping, there is no need for changes. As long as the IFC entities are properly distinguished they are automatically matched with the corresponding CityGML entities.

4. How can a CityGML model be extended in terms of semantics and whether the proposed methodology is capable of doing so or not. In addition, how is the semantic modelling in BIM differentiated according to the intended use of the generated model?

It has been clearly presented that a CityGML model can be semantically and geometrically extended via two different methods: Generics and ADEs. The generated CityGML buildings are semantically enriched in order to investigate that capability. The developed methodology is categorized in three phases as mentioned above. In the 1st phase, the semantics are generated and are successfully maintained and exported to IFC format. In the 2nd phase, semantics are successfully imported in order to be converted. Regarding the semantic mapping of the standard CityGML features, it can be concluded that the conversion is solid. But what about the additional information? The developed methodology is capable of preserving the additional semantic information until the writing in CityGML. Even though a geometric adjustment is interposed in an external environment from FME Workbench, the information is maintained. It can be safely concluded, that the developed methodology can preserve semantic information. It should always be taken into consideration though the application field that the model is generated for. A characteristic example is the field of Cadastre and Land Administration. In fact, a model that is designed to be implemented for cadastral purposes in Greece, could be proven invalid in terms of semantic properties in the Netherlands for example, since the cadastral information could differ considerably. Having that in mind, the developed methodology can adjust to fit the special requirements and limitations of application fields that serve the same purpose but are required to follow different rules and protocols.

6.2 Conclusions

Based on the overall process and the research questions that were set, the following conclusions highlight the pros and cons of the developed methodological approach:

First of all, the developed methodology can generate valid CityGML LoD 4 models by implementing ETL process. The two prototypes that have been modelled and implemented are characterized of structural complexity and semantic enrichment. They represent real-world objects and the generated CityGML models contain plentiful features of the CityGML Building features. Furthermore, the developed methodology utilizes the multiscale concept of CityGML and represents the features in the appropriate LoD. This could be proven particularly useful during the management of the model, since an extraction of certain elements based on the LoD within a spatial database is feasible. Additionally, the modelling process in BIM has highlighted the capabilities of adding multiple information on multiple elements regardless if they contain geometry or not. Within this context, certain issues that arise should be taken into consideration when converting to a CityGML model, such as the mapping of the elements between BIM and IFC and the role of slabs in terms of semantic and geometry when converted to CityGML. Moreover, it can be concluded that BIM is a valuable source of information in order to enrich a CityGML model in terms of the Building class. The results regarding the semantic enrichment of the model encourage a detailed investigation about the prospects and limitations of joining BIM and CityGML in targeted application fields, such as energy management and 3D Cadastre. Of course, none of the above would be feasible if semantic information is missing or altered. One of the key advantages of this methodology is the successful conversion of both geometry and semantics from an IFC model to CityGML, where according to multiple sources [Zlatanova, 2013; Luut and v. Berlo, 2011] constitutes a great challenge for efficient interoperability between the two standards. Additionally, the semantics can be double-checked and modified to correct possible unintentional errors throughout the modelling process, since they can be stored on a separate file. With regard to geometry, it can be concluded from the evaluation of the models, that the generated CityGML elements comply with the CityGML standard specifications. On top of that, the geometries can also be checked during two phases. Initially, during the modelling process via BIM and afterwards stage via Trimble SketchUp, which results to the fixing of unintentionally damaged geometries that may alter the representation of the final CityGML model. What's more, a collaboration between Revit and Trimble SketchUp can provide a detailed and heavily semantized building, but also an adequately representation of other real-world objects. Furthermore, the extension of the generated CityGML model is investigated via two specified methods. Even though, the models are not implemented in a specific application field, it can be efficiently done so by importing semantic information relevant to the designated field of interest. Lastly, the proposed methodology is able to convert models in lower LoDs, reducing significantly the complexity in the conversion algorithm and be able to contribute to application fields that require 3D models in lower LoDs.

There are however, specific disadvantages of the developed methodology. More specifically, in complex buildings that need to be converted in CityGML LoD 4 models, the overall conversion process can become quite time-demanding. There are multiple reasons for that: firstly, the separation and manipulation of the entities in order to generate a LoD 4 model can be quite challenging, since the interior of a building usually encloses more geometric and semantic information than the exterior. Moreover, the familiarity of a user with FME Workbench or Trimble SketchUp should not be implied and thus it may delay significantly the conversion process. In terms of the conversion process to a CityGML LoD 4 model, there are certain limitations that need to be investigated. First of all, how should common surfaces between two buildings be manipulated during the conversion. In LoD 3 models, that issue can be tackled since there is only one face of the geometry that needs to be shared as instructed by CityGML. In LoD 4 though, both the wall surface and the interior wall surface must be shared and on top of that, they should be mapped accordingly depending on the examined building part. However, in IFC the walls are solid geometries and in more complex cases where a shared geometry is part of another geometry and not an extension of its physical boundaries, the conversion is even trickier and cannot be tackled at the moment from the developed methodology. Lastly, the semantics are preserved in the results of the implemented buildings, but it should not be forgotten that BIM offers unlimited capabilities that have not been investigated in this thesis, since it is outside the scope of it. Therefore, even though the first results are promising, it cannot be safely stated that the methodology preserves the semantic information of all BIM models.

It can be stated that the proposed conversion methodology is particularly effective when it is combined with the enrichment of a CityGML model with additional semantic information. It is not an automatic process, therefore compared to methodologies that generate LoD 3 and lower CityGML models, it is less time efficient. However, the three phases of the conversion provide enough space to the user to double check the converted model in order to locate and fix issues that cannot be tackled by automatic conversion methodologies. Additionally, it extends successfully the generation of CityGML models to the higher LoD, allowing the introduction of considerably more semantic information. Within this context, it may not be the most effective approach in terms of time for generating CityGML models for visualization purposes, even though it is capable of doing so, but it can be implemented as a holistic process that is able to generate from scratch a building, enrich it with semantic information, preserve it and convert it to a CityGML model which can be applied in targeted application fields in 3D city modelling.

6.3 Future Research

A three-phase process, recommendations for future research can be categorized as follows:

Phase 1-BIM: Only a small part of BIM capabilities has been investigated so far. There are multiple fields of research that open up based on the results of the current thesis. In lower LoDs, both the modelling and the conversion process is faster. Biljecki [2015] states that it is not always required a CityGML model in maximum detail depending of course on the application field it is implemented. Within this context, the type and amount of information that can be implemented to a BIM model and the application fields that can benefit should be investigated, thus, setting the extents and the potential limitations of the current methodology. Additionally, each application field has different needs and structure in order to be effectively served by BIM, which means that the structure of the semantics can change as well. Therefore, more and more BIM models need to be tested.

Phase 2-Conversion: The main challenge of the methodology is to reduce the amount of manual intervention. Even though it can provide certain benefits, it can be proven quite time-consuming. The issues in terms of handling the geometry were tackled by manipulating it separately in Trimble SketchUp, due to certain limitations of the FME Workbench. However, those limitations can be tackled by utilizing the API of the software and implement scripts that are able tackle the challenges presented in chapter 4. Additionally, the topology between common surfaces in LoD 4 is an intriguing field of future research. Moreover, the conversion route of CityGML to IFC will assist towards a more thorough understanding of the communication between the two standards. On top of that, it is important to investigate the concept of generating lower LoDs CityGML models from the higher LoDs models and the generalization relationships that should be taken into consideration.

Phase 3-Semantic extension: The results of the methodology open up a whole new field for further investigation in terms of semantics. Within this context, we intend to investigate the enrichment of a CityGML model in order to be successfully implemented for cadastral purposes. The generation of an ADE is essential and the collaboration between BIM and CityGML must be investigated in order to tackle efficiently and methodically the complexity of the legal space. A primary approach towards the development of an ADE that contains legal information has been presented in chapter 4. There is however, a lot of room for further investigation in order to be tackle efficiently the issues that arise in the legal environment of a city model. More specifically, the current attributes, even though they are important cadastral information need to be enriched based on the structure of the Hellenic Cadastre. Additionally, the extent in which BIM can successfully represent legal properties must be examined. For example, IFC Space is generated represents the interior of an area that has been designated as Room. In Cadastre though, there are legal properties that may include the inside area of a Room but they are extended up to the party wall surface and not just the interior wall surface.

6.4 Recommendations

In order to address a problem, a team of multiple professions can collaborate, and the same applies for software tools and more specifically, when working with BIM technology, in order to represent buildings, or whole city models. A combination of detailed buildings and an accurate representation of the surrounding environment and its contexts can enhance even further the efficiency of 3D city models. The developed methodology demonstrated the potential collaboration between Revit and SketchUp in order to generate integrated models. Over and above, the collaboration between BIM and CityGML has to be further promoted, since they may learn from each other, source each other and therefore form an invaluable tool towards the generation of semantized 3D city models.

APPENDIX I

CityGML Building UML Diagram

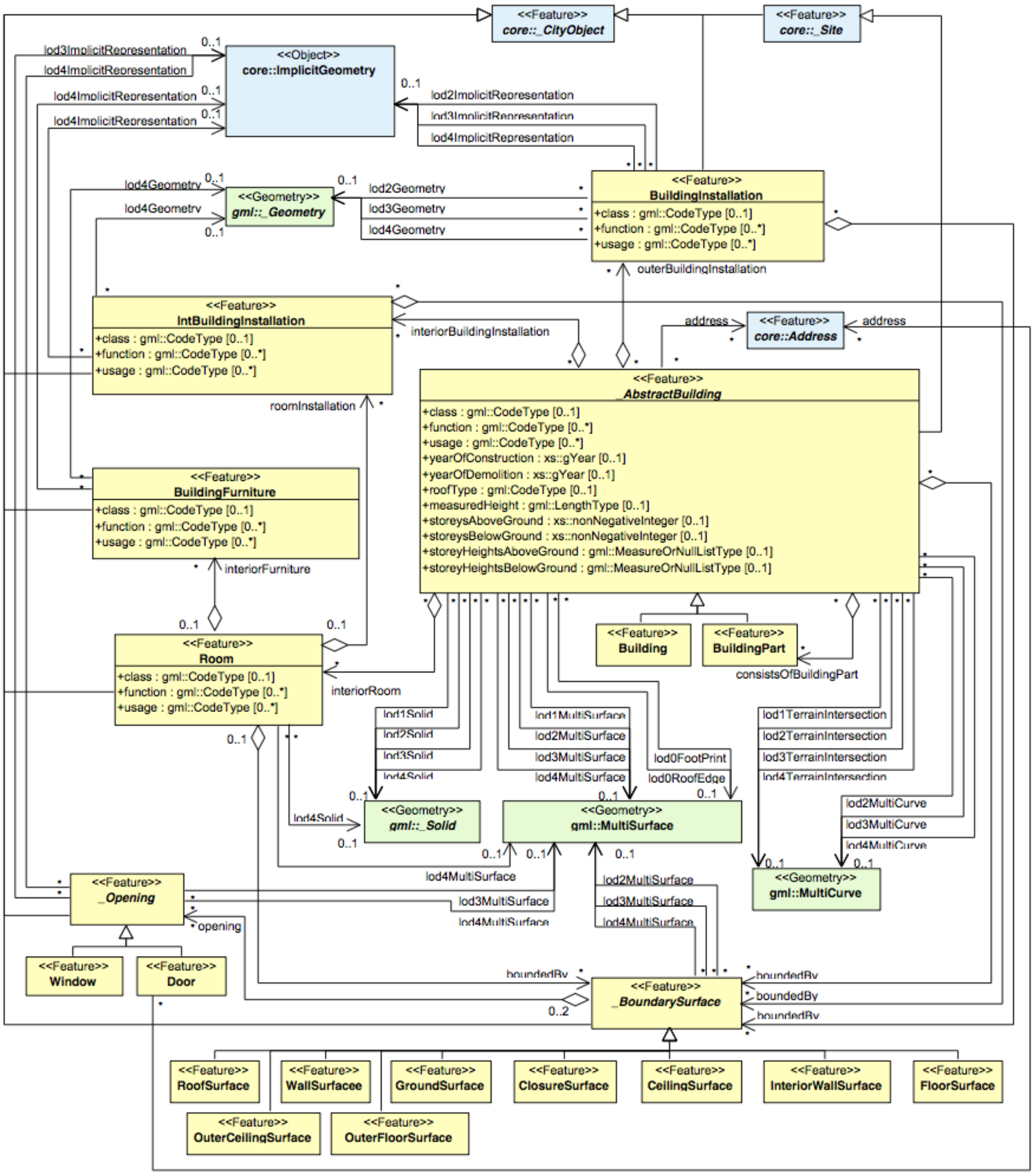


Figure 52: CityGML UML Building diagram [OGC 12-019, 2012]

APPENDIX II

IFC 2X3 Architecture Diagram

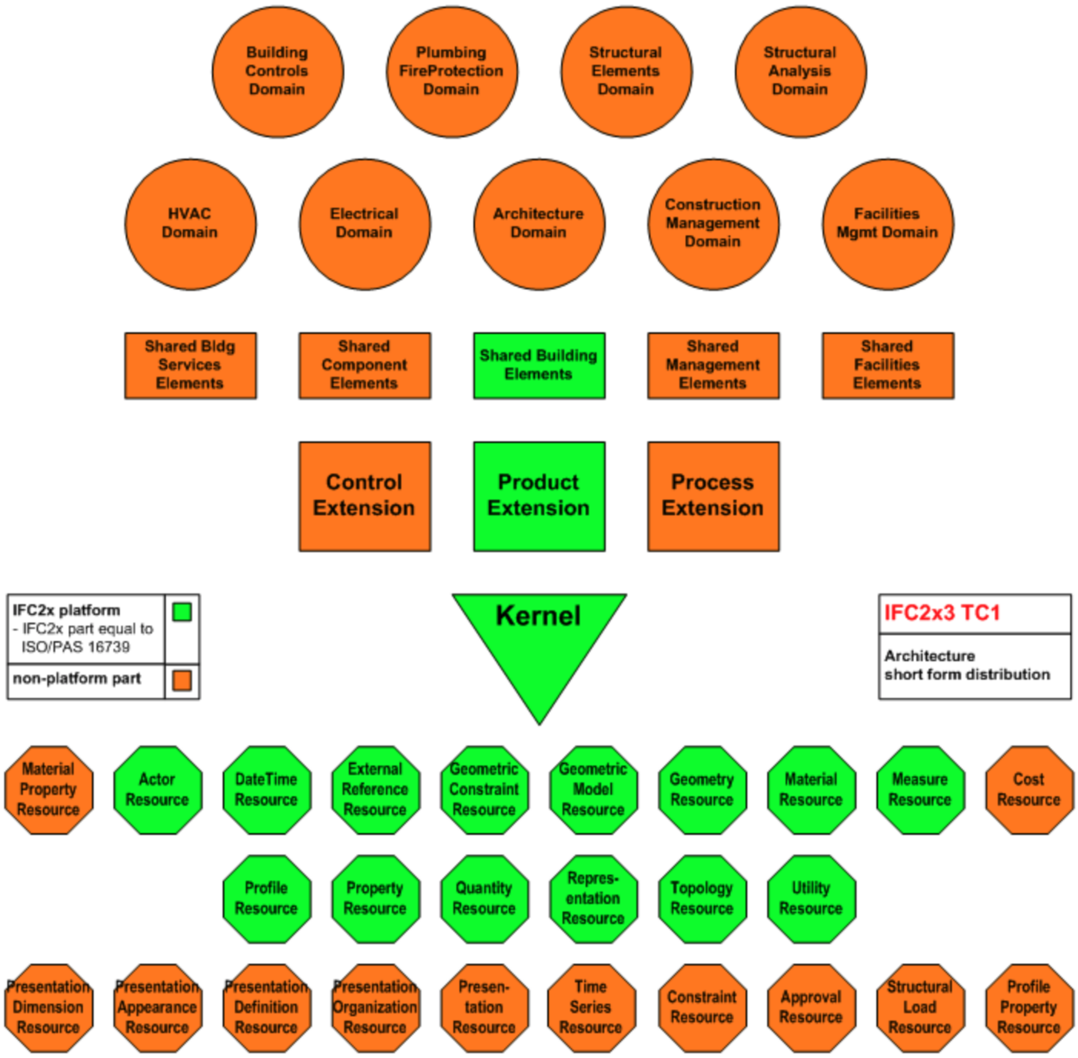


Figure 53: IFC Architecture Diagram [Source: buildingSMART, 2007]

APPENDIX III

Conversion Algorithm (1/2)

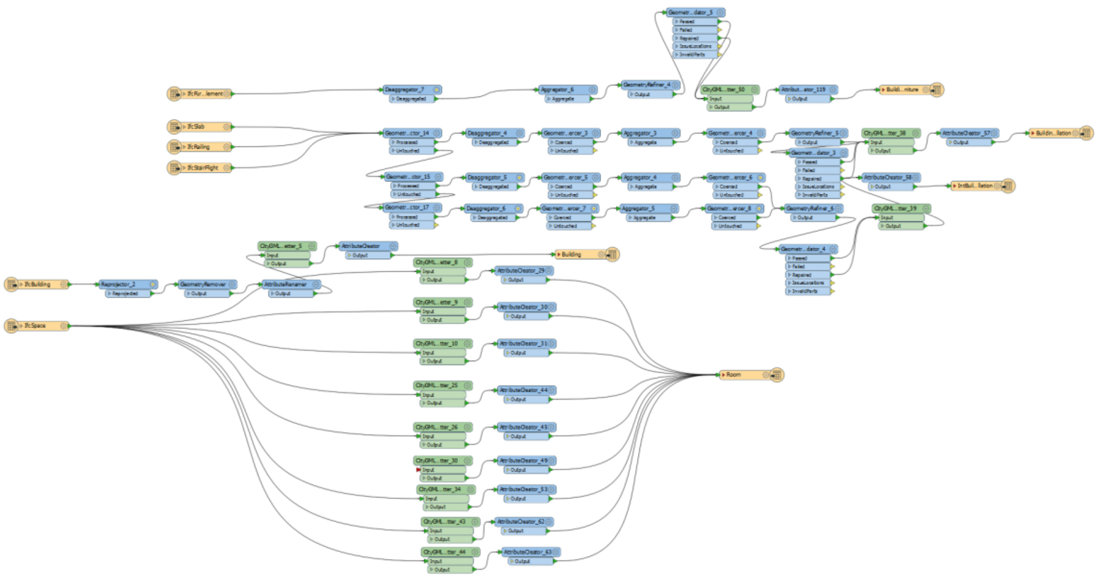


Figure 54: Conversion to CityGML Building, Room, Furniture and Installations

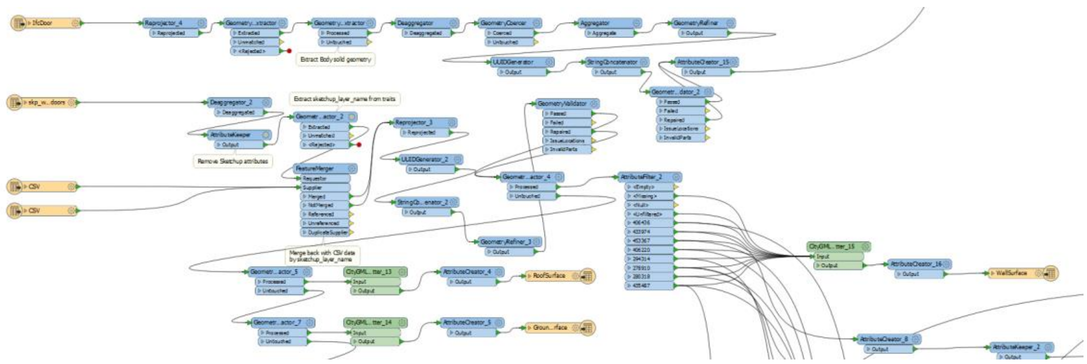


Figure 55: Conversion to CityGML Exterior Boundary Surfaces

APPENDIX IV

Conversion Algorithm (2/2)

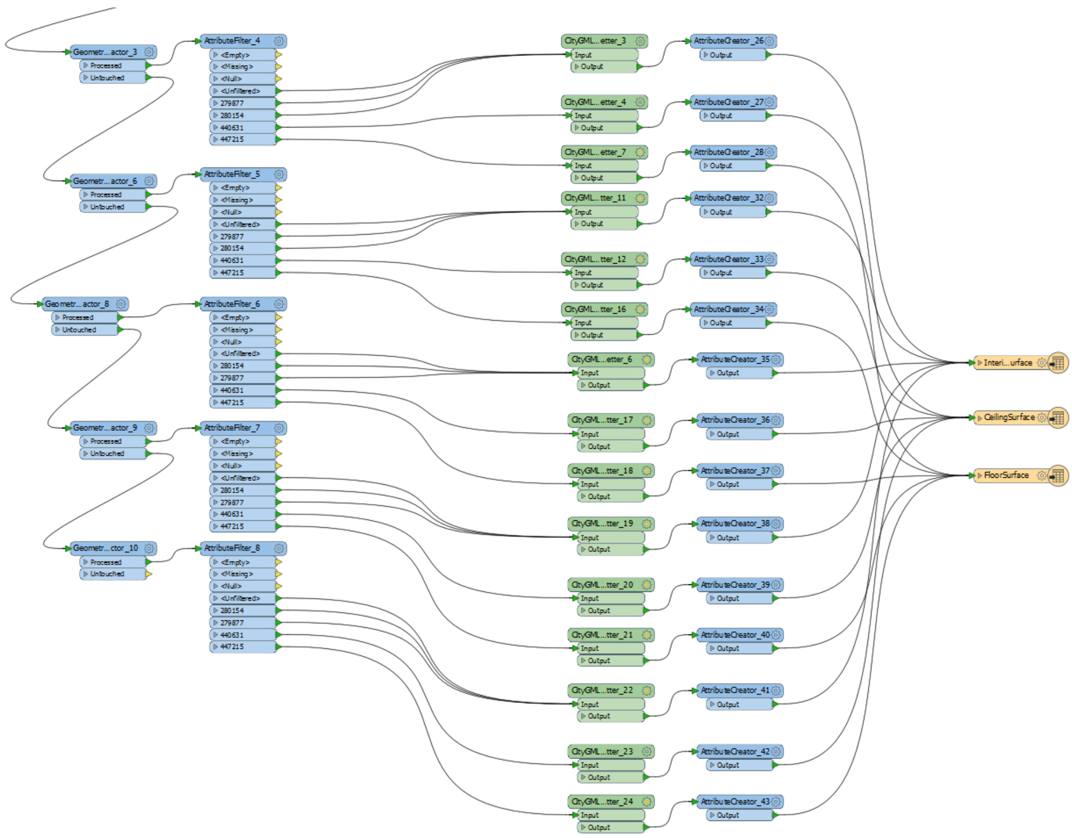


Figure 56: Conversion to CityGML Interior Boundary Surfaces

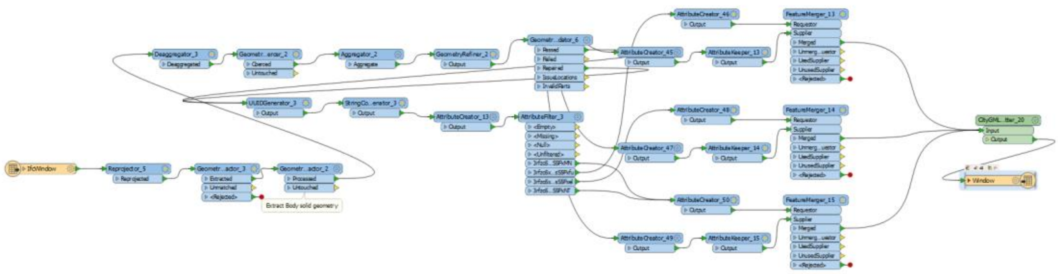


Figure 57: Conversion to CityGML Doors and Windows

APPENDIX V

IFC to SKP Algorithm

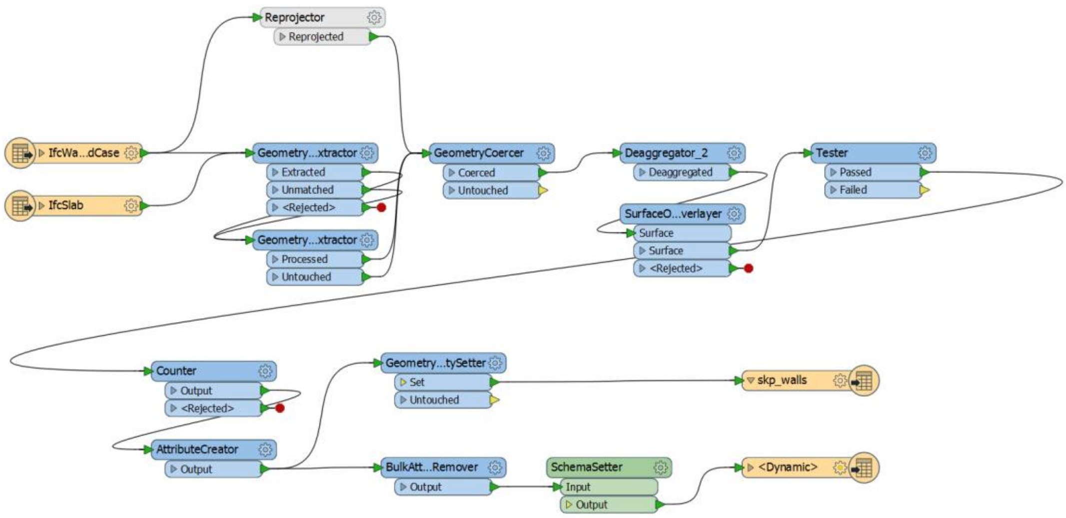


Figure 58: Conversion to .skp format

References

Aien, A., Kalantari, M., Rajabifard, A., Williamson, I. and Wallace, J. [2013]. Towards Integration of 3D Legal and Physical Objects in Cadastral Data Models, *Land Use Policy Vol. 35,* (pp. 140-154).

Amirebrahimi, S., Rajabifard, A., Mendis, P. and Ngo, T. [2015]. A data model for integrating GIS and BIM for assessment and 3D visualization of flood damage to building. *Locate* 2015, *15*.

Bahu, J. M., Koch, A., Kremers, E. and Murshed, S. M. [2013]. Towards a 3D spatial urban energy modelling approach. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* 2013, *II-2/W1,* (pp. 33–41).

Batty, M., Axhausen, W., K., Giannotti, F., Pozdnoukhov, A., Bazzani, A., Wachowicz, M., Ouzounis, G. and Portugali, Y. [2012]. Smart cities of the future. *The European Physical Journal Special Topics*, (pp. 481-518).

Bedrick, J. and Vandezande, J. [2013]. Defining Level of Development- Specifying BIM Deliverables, AIA AEC Process Engineering HOK, BIMforum.

Benner, J., Geiger, A. and Leinemann, K. [2005]. Flexible Generation of Semantic 3D Building Models. In *Proceedings of the 1st international workshop on next generation 3D city models*, (pp. 17–22), Bonn, Germany, 21–22 June 2005.

Biljecki, P., Stöter, J., Ledoux, H., Zlatanova, S. and Çöltekin, A. [2015]. Applications of 3D City Models: State of the Art Review. In *ISPRS Int. J. GeoInf.* 2015, *4*, (pp. 2842-2889), doi:10.3390/ijgi4042842.

Biljecki, P., Ledoux, H. and Stöter, J. [2017]. Does a Finer Level of Detail of a 3D City Model Bring an Improvement for Estimating Shadows? In *Advances in 3D Geoinformation, Chapter: 2,* Publisher: Springer International Publishing, Editors: Alias Abdul-Rahman, (pp.31-47). doi:10.1007/978-3-319-25691-7_2.

Borgia, E. [2014]. The internet of things vision: key features, applications and open issues. *Computer Communications, 54,* (pp. 1–31).

Boyes, G., Thomson, C. and Ellul, C. [2015]. Integrating BIM and GIS: Exploring the use of IFC space objects and boundaries. In *Proceedings of the GISRUK 2015,* Leeds, UK, 15–17 April 2015; University of Leeds: Leeds, UK, 2015.

Building SMART International [2007]. Industry Foundation Classes (IFC), IFC2x3. Available from: http://www.buildingsmart- tech.org/specifications/IFC-releases/summary.

Caragliu, A., Del Bo, C. and Nijkamp, P. [2011]. Smart Cities in Europe. *Journal of Urban technology, Vol. 18, Iss. 2, 2011,* http://dx.doi.org/10.1080/10630732.2011.601117

Chang, V., Bacigalupo, D., Wills, G. and Roure, D. D. [2010]. A categorization of cloud computing business models. In *Proceedings of the 2010 10th IEEE/ACM International Conference on Cluster, Cloud and Grid Computing.*

Chang, V., Walters, R. J. and Wills, G. [2013]. The development that leads to the cloud computing business framework. *International Journal of Information Management, 33(3),* (pp. 524–538). http://dx.doi.org/10.1016/j.ijinfomgt.2013.01.005

Chatuverdi, K. and Kolbe, T. H. [2016]. INTEGRATING DYNAMIC DATA AND SENSORS WITH SEMANTIC 3D CITY MODELS IN THE CONTEXT OF SMART CITIES. In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* Volume IV-2/W1, 2016 11th 3D Geoinfo Conference, 20–21 October 2016, Athens, Greece.

Cheng, J. C. P., Deng, Y. and Du, Q. [2013]. Mapping between BIM Models and 3D GIS City Models of Different Levels of Detail. In *Proceedings of the 13th International Conference on Construction Applications of Virtual Reality* (CONVR 2013), London, UK, 30–31 October 2013.

De Laat, R. and van Berlo, L. [2011]. Integration of BIM and GIS: The development of the citygml GeoBIM extension. In *Advances in 3D Geo-Information Sciences*; Springer: New York, NY, USA, 2011; (pp. 211–225).

Deng, Y., Cheng, J. C. and Anumba, C. [2016]. Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison. *Autom. Constr.* 2016, *67*, (pp. 1–21).

Diakité, A. A, Damiand, G. and Gesquière, G. [2014]. Automatic Semantic Labelling of 3D Buildings Based on Geometric and Topological Information. In *Proceedings of 9th International 3D GeoInfo Conference (3D GeoInfo),* Nov. 2014, Dubai. United Arab Emirates. Karlsruhe Institute of Technology, 3DGeoInfo conference proceedings series.

Dimopoulou, E. and Elia, E. [2012]. Legal aspects of 3D property rights, restrictions and responsibilities in Greece and Cyprus. In *Proceedings of the 3rd International Workshop on 3D Cadastres,* Developments and Practices (pp. 25-26).

Dimopoulou, E., Tsiliakou, E., Kosti, V., Floros, G. and Labropoulos, T. [2014]. Investigating Integration Possibilities between 3D Modeling Techniques. In *Proceedings of 9th International 3D GeoInfo Conference*, Nov. 2014, Dubai. United

Arab Emirates.

Donkers, S. [2013]. Automatic Generation of CityGML LoD3 Building Models from IFC Models. MSc thesis, Delft University of Technology, Department of GIS Technology, OTB Research Institute for the Built Environment.

El-Mekawy, M., Östman, A. and Hijazi, I. [2012]. An Evaluation of IFC-CityGML Unidirectional Conversion. *International Journal of Advanced Computer Science and Application.*

El-Mekawy, M. [2010]. Integrating BIM and GIS for 3D City Modelling: The Case of IFC and CityGML. Licentiate Thesis, KTH, Stockholm, Sweden.

Floros, G. and Dimopoulou, E. [2016]. INVESTIGATING THE ENRICHMENT OF A 3D CITY MODEL WITH VARIOUS CITYGML MODULES. In *Proceedings of 11th Joint International 3D GeoInfo Conference*, Oct. 2016, Athens, Greece.

Floros, G., Solou, D., Pispidikis, I. and Dimopoulou, E. [2016]. A ROADMAP FOR GENERATING SEMANTICALLY ENRICHED CITYGML MODEL VIA TWO DIFFERENT METHODOLOGIES. In *Proceedings of 11th Joint International 3D GeoInfo Conference*, Oct. 2016, Athens, Greece.

Floros, G., Tsiliakou, E., Kitsakis, D., Pispidikis, I. and Dimopoulou, E. [2015]. Investigating Semantic Functionality of 3d Geometry for Land Administration. In *Proceedings of 10th Joint International 3D GeoInfo Conference*, Oct. 2015, Kuala Lumpur, Malaysia.

Gani, A., Siddiqa, A., Shamshirband, S. and Hanum, F. [2016]. A survey on indexing techniques for big data: taxonomy and performance evaluation. Knowledge and Information Systems, 46(2), (pp. 241–284).

Geiger, A., Benner, J. and Häfele, K. H. [2015]. Generalization of 3D IFC building models. In *3D Geoinformation Science*; Springer: New York, NY, USA, 2015, (pp. 19–35).

Gröger, G., Kolbe, T. H., Nagel, C. and Häfele, K. H. [2012]. OGC City Geography Markup Language (CityGML) Encoding Standard, Open Geospatial Consortium.

Gröger, G. and Plümer, L. [2012]. CityGML – Interoperable semantic 3D city models. *ISPRS Journal of Photogrammetry and Remote Sensing 71*, (pp. 12–33).

Hancke, G. P., Bde, S. and Hancke G. P. Jr. [2012]. The role of advanced sensing in smart cities. doi: 10.3390/s130100393.

Hashema, T. A. I., Chang, V., Anuara, N. B., Adewolea, K., Yaqooba, I., Gania, A., Ahmeda, E. and Chiromac, H. [2016]. The role of big data in smart city. In *International Journal of Information Management 36 (2016),* (pp. 748–758).

Hollands, R. G. [2015]. Critical interventions into the corporate smart city.

Cambridge Journal of Regions, Economy and Society, 8(1), (pp. 61–77).

Howell, I., and Batcheler, B. [2005]. "Building Information Modelling Two Years Later–Huge Potential, Some Success and Several Limitations Retrieved." Available from: LaiserinLetter< http://www. laiserin. com/features/bim/newforma_bim. Pdf.

Irizarry, J., Karan, E. P. and Jalaei, F [2013]. Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Autom. Constr.* 2013, *31*, (pp. 241–254).

Isikdag, U. and Zlatanova, S. [2009]. Towards Defining a Framework for Automatic Generation of Buildings in CityGML using Building Information Models. In *Lee J. and Zlatanova, S. (Eds.) 3D Geoinformation Sciences*, (pp.79-96), Springer Berlin Heidelberg.

Ju, G., Cheng, M., Xiao, M., Xu, J., Pan, K., Wang, X. and Shi, F. [2013]. Smart transportation between three phases through a stimulus-responsive functionally cooperating device. In *Advanced Materials, 25(21),* (pp. 2915–2919).

Khan, N., Yaqoob, I., Hashem, I. A. T., Inayat, Z., Mahmoud Ali, W. K., Alam, M., and Gani, A. [2014]. Big data: survey, technologies, opportunities, and challenges. In *The Scientific World Journal, 2014, 8,* http://dx.doi.org/10.1155/2014/712826

Kolbe, T. H. [2009]. Representing and Exchanging 3D City Models with CityGML. In Proceedings of the 3rd International Workshop on 3D GeoInformation, Seoul, Korea. *Lectures in Geoinformation and Cartography*, Springer Verlag.

Kolbe, T. H. and Plümer, L. [2004]. Bridging the Gap between GIS and CAAD. *GIM International 2004, Vol. 18, No. 7.*

Kurakula, V. [2007]. A GIS-Based Approach for 3D Noise Modelling Using 3D City Models. Master's Thesis, International Institute for Geoinformation Science and Earth Observation, Enschede, The Netherlands.

Lai, C. S. and McCulloch, M. D. [2015]. Big data analytics for smart grid. Retrieved from http://smartgrid.ieee.org/newsletters/october-2015/big-data-analytics-for-smart-grid. Accessed 02.07.17.

Ledoux, H. [2013]. On the validation of solids represented with the international standards for geographic information. In *Computer-Aided Civil and Infrastructure Engineering,* 28(9), (pp. 693–706), October 2013.

Li, K.-J., Lee, J., Zlatanova, S. and Morley, J. [2016]. Indoorgml SWG. Available online: http://www.opengeospatial.org/projects/groups/indoorgmlswg. Accessed 02.07.17.

Li, D., Shan, J., Shao, Z., Zhou, X. and Yao, Y. [2013]. Geomatics for Smart Cities - Concept, Key Techniques, and Applications. In *Geospatial Information Science,* 16:1, (pp. 13-24), doi: 10.1080/10095020.2013.772803

Liu, X., Wang, X., Wright, G., Cheng, J., Li, X. and Liu, R. [2017]. 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), pp. 53.

Manville, C., Cochrane, G., Cave, J., Millard, J., Pederson, J. K., Thaarup, R. K. and Kotterink, B. [2014]. Mapping smart cities in the EU. Retrieved from http://www.smartcities.at/assets/Publikationen/Weitere-Publikationen-zum-Thema/mappingsmartcities.pdf. Accessed 10.07.17.

Mell, P. and Grance, T. [2011]. The NIST definition of cloud computing.

Nagel C. [2007]. Conversion of IFC to CityGML. Meeting of the OGC 3DIM Working Group at OGC TC/PC Meeting, Paris (Frankreich), July 2007.

Nagel, C., Stadler, A. and Kolbe, T. H. [2009]. Conceptual requirements for the automatic reconstruction of building information models from uninterpreted 3D models. *Proc. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2009.

Nam, T. and Pardo, A. T. [2011]. Conceptualizing Smart City with Dimensions of Technology, People, and Institutions. In *Proceedings of the 12th Annual International Conference on Digital Government Research*, University at Albany, State University of New York, U.S.

Niu, S., Pan, W. and Zhao, Y. [2015]. A BIM-GIS integrated web-based visualization system for low energy building design. In *Procedia Eng.* 2015, *121*, (pp. 2184–2192).

Rathore, M. M., Ahmad, A., Paul, A. and Rho, S. [2015]. Urban planning and building smart cities based on the Internet of Things using Big Data Analytics. In *Computer Networks, (*pp. 63-80). https://doi.org/10.1016/j.comnet.2015.12.023.

Roy, N., Pallapa, G. and Das, S. K. [2007]. A middleware framework for ambiguous context mediation in smart healthcare application. Paper presented at the Third IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, 2007. WiMOB 2007.

Shahrokni, H., Van der Heijde, B., Lazarevic, D. and Brandt, N. [2014]. Big data GIS analytics towards efficient waste management in Stockholm. Paper presented at the Proceedings of the 2014 Conference ICT for Sustainability.

Shojaei, D., Rajabifard, A., Kalantari, M., Bishop, I.D. and Aien, A. [2015]. Design and development of a web-based 3D cadastral visualisation prototype. *Int. J. Digit. Earth* 2015, *8*, (pp. 538–557).

Stoter, J. and Salzmann, M. [2003]. Towards a 3D cadastre: where do cadastral needs and technical possibilities meet?. Computers, environment and urban systems, Volume 27, Issue 4, (pp. 395-410).

Tao, W. [2013]. Interdisciplinary urban GIS for smart cities: advancements and opportunities. *Geospatial Information Science,* (pp. 25-34), http://dx.doi.org/10.1080/10095020.2013.774108.

United Nations [2015]. World Population Prospects: The 2015 Revision, *Key Findings and Advance Tables,* New York.

Yaqoob, I., Chang, V., Gani, A., Mokhtar, S., Abaker, I., Hashem, T., et al. [2016]. Information fusion in social big data: Foundations, state-of-the-art, applications, challenges, and future research directions. In *International Journal of Information Management*, http://dx.doi.org/10.1016/j.ijinfomgt.2016.04.014.

Zhu, Q., Zhao, J., Du, Z., Zhang, Y., Xu, W., Ding, Y. Wang, F. and Wang, T. [2011]. Towards semantic 3D City Modeling and Visual Explorations.

Zlatanova, S., Beetz, J., Boersma, A., Mulder, A. and Goos, J. [2013]. 3D spatial information infrastructure for the port of rotterdam. In Proceedings of the International Workshop on "Global Geospatial Information", Novosibirsk, Russia, 25 April 2013.

Autodesk. BIM AND THE FUTURE OF AEC. URL: https://www.autodesk.com/solutions/bim, Accessed 28/08/2017.

buildingSMART. Industry Foundation Classes IFC2*x* Edition 3, Technical Corrigendum 1, URL: http://www.buildingsmart-tech.org/ifc/IFC2x3/TC1/html/index.html, Accessed 05/09/2017.

CityGML. Application Domain Extensions (ADE), URL: https://www.citygml.org/ade/, Accessed 05/09/2017.

Safe Software. IFC LOD 300 to LOD 4 CityGML. URL: https://knowledge.safe.com/articles/1025/bim-to-gis-intermediate-ifc-lod-300-to-lod-4-cityg.html, Accessed 03/09/2017.

Val3dity. Geometric validation of 3D primitives. URL: http://geovalidation.bk.tudelft.nl/val3dity/, Accessed 15/08/2017.

ΕΚΧΑ Α.Ε. Θέαση ορθοφωτογραφιών. URL: https://www.ktimanet.gr/CitizenWebApp/Orthophotographs_Page.aspx, Accessed 10/08/2017.