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BIM Development for Cultural Heritage Management

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Diploma Thesis

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ABSTRACT

This diploma thesis is the result of the collaboration of two Universities, the National Technical University of Athens (NTUA) and the Polytechnic University of Milan (Politecnico di Milano- PoliMi). In particular this collaboration was realized between the Laboratory of Photogrammetry (NTUA) and the Department of Building Environment Science & Technology (B.E.S.T -PoliMi). Its practical implementation is part of the INTERREG program (2007-2013) for Italy and Switzerland (*INTERREG Italia-Svizerra*) for the development of the regions near their borders. The object of interest is the Catholic Church of Santa Maria at Scaria in the Province of Como in Northern Italy.

The survey field works for the data acquisition took place during the period March-April of 2012 and the first part of the data processing was completed in Milan until July of 2012. Both data acquisition and processing were performed in collaboration with a group of Architects and Geomatics Engineers. The main objectives of these works were the production of documentation drawings for the church, orthophotos of its vault system, but also the development of a Building Information Modeling (BIM) for it. With few exceptions, all the necessary work for these products was the result of a close collaboration with the architect Anna Raimondi for her master thesis.

The drawings of the church are based on the laser scanner's point clouds which were processed with *Cloudworx®(Leica®)* inside *AutoCAD® (Autodesk®)* by extracting sections and floor plans. These drawings and the geometric information that they contain, were used in order to develop the BIM model of the church.

For the production of the orthophotos *Photomodeler Scanner 2012®*, *Photogrammetric Lab Suite (LPS – Erdas®)* and *Image Master® (Topcon®)* were used, while for the orthomosaic *ArcMap® (ESRI®)* and *Photoshop CS5® (Adobe®)* were employed. In order to produce surfaces from the point cloud and create also a sample textured model, *Geomagic Studio®(3D Systems®)* was used, while for the BIM model *Revit® 2013 (Autodesk®)* was chosen.

All the data of this diploma thesis are at the disposal of both universities for further use and research.

ΠΕΡΙΛΗΨΗ

Η παρούσα διπλωματική εργασία είναι αποτέλεσμα συνεργασίας δύο Πανεπιστημίων, του Εθνικού Μετσόβιου Πολυτεχνείου της Αθήνας (ΕΜΠ) και του Πολυτεχνείου του Μιλάνου (Politecnico di Milano - PoliMi). Συγκεκριμένα η συνεργασία πραγματοποιήθηκε μεταξύ του Εργαστηρίου Φωτογραμμετρίας (ΕΜΠ) και του Τμήματος Δομημένου Περιβάλλοντος Επιστήμης και τεχνολογίας (B.E.S.T. - PoliMi). Η πρακτική της εφαρμογή είναι μέρος του προγράμματος INTERREG (2007-2013) για την Ιταλία και τη Ελβετία (INTERREG Italia - Svizerra) για την ανάπτυξη των περιοχών κοντά στα σύνορά τους. Το αντικείμενο ενδιαφέροντος είναι η Καθολική Εκκλησία Santa Maria στο χωριό Σκάρια, στην επαρχία του Κόμο (περιφέρεια Λομβαρδίας) στη Βόρεια Ιταλία.

Οι εργασίες πεδίου για την συλλογή των δεδομένων έλαβαν χώρα κατά την περίοδο Μαρτίου – Απριλίου του 2012 και το πρώτο μέρος της επεξεργασίας των δεδομένων είχε ολοκληρωθεί στο Μιλάνο έως τον Ιούλιο του 2012. Τόσο η συλλογή όσο και η επεξεργασία των δεδομένων έγινε σε συνεργασία με ομάδα Αρχιτεκτόνων και Τοπογράφων Μηχανικών. Οι κύριοι στόχοι των εργασιών αυτών ήταν η παραγωγή σχεδίων τεκμηρίωσης της εκκλησίας, ορθοφωτογραφιών για τους θόλους της, και ακόμη η ανάπτυξη ενός Building Information Model (BIM). Με ελάχιστες εξαιρέσεις, όλες οι απαραίτητες εργασίες για την παραγωγή αυτών των προϊόντων ήταν αποτέλεσμα στενής συνεργασίας με την τελειόφοιτο Αρχιτέκτων Anna Raimondi, στο πλαίσιο του master της.

Τα σχέδια της εκκλησίας βασίζονται σε νέφη σημείων προερχόμενα από σαρωτή laser, τα οποία υπέστησαν επεξεργασία με το λογισμικό *Cloudworx® (Leica®)* στο περιβάλλον του *AutoCAD® (Autodesk®),* εξάγοντας τομές και κατόψεις. Τα εν λόγω σχέδια και η γεωμετρική πληροφορία που περιέχουν χρησιμοποιήθηκαν ώστε να αναπτυχθεί το BIM για την εκκλησία.

Για την παραγωγή των ορθοφωτογραφιών χρησιμοποιήθηκαν τα λογισμικά *Photomodeler Scanner 2012®*, *Photogrammetric Lab Suite (LPS – Erdas®)* και *Image Master® (Topcon®)*, ενώ για τα ορθομωσαϊκά τα *ArcMap® (ESRI®)* και *Photoshop CS5® (Adobe®).*Για την παραγωγή επιφανειών από τα νέφη σημείων και τη απόδοση υφής στο μοντέλο χρησιμοποιήθηκε το λογισμικό *Geomagic Studio®(3D Systems®),* ενώ για το BIM επιλέχθηκε το *Revit® 2013 (Autodesk®).*

Όλα τα δεδομένα της παρούσας Διπλωματικής είναι διαθέσιμα και στα δύο Πανεπιστήμια για μελλοντική χρήση και έρευνα.

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ΕΚΤΕΤΑΜΕΝΗ ΠΕΡΙΛΗΨΗ

I. Εισαγωγή

Η τρισδιάστατη ψηφιακή σχεδίαση και καταγραφή των υπαρχόντων Μνημείων Πολιτιστικής Κληρονομιάς είναι μία πολύπλοκη διαδικασία που συνήθως περιλαμβάνει μία υβριδική προσέγγιση οπτικοποίησης των ετερογενών δεδομένων, όπως είναι οι τοπογραφικές μετρήσεις, ψηφιακά διανυσματικά σχέδια (CAD), φωτογραφίες και τρισδιάστατα εικονικά δεδομένα –π.χ. δεδομένα από λέιζερ σαρωτές, προϊόντα φωτογραμμετρίας κ.ά. (El-Hakim et al. 2005; Remondino et al 2009).

Την προηγούμενη δεκαετία πολλοί ερευνητές ασχολήθηκαν με τις μεθοδολογίες που ακολουθούνται σε αυτές τις περιπτώσεις, από την συλλογή δεδομένων για την αποτύπωση και καταγραφή των μνημείων έως την αναπαράστασή τους με υψηλής πιστότητας τρισδιάστατα μοντέλα. Στη καταγραφή Πολιτιστικής Κληρονομιάς είχαν πάντα πρωτεύουσα σημασία η υψηλή εικονιστική ποιότητα, η μετρητική ακρίβεια και ο συνδυασμός διαφόρων τύπων πολυμέσων. Ωστόσο πιο πρόσφατα, ο κλάδος της καταγραφής και διαχείρισης της Πολιτιστικής Κληρονομίας έχει στραφεί στα «έξυπνα» δεδομένα που αφορούν στην ανάλυση και συντήρηση των μνημείων (Pauwels et al. 2008; Attar et al. 2010).

Όπως αναφέρει και ο Fai (2012), η ανάδειξη του BIM (Building Information Modeling) έπαιξε σημαντικό ρόλο σε αυτή τη στροφή, καθώς είναι μία τεχνολογία που αναδεικνύει την αυξανόμενη ανάγκη για την ύπαρξη μίας διεπιστημονικής γνωστικής βάσης, καθώς είναι απαραίτητα για τη διαχείριση μέσα στο πλαίσιο του *κύκλου ζωής* ενός κτιρίου (λειτουργία, ανάπτυξη και ανανέωση του καταλόγου των μνημείων, κλπ.). Υπάρχει επίσης η πεποίθηση ότι το BIM μπορεί εν δυνάμει να συνεισφέρει στην απόδοση των πολύπλοκων σχέσεων μεταξύ Υλικής και Άυλης Πολιτιστικής Κληρονομιάς.

Σε αυτό το κεφάλαιο γίνεται μία εκτεταμένη περίληψη της παρούσας διπλωματικής εργασίας, που σκοπός της είναι ο σχεδιασμός ενός μοντέλου BIM για την καθολική εκκλησία της Santa Maria, στην Scaria, εξερευνώντας παράλληλα τις δυνατότητες του BIM στον τομέα της Πολιτιστικής Κληρονομιάς.

II. Building Information Modeling (BIM)

Στόχος αυτού το υποκεφαλαίου είναι η εξοικείωση του αναγνώστη με την έννοια του BIM, παρουσιάζοντας το βασικό εννοιολογικό υπόβαθρό του, μέσα από τους κύριους επίσημους ορισμούς του, καθώς και με άλλες έννοιες που συνδέονται με αυτό, όπως η *Διαχείριση σε επίπεδο Κύκλου Ζωής (Life Cycle Management-LCM)* και η *Διαλειτουργικότητα (Interoperability)*. Γίνεται επίσης αναφορά στην εξέλιξη του μέσα στον χρόνο, καθώς στις θετικές και αρνητικές του πλευρές με έμφαση σε ότι αφορά στην εφαρμογή του στον τομέα της Πολιτιστικής Κληρονομιάς.

II.1. Η Εξέλιξη του BIM

Οι παρακάτω παράγραφοι έχουν βασιστεί στο άρθρο του Bergin, M., "BIM history" (http://www.architectureresearchlab.com/arl/2011/08/21/bim-history/)

Με το πέρασμα των χρόνων οι απαιτήσεις για αναπαράσταση των μορφών αυξάνονταν, με παράλληλη εξέλιξη των δισδιάστατων και τρισδιάστατων σχεδίων. Το BIM δεν είναι η εξέλιξη του CAD, καθώς έχουν διαφορετική λογική. Οι θεωρητικές απαρχές του τοποθετούνται γύρω στο 1962 όπου πρώτος ο Engelbart μίλησε για την εισαγωγή επιπλέον πληροφοριών στα αντικείμενα που σχεδιάζονται. Στη συνέχεια τη δεκαετία 1970-1980 εμφανίστηκαν τα συστήματα CAD που υιοθέτησαν την τρισδιάστατη σχεδίαση επιτρέποντας τη δημιουργία κτιριακών μοντέλων. Τη ίδια περίοδο ο Eastman κάνει λόγο για τη χρήση βιβλιοθηκών στον σχεδιασμό από την σκοπιά των βάσεων δεδομένων με το Building Description System (BDS) (Eastman, 1979). Στη συνέχεια και σχεδόν παράλληλα εμφανίζεται το ArchiCAD® (Graphisoft®) και το Pro/ENGINEER® (PTC®), που αργότερα εξελίχθηκε σε Revit® και αγοράστηκε από την Autodesk® το 2002. Το Revit® αποτέλεσε επαναστατική εξέλιξη στον τομέα του BIM, αφού προσέθεσε τη διάσταση του χρόνου μετατρέποντας τα 3D σε nD μοντέλα. Οι πιο πρόσφατες εξελίξεις αφορούν στην ανάπτυξη των IFC (Industry Foundation Classes) από την building Smart® (IAI- International Alliance for Interoperability) με στόχο την απρόσκοπτη ανταλλαγή πληροφορίας μεταξύ διαφορετικών προγραμμάτων και χρηστών. Αυτή η πληροφορία περιγράφει πλήρως τα αντικείμενα και περιέχεται μέσα στα IFC. Έτσι σήμερα το αρκτικόλεξο «BIM» αποτελεί αντικείμενο μεγάλης συζήτησης και ενδιαφέροντος στην AEC βιομηχανία, καθώς ο κόσμος της τώρα έχει αρχίσει να αντιλαμβάνεται τη δυναμική των μοντέλων αυτών.

II.2. Ορισμός του BIM

Ορίζοντας με απλά λόγια το BIM, θα μπορούσε κανείς να πει ότι είναι η τρισδιάστατη αναπαράσταση μίας κατασκευής που, εκτός από τα γεωμετρικά χαρακτηριστικά και τις χωρικές σχέσεις των στοιχείων που την απαρτίζουν, περιλαμβάνει όλες τις ιδιότητες και τα χαρακτηριστικά καθενός από αυτά (π.χ. για κάθε τοίχο ή κολώνα). Αυτό σημαίνει ότι εμπεριέχεται πληροφορία που αφορά στα υλικά κάθε δομικού στοιχείου, στην λειτουργία του (π.χ. εξωτερικός ή εσωτερικός τοίχος ή στο αν συνεισφέρει στατικώς στην κατασκευή) ή ακόμα και στην ενεργειακή του συμπεριφορά. Με άλλα λόγια είναι ένας τρόπος ώστε να σχεδιάζονται κατασκευές, υπάρχουσες ή μη, με δομική μονάδα το ίδιο το στοιχείο (object-oriented design) και όχι τις γραμμές που το ορίζουν (όπως στα συμβατικά σχέδια CAD) με ταυτόχρονη παραμετρική προσέγγιση.

Σύμφωνα με τους Eastman κ.ά. (2008) το BIM είναι μία από τις πιο υποσχόμενες εξελίξεις στον τομέα της Αρχιτεκτονικής, της Μηχανικής και των Κατασκευών (Architecture-Engineering-Construction Industry). Το BIM ουσιαστικά προσομοιώνει τη διαδικασία κατασκευής σε ένα εικονικό περιβάλλον. Με το BIM, ένα ακριβές εικονικό μοντέλο ενός κτιρίου δημιουργείται ψηφιακά και όταν ολοκληρώνεται περιλαμβάνει ακριβή γεωμετρία και τα αντίστοιχα δεδομένα που χρειάζονται για να υποστηρίξουν όλη τη διαδικασία κατασκευής του κτιρίου.

Η έννοια του BIM όμως συνδέεται άμεσα και με άλλες έννοιες όπως η Διασυνδεδεμένη Παράδοση Έργου (Integrated Project Deliver –IPD), η Διαλειτουργικότητα και η Διαχείριση σε επίπεδο Κύκλου Ζωής των κατασκευών. Όσον αφορά στην IPD, το BIM αποτελεί εργαλείο-κλειδί αφού καθιστά απρόσκοπτη την συνεργασία μεταξύ των διαφόρων μελών και την ανταλλαγή των απαραίτητων δεδομένων και μετα-δεδομένων (που είναι και η βάση της IPD). Η Διαλειτουργικότητα από την άλλη είναι ουσιαστικά η ικανότητα δύο ή περισσότερων συστημάτων να ανταλλάσουν και να χρησιμοποιούν πληροφορίες. Το συγκεκριμένο κομμάτι του BIM είναι υπό συνεχή έρευνα καθώς γίνεται προσπάθεια ορισμού κάποιων standards, για την βελτιστοποίηση της ροής των δεδομένων σε «αγνή» μορφή, όπως με την ανάπτυξη των Industry Foundation Classes (IFC). Τέλος, η δυνατότητα εφαρμογής του BIM σε όλη τη διαδικασία κατασκευής ενός έργου, το καθιστά αναπόσπαστο κομμάτι του LCM και της διαδικασίας αποφάσεων.

II.3. Θετικά και αρνητικά του BIM

Το γεγονός ότι όλο και περισσότεροι χρήστες υιοθετούν το BIM στα έργα τους δικαιολογείται από τα προτερήματα που αυτό έχει. Καταρχάς είναι ένα τρισδιάστατο μοντέλο προσφέροντας στον χρήστη μία άμεση και εποπτική παρουσίαση του αντικειμένου. Από αυτό το 3D μοντέλο είναι εύκολη η μετάπτωση στις δύο διαστάσεις, αφού μπορούν να παραχθούν αυτόματα κατόψεις σε διάφορα επίπεδα και τομές είτε οριζόντιες είτε κατακόρυφες, αλλά και το αντίθετο (δηλαδή από 2D σε 3D). Παράλληλα, όταν αλλάζει κάτι σε ένα από αυτά τα σχέδια ενημερώνονται ταυτόχρονα και όλα τα άλλα, μειώνοντας δραματικά το χρόνο επεξεργασίας.

Το BIM όμως δεν είναι πανάκεια. Πολλές φορές τα αρχεία είναι δύσκολο να υποστούν διαχείριση καθώς έχουν πολύ μεγάλο όγκο, λόγω της πολυεπίπεδης πληροφορίας που περιέχουν. Επίσης με την αυτόματη ανανέωση των αλλαγών μπορεί να μειώνεται μεν ο χρόνος επεξεργασίας, αν γίνει λάθος δε μπορεί να είναι πιο δύσκολο να διορθωθεί, ειδικά όταν το BIM μοντέλο υπόκειται σε διαχείριση από πολλούς χρήστες. Τέλος, από αυτή την εμπλοκή πολλών και διαφορετικών χρηστών αναδεικνύονται συχνά προβλήματα ως προς τα πνευματικά δικαιώματα αυτών των μοντέλων.

Όσον αφορά στην χρήση του BIM στην διαχείριση Πολιτιστικής Κληρονομιάς, η δυναμική του και η αξία του είναι στην παρούσα φάση υπό έρευνα με θετικά τα πρώτα δείγματα. Η δυνατότητα που προσφέρει το BIM για παραμετρικό σχεδιασμό μπορεί να μειώσει αισθητά τον χρόνο σχεδιασμού σχετικά με παρόμοια αρχιτεκτονικά στοιχεία με τελικό στόχο τη δημιουργία βιβλιοθηκών για αυτά, ώστε να είναι προσβάσιμα σε όσους ασχολούνται με τα Μνημεία και την διαχείρισή τους. Πέρα από την γεωμετρία για αυτά υπάρχει η δυνατότητα απόδοσης των υλικών των στοιχείων, αλλά και η παρουσίαση των διαφόρων φάσεων κατασκευής ή ανακατασκευής, όπου υπάρχουν. Ιδιαίτερο ενδιαφέρον παρουσιάζει και η σύνδεση BIM μοντέλων με εξωτερικές βάσεις δεδομένων ή με ένα τρισδιάστατο σύστημα γεωγραφικών πληροφοριών (3D GIS) , για μία πιο ολοκληρωμένη προσέγγιση προσθέτοντας διάφορα δεδομένα αλλά και χωρική πληροφορία.

Παρά όμως όλα τα παραπάνω, το BIM εξακολουθεί να είναι μία τεχνολογία που προορίζεται για μοντέρνες κατασκευές. Τα Μνημεία Πολιτιστικής Κληρονομιάς ως επί το πλείστον παρουσιάζουν ιδιαίτερα χαρακτηριστικά και πολύπλοκη γεωμετρία, που συχνά δεν είναι δυνατόν να αποδοθεί κατάλληλα με τα υπάρχοντα λογισμικά BIM.

Αυτή η θεωρητική προσέγγιση αξιολόγησης του BIM γενικά αλλά κυρίως σε εφαρμογές Πολιτιστικής Κληρονομιάς, γίνεται σε αυτή τη διπλωματική εργασία μέσω της ανάπτυξης του μοντέλου BIM της εκκλησίας της Santa Maria

III. Παραδείγματα Εφαρμογών του BIM

Στις παρακάτω παραγράφους γίνεται μια συνοπτική παρουσίαση του πώς χρησιμοποιείται το BIM στις μοντέρνες κατασκευές και αναφέρονται κάποια χαρακτηριστικά παραδείγματα από την έρευνα που ήδη γίνεται για την υιοθέτησή του και στο πεδίο της καταγραφής και διαχείρισης Μνημείων Πολιτιστικής Κληρονομιάς.

III.1. Εφαρμογές του BIM στις Σύγχρονες Κατασκευές

Όπως έχει ήδη αναφερθεί η τεχνολογία του BIM σχεδιάστηκε για χρήση σε μοντέρνες κατασκευές και παρουσιάζει τα πλεονεκτήματα που παρουσιάστηκαν παραπάνω. Πρακτικά, η υιοθέτηση του BIM στην AEC βιομηχανία δίνει στους διάφορους εμπλεκόμενους (αρχιτέκτονες, πολιτικοί μηχανικοί, εργολάβοι κλπ.) τη δυνατότητα να δουλεύουν ταυτόχρονα σε ένα μοντέλο όντας ταυτόχρονα ενημερωμένοι για την πορεία εργασιών των υπολοίπων.

Με παράδειγμα λογισμικού το Revit®, οι χρήστες μπορούν μέσα σε αυτό να φτιάξουν το αρχιτεκτονικό μοντέλο μίας κατασκευής με όλα τα στοιχεία που το απαρτίζουν, στη συνέχεια σε αυτά τα στοιχεία να προστεθεί η πληροφορία για τη στατική τους συμπεριφορά (π.χ. ο οπλισμός του σκυροδέματος), να σχεδιαστούν τα ηλεκτρολογικά και υδραυλικά συστήματα και τέλος όλα αυτά να παρουσιαστούν ως ένα τρισδιάστατο μοντέλο με φωτορεαλιστικό τρόπο (Figure 2.1 έως Figure 2.5 σελ. 40 - 41).

Αξίζει τέλος να αναφερθεί ότι τα περισσότερα λογισμικά BIM, όπως και το Revit®, έχουν τη δυνατότητα σύνδεσης με εξωτερικές εφαρμογές συνήθως μέσω internet για περαιτέρω ανάλυση της στατικής ή ενεργειακής συμπεριφοράς του κτιρίου, προσφέροντας μία ολοκληρωμένη λύση για τον σχεδιασμό και διαχείριση του κτιρίου.

III.2. Εφαρμογές του BIM στην Καταγραφή και Διαχείριση της Πολιτιστικής Κληρονομιάς

Στόχος αυτού του κεφαλαίου είναι η συνοπτική παρουσίαση κάποιων από τα παραδείγματα εφαρμογής του BIM σε Μνημεία Πολιτιστικής Κληρονομιάς που περιλαμβάνει αναλυτικά το Κεφάλαιο 2, υποβοηθώντας την διαδικασία εξαγωγής συμπερασμάτων για την αξία εφαρμογής του BIM σε τέτοιες περιπτώσεις.

Ένα τέτοιο αξιόλογο παράδειγμα είναι αυτό του HBIM (Historical Building Information Modeling) από τον Murphy κ.ά. (2009, 2011), που είναι μία βιβλιοθήκη παραμετρικών αντικειμένων σχεδιασμένων σύμφωνα με ιστορικά δεδομένα με προγραμματισμό στη γλώσσα GDL (Geometric Descriptive Language®) μαζί με ένα σύστημα που προβάλλει αυτά τα στοιχεία πάνω σε νέφη σημείων και εικόνες, ενώ λειτουργεί ως πρόσθετο (plug-in) στο λογισμικό BIM ArchiCAD® (Graphisoft®) (Εικόνα 2.6). Στη συνέχεια το τελικό μοντέλο BIM (Εικόνα 2.8) εισήχθη μέσα στο CityGML (αποτελεί μοντέλο πληροφοριών για την αναπαράσταση 3D αστικών αντικειμένων), για διερεύνηση του συνδυασμού BIM και 3D GIS εφαρμογών (Εικόνα 2.9). παρόμοια προσέγγιση ακολουθήθηκε και στην περίπτωση ανακατασκευής της συναγωγής του Vinohrady στην Πράγα, από το Καθολικό Πανεπιστήμιο της Βιέννης (KU Vienna) (Εικόνες 2.14 και 2.16).

Μία ακόμα εφαρμογή του BIM στο πεδίο της Πολιτιστική Κληρονομιάς είναι η περίπτωση του «Batawa Project» που αφορά σε ένα εργοστάσιο παπουτσιών στον Καναδά, από τον Fai κ.ά. (2011). Έγινε προσπάθεια συνολικής εκτίμησης του ρόλου του BIM χρησιμοποιώντας ετερογενή δεδομένα, δίνοντας διάφορες ιδιότητες και δημιουργώντας μία χρονολογική παρουσίαση του αντικειμένου (Εικόνα 2.18).

Τέλος, ενδιαφέρον παρουσιάζει η δουλειά των Garagnani κ.ά. (2013), για την ανάπτυξη του GreenSpider®, ενός πρόσθετου για το Revit®(Autodesk®) που προσφέρει μία λύση για την δημιουργία επιφανειών από ισοϋψείς καμπύλες σχεδιασμένες με βάση νέφη σημείων. Το αξιοσημείωτο είναι ότι αυτές οι επιφάνειες αποτελούν αντικείμενα του Revit® (Εικόνα 2.20), άρα μπορούν να τους αποδοθούν χαρακτηριστικά όπως το υλικό κ.ά.. Αντίστοιχη εφαρμογή του GreenSpider® έγινε και στην περίπτωση της Santa Maria (Κεφάλαιο 3).

Εν κατακλείδι αξίζει να σημειωθεί πως στην περισσότερη βιβλιογραφία επισημαίνονται οι περιορισμοί που θέτουν τα λογισμικά στην αντιμετώπιση πολύπλοκων αντικειμένων, όπως συνήθως είναι τα Μνημεία. Έτσι, προκύπτει και η ανάγκη ανάπτυξης βιβλιοθηκών με παραμετρικά αρχιτεκτονικά αντικείμενα, πιθανότατα βασισμένων σε IFCs διευκολύνοντας την χρήση, μορφοποίηση και ανταλλαγή τους.

IV. Case Study: Η Εκκλησία της Santa Maria (Σκάρια, Ιταλία)

Στο εν λόγω κεφάλαιο γίνεται αρχικά μια σύντομη αναφορά στην εκκλησία της Santa Maria. Στη συνέχεια περιγράφεται η πορεία εργασιών, από τη συλλογή των δεδομένων και την επεξεργασία τους μέχρι την δημιουργία τόσο του «αρχιτεκτονικού» όσο και του «ενεργειακού» μοντέλου BIM για την εκκλησία.

IV.1. Σύντομη περιγραφή της Εκκλησίας της Santa Maria

Η εκκλησία της Santa Maria βρίσκεται στο χωριό Σκάρια, στην επαρχία του Κόμο, κοντά στα σύνορα Ελβετίας-Ιταλίας (Εικόνες 3.1, 3.2). Η εκκλησία έχει διαστάσεις περίπου 23x10x20 m και το καμπαναριό που συνδέεται με αυτή είναι 4x4x20 m περίπου. Η εκκλησία αποτελείται από τρεις κύριους χώρους, που οριοθετούνται από κολώνες στις γωνίες τους και διαχωρίζονται μεταξύ τους με τόξα. Καθένας από τους τρεις χώρους περικλείεται από έναν θόλο με πλούσιες ζωγραφιές και διακοσμητικά στοιχεία από γύψο, ενώ ο τελευταίος χώρος έχει και μία αψίδα (Εικόνα 3.4). Όλο το εσωτερικό της εκκλησίας καθώς και η πρόσοψη έχουν πλούσιο διάκοσμο και αυτό αποτελεί ένα από τα βασικά χαρακτηριστικά της εκκλησίας.

Η χρονολογία κατασκευής της δεν είναι ξεκάθαρη, καθώς υπάρχουν διάφορες μαρτυρίες, αλλά πιθανότατα χρονολογείται γύρω στον $15^{ο}$ αιώνα. έχει έχει υποστεί διάφορες ανακατασκευές μέχρι και τον $19^{ο}$ αιώνα. Η σημαντικότερη ήταν αυτή από την οικογένεια τεχνιτών Carloni, καθώς σε αυτούς οφείλει και την μεταμόρφωση της σε ένα αντιπροσωπευτικό παράδειγμα της Μπαρόκ Αρχιτεκτονικής.

IV.2. Συλλογή και Επεξεργασία των Δεδομένων

Η συλλογή δεδομένων ξεκίνησε με την ίδρυση ενός γεωδαιτικού δικτύου με 9 στάσεις (7 εξωτερικά και 2 εσωτερικά του ναού). Η ίδρυσή του ήταν απαραίτητη για τον προσδιορισμό των συντεταγμένων των στόχων που χρησιμοποιήθηκαν με τον σαρωτή ώστε να γεωαναφερθούν τα νέφη, καθώς και των φωτοσταθερών σημείων (ΦΣ) για τον προσανατολισμό τον εικόνων που λήφθηκαν (Εικόνες 3.9, 3.10).

Χρησιμοποιήθηκε ο γεωδαιτικός σταθμός TS30 (Leica®) με ακρίβεια 0,5'' στις μετρήσεις γωνιών και ±1mm±1ppm και ±5mm±3ppm με ή χωρίς πρίσμα αντίστοιχα στις μετρήσεις αποστάσεων. Η επεξεργασία του νέφους έγινε στο Cyclone®(Leica®) και η γεωαναφορά έγινε με σφάλμα κλεισίματος της τάξης του χιλιοστού με τη μέθοδο του indirect registration. Η συνόρθωση του δικτύου έγινε με το Leica ® Geo-Office®.

Για την λήψη φωτογραφιών για το σύστημα των θόλων με στόχο την παραγωγή ορθοφωτομωσαϊκού χρησιμοποιήθηκε η φωτογραφική μηχανή DSLR Canon EOS 1D Mark IV, με διαστάσεις εστιακού επιπέδου 27.9x18.6 mm (τα 2/3 του full frame 36x24 mm) και ένας φακός των 20.4 mm. Η κλίμακα του τελικού προϊόντος υποδείχθηκε να είναι ίση με 1:20, άρα ορίστηκε εδαφοψηφίδα ίση με 2 mm. Η κλίμακα λήψης ήταν περίπου 1:300, που δίνει τελικά εδαφοψηφίδα ίση με 1.71 mm (5μm το μέγεθος του pixel x 300). Συνολικά έγινε η λήψη 86 φωτογραφιών με 2 λωρίδες για κάθε θόλο και 1 ακόμα λωρίδα για κάθε τόξο, με 4 φωτογραφίες οι καθεμία). Οι 24 ήταν για τα σφαιρικά τρίγωνα των θόλων σε πλάγια λήψη. Οι υπόλοιπες κάλυπταν τους θόλους και λήφθηκαν με 80% κατά μήκος και 20% κατά πλάτος επικάλυψη, με χρήση τρίποδα, άξονα λήψης το ζενίθ και ύψος περίπου στο 1.5 m από το δάπεδο της εκκλησίας.

Για τον προσανατολισμό των εικόνων χρησιμοποιήθηκε το Photomodeler Scanner® 2012, που δίνει την δυνατότητα γρήγορης εφαρμογής του σχετικού προσανατολισμού μέσω ενός αλγορίθμου συνταύτισης ομόλογων σημείων (SIFT algorithm, Lowe, 2004), αφού πρώτα εισήχθησαν τα στοιχεία του εσωτερικού προσανατολισμού (x_0, y_0, c, dr) . Στη συνέχεια μετρήθηκαν όλα τα ΦΣ, ενώ εισήχθη και το αρχείο με τις γεωδαιτικές τους συντεταγμένες και με την μέθοδο των δεσμών προσδιορίστηκε ο εξωτερικός προσανατολισμός των εικόνων (X_0, Y_0, Z_0, ω, φ, κ). Τέλος, παρήχθησαν εικόνες απαλλαγμένες από την ακτινική διαστροφή και υπολογίστηκε το νέο μέγεθος pixel ίσο με 5,9 μm (γίνεται resampling άρα αναγκαστικά μεγαλώνει η εικόνα για να μην χαθεί πληροφορία) μέσα από το LPS® λογισμικό (Leica®). Εκεί δημιουργήθηκε Ψηφιακό Μοντέλο Επιφανείας (ΨΜΕ) από το «καθαρισμένο» νέφος σημείων και παρήχθησαν οι ορθοφωτογραφίες με pixel 2 mm. Για το ορθοφωτομωσαϊκό χρησιμοποιήθηκε το ArcMap® 10 (ESRI®) Adobe Photoshop CS4® (Εικόνα 3.14).

Ωστόσο, κρίθηκε ότι το αποτέλεσμα αυτής της διαδικασίας δεν ήταν απόλυτα ικανοποιητικό, καθώς παρουσίαζε προβλήματα (pixel που «πέταγαν») που υποδείκνυαν προβλήματα στο ΨΜΕ. Έτσι επιλέχθηκε μία προβληματική περιοχή (Εικόνα 3.15) και οι εικόνες προσανατολίστηκαν ξανά με το Image Master® (Topcon®). Έγινε η δημιουργία επιφάνειας (TIN) από το νέφος μέσα στο Geomagic Studio® (Εικόνα 3.16) με την κατάλληλη επεξεργασία (καθαρισμός σημείων και «ανάποδων» τριγώνων, «κλείσιμο τρυπών») το οποίο εισήχθη στο Image Master® και δημιουργήθηκαν οι νέες ορθοφωτογραφίες. Το νέο ορθοφωτομωσαϊκό (Εικόνα 3.18) έδειξε ότι όντως το πρόβλημα αφορούσε στο ΨΜΕ, καθώς το αποτέλεσμα ήταν σαφώς καλύτερο (Εικόνα 3.18).

IV.3. Δημιουργώντας το BIM Μοντέλο

Για την ανάπτυξη του μοντέλου BIM της εκκλησίας επιλέχθηκε το Revit® 2012 (Autodesk®). Κάθε Revit® Project είναι μία μοναδική βάση δεδομένων που περιλαμβάνει όλη την πληροφορία που προσθέτει ο χρήστης, από τα στοιχεία που απαρτίζουν το μοντέλο με τα χαρακτηριστικά τους ως τα διάφορα “views” που παράγονται, π.χ. κατόψεις, τομές. Τα διάφορα στοιχεία που σχεδιάζονται κατατάσσονται (α) σε Categories που είναι ομάδες όμοιων στοιχείων, π.χ. «κολώνες», (β) σε Families που είναι μία τάξη μέσα στην κατηγορία που ανήκει και διαφοροποιείται από τις άλλες με τις παραμέτρους που την καθορίζουν, π.χ. το ότι είναι από τσιμέντο και σε επόμενο βαθμό (γ) σε Types, που διαφοροποιούνται και ως προς άλλο χαρακτηριστικό όπως π.χ. στο μέγεθος της διαμέτρου, ενώ μπορεί να είναι όλες από τσιμέντο.

Όλα τα γεωμετρικά στοιχεία για τον σχεδιασμό του μοντέλου προήλθαν από τα σχέδια της Anna Raimondi και έχουν παραχθεί από το νέφος σημείων.

Αρχικά δημιουργήθηκαν τα Families των τοίχων (Wall families) που ορίστηκαν σύμφωνα με το διαφορετικό τους πάχος (Πίνακας 3.1, Εικόνες 3.22 ως 3.25). Στις περιπτώσεις όπου οι τοίχοι παρουσίαζαν ακανόνιστο πάχος, τα κομμάτια που αντιστοιχούσαν σε αυτές τις «ανωμαλίες» σχεδιάστηκαν ξεχωριστά ως Column Families (κολώνες) (Πίνακας 3.5, Εικόνα 3.22) προκειμένου να ενσωματωθούν με τους τοίχους, ως προκαθορισμένη ιδιότητα αυτού του Family, μαζί με τις κανονικές κολώνες (Εικόνα 3.31). Σε κάποιους από τους τοίχους της εκκλησίας δημιουργήθηκαν οι εσοχές για τα εσωτερικά παρεκκλήσια που υπάρχουν και το βαπτιστήριο (Εικόνα 3.29). Η πρώτη προσέγγιση έγινε με την χρήση in-place στοιχείων (δηλαδή στοιχείων που δεν επαναλαμβάνονται στο project). Η εναλλακτική ήταν με τη χρήση nested family, δηλαδή τη δημιουργία ενός νέου family μέσα στο family του τοίχου στην Category των Doors, ώστε να δημιουργηθεί το απαραίτητο άνοιγμα, βάσει των ιδιοτήτων του family.

Για τον σχεδιασμό των κιονοκράνων χρησιμοποιήθηκαν Generic face-based models, προκειμένου να διατηρηθεί η σχετική τους θέση με τους τοίχους που αυτά βρίσκονται. Προκειμένου να σχεδιαστούν χρειάστηκε η χρήση διαφόρων solid και void στερεών με το κατάλληλο προφίλ (Εικόνα 3.33). Και επειδή παρουσίαζαν σημαντικές διαφορές ως προς τη μορφή τους, προσεγγίστηκαν παραμετρικά μόνο ως ένα βαθμό. Π.χ. όπου ήταν δυνατό δημιουργήθηκε ένα family για τις κολώνες του ενός χώρου και διαφορετικά Types για την κάθε κολώνα σε αυτό.

Ο σχεδιασμός των παραθύρων της Santa Maria είναι ένα καλό παράδειγμα παραμετρικού σχεδιασμού. Τα διάφορα Types δημιουργήθηκαν με την χρήση πολλαπλών παραμέτρων που στο σύνολό τους όριζαν το σχήμα και μέγεθος κάθε παράθυρου, όπως π.χ. το ύψος του ή η γωνία που σχηματίζει με τον τοίχο (Εικόνα 3.27 και 3.28). Έτσι μέσα στο Category Windows, δημιουργήθηκαν τα διάφορα families και types βασισμένα στη θέση τους (“presbytery right”, “presbytery left”) και στις γεωμετρικές διαφορές τους.

Στη συνέχεια σχεδιάστηκαν τα στοιχεία της οροφής, βασισμένα σε αναλύσεις των φωτογραφιών και των υποθέσεων που έγιναν από την Anna Raimondi. Τα δομικά στοιχεία της οροφής ήταν διάφορα και κάποια ήταν μοναδικά, έτσι δεν μπορούσαν να προσεγγιστούν παραμετρικά. Όλα ανήκουν στην κατηγορία του Structural Framing (Εικόνα 3.35, 3.36, 3.37 και Πίνακας 3.8) .

Στη συνέχεια δημιουργήθηκαν τα τόξα μεταξύ των θόλων μέσα στο Roof Category και ως type του Family Basic Roof. Το σχήμα τους προήλθε από τα σχέδια τομών από το νέφος σημείων του σαρωτή και τους δόθηκε το κατάλληλο πάχος. Μέσα στο ίδιο Category δημιουργήθηκαν τα families για την στέγη της εκκλησίας, του καμπαναριού και των στεγάστρων των παρεκκλησιών.

Τέλος, σχεδιάστηκαν και τα διάφορα διακοσμητικά στοιχεία της οροφής ως Generic Models καθώς και τα εσωτερικά διακοσμητικά στα παρεκκλήσια και στο βαπτιστήριο, μέσα στο Category Furniture (Εικόνα 3.41, Πίνακας 3.10).

Ιδιαίτερο ενδιαφέρον παρουσίασε ο σχεδιασμός του συστήματος των θόλων. Παρόλο που υπήρχε η πληροφορία από τον επίγειο σαρωτή, η διαχείρισή της δεν ήταν εύκολη. Αρχικά με δείγμα τον πρώτο θόλο δημιουργήθηκε μία επιφάνεια από TIN μέσα στο Geomagic Studio® και εισήχθη σαν *Mass Family* στο project του Revit®, αλλά δεν θεωρήθηκε κατάλληλη τόσο αισθητικά όσο και από το γεγονός ότι δεν μπορούσαν να του αποδοθούν υλικά κλπ.. Έτσι έγινε δοκιμή με το GreenSpider® (Κεφάλαιο 2) και με τη χρήση ισοϋψών καμπυλών από το νέφος, σχηματίστηκε από επιμέρους *Forms* δίνοντας καλύτερα αποτελέσματα αισθητικά, ενώ αποδόθηκαν και υλικά και καθορίστηκε η ιστορική φάση κατασκευής του.

Αφότου σχεδιάστηκαν όλα τα στοιχεία της εκκλησίας, έπρεπε να τους αποδοθούν και τα αντίστοιχα υλικά. Η διαδικασία αυτή μπορεί να διαχωριστεί σε δύο μέρη: πρώτα στον προσδιορισμό των υλικών για κάθε στοιχείο, μαζί με το πάχος των επιχρισμάτων όπου αυτά υπάρχουν και σε δεύτερη φάση στην απόδοση χρώματος από εικόνες για μια πιο πιστή εικονική αναπαράσταση,

Το Revit® προσφέρει μία μεγάλη ποικιλία υλικών μέσα σε μία βιβλιοθήκη (Material Browser), όπου παρατίθενται και όλα τους τα χαρακτηριστικά ως προς τα γραφικά, τη θερμική τους συμπεριφορά κ.ά.. Στην περίπτωση της Santa Maria, τα περισσότερα αντικείμενα αποτελούνταν από συνδυασμό υλικών και έπρεπε να προσδιοριστούν από τον χρήστη (Εικόνα 3.44). Όσον αφορά στο χρώμα και την υφή, το Revit® δεν δέχεται obj αρχεία, δηλαδή μοντέλα με χρώμα, επομένως έγινε χρήση επιμέρους τμημάτων των φωτογραφιών για τη δημιουργία των κατάλληλων υφών (pattern). Το τελικό αποτέλεσμα φαίνεται στην παρακάτω εικόνα (Εικόνα 3.45).

Τέλος, προκειμένου να αξιοποιηθούν όσο το δυνατόν περισσότερο τα εργαλεία που προσφέρει το BIM, δημιουργήθηκε ένα μοντέλο BIM όπου κάθε στοιχείο του έχει αντιστοιχηθεί στην φάση κατασκευής του (Phasing). Για να επιτευχθεί αυτό ορίστηκε μία επιπλέον παράμετρος στις παραμέτρους του project με το όνομα “history” και αντιστοιχήθηκε με όλες τις κατηγορίες που σχεδιάστηκαν. Για κάθε τιμή που αυτή παίρνει, δηλαδή για καθεμία από τις πέντε «γενικευμένες» φάσεις που ορίστηκαν (XV με XIX αιώνας), ορίστηκε διαφορετικό φίλτρο που παρουσιάζεται με διαφορετικό χρώμα. Προέκυψε δηλαδή ένα μοντέλο που κάθε στοιχείο του ανήκει σε μία φάση και απεικονίζεται με το χρώμα αυτής μέσω του φίλτρου, όπως φαίνεται και στην Εικόνα 3.49 (απόσπασμα).

IV.4. BIM και Ανάλυση Ενεργειακής Συμπεριφοράς Κτιρίων (Building Performance Analysis –BPA)

Στην παρούσα διπλωματική από όλα τα εργαλεία του BIM αποφασίστηκε να εξεταστούν οι δυνατότητές του στον τομέα της BPA για Μνημεία Πολιτιστικής Κληρονομιάς. Η BPA εφαρμόζεται συνήθως στην φάση προκαταρτικής μελέτης σχεδιασμού ενός κτιρίου, ώστε να τηρούνται οι αρχές του βιώσιμου/ αειφόρου σχεδιασμού. Η εκτίμηση όμως της ενεργειακής συμπεριφοράς ενός κτιρίου και κατ’ επέκταση το κόστος που συνοδεύει την λειτουργία του, θα μπορούσαν να αποτελέσουν σημαντικά στοιχεία για τη διαδικασία λήψης αποφάσεων και διαχείρισης και των μνημείων, όπως π.χ. για ένα μουσείο. Για την εκκλησία της Santa Maria έγινε μία προσομοίωση, καθώς δεν υπήρχε η απαραίτητη πληροφορία και ο προσδιορισμός διαφόρων παραμέτρων στηρίχτηκε σε υποθέσεις.

Σχεδιάστηκε ένα νέο μοντέλο BIM της εκκλησίας που πλέον περιλάμβανε και το γειτονικό οικοδόμημα, μία μοντέρνα κατασκευή που λειτουργεί ως γραφείο του ιερέα και για το κατηχητικό, ενώ πρόκειται αργότερα να στεγαστεί εκεί ένα μικρό μουσείο για της εκκλησίες στην κοιλάδα του Intelvi. Το νέο αυτό μοντέλο σχεδιάστηκε αρκετά απλοποιημένα, αφού για την ενεργειακή ανάλυση οι απαιτήσεις σχεδιασμού ήταν διαφορετικές και υποδεικνύονταν από το Green Building Studio® (Autodesk®), την εφαρμογή στην οποία εξήχθη το νέο μοντέλο από το Revit®.

Το Φυσικό Μοντέλο έπρεπε να σχεδιαστεί με συγκεκριμένο τρόπο ώστε να προκύψει από αυτό το ορθό Αναλυτικό Μοντέλο, κατά την μετατροπή του σε gbXML. Το gbXML είναι ένα «ανοιχτό» σχήμα που επιτρέπει τη μεταφορά των κατασκευαστικών ιδιοτήτων του μοντέλου από τα BIM λογισμικά στα εργαλεία ανάλυσης. Για να γίνει αυτό έπρεπε στο Φυσικό Μοντέλο να οριστούν τα *Rooms* και οι *Spaces,* τα οποία οριοθετούνται από τα διάφορα Levels, που περιλαμβάνουν οροφές και δάπεδα (Εικόνα 3.55-απόσπασμα). Η εν λόγω ανάλυση θα γίνει με βάση τα Spaces.

Σε καθένα από τα Spaces ορίστηκαν παράμετροι όπως ο τύπος κατασκευής που περιέχει πληροφορία για τα υλικά με τα οποία έχει κατασκευαστεί το κάθε στοιχείο, το αν ο χώρος είναι κλιματιζόμενος ή όχι, αν χρησιμοποιείται από ανθρώπους. Επίσης ορίζεται ο τύπος του κτιρίου που εδώ είναι *Religious Building* και αυτό μεταφράζεται σε ώρες λειτουργίας. Οι ιδιότητες των διαφόρων στοιχείων βασίστηκαν σε εκείνη τη φάση σε υποθέσεις μέσω παρατήρησης των εικόνων και σε συνεργασία με την αρχιτ. Anna Raimondi, καθώς δεν είχε ολοκληρωθεί ακόμα η στρωματογραφική ανάλυση της εκκλησίας. Τέλος, το μοντέλο έπρεπε να είναι προσανατολισμένο σύμφωνα με τον πραγματικό Βορρά.

Αφού σχεδιάστηκαν όλα τα απαραίτητα στοιχεία έγινε εξαγωγή του μοντέλου σε gbXML (Εικόνα 3.65).

Κατά την εισαγωγή του στο GBS® ορίστηκε η τοποθεσία της εκκλησίας και οι ώρες λειτουργίας. Μετά την ανάλυση προκύπτουν εκτεταμένες αναφορές για τα αποτελέσματα μαζί με τις αντίστοιχες υποθέσεις που έγιναν για τον προσδιορισμό τους. Ενδεικτικά αυτά τα αποτελέσματα αφορούν στις εκπομπές CO_2, στην κατανάλωση ενέργειας και στο αντίστοιχο κόστος σε ετήσιο και μηνιαίο χρονικό ορίζοντα, αλλά και σε αποτελέσματα που αφορούν στο να γίνει πιο «πράσινο» το κτίριο αν αξιοποιηθούν π.χ. φωτοβολταϊκά στοιχεία ή αιολική ενέργεια.

Συνοψίζοντας τα παραπάνω, φαίνεται πως αυτή η προσέγγιση εφαρμογής της BPA μπορεί να χρησιμοποιηθεί για προκαταρτικές εκτιμήσεις και να συνεισφέρει στην καλύτερη διαχείριση εγκαταστάσεων, ακόμα και σε περιπτώσεις μνημείων.

V. Πρώτες Εκτιμήσεις και Συμπεράσματα

Τα λογισμικά BIM έχουν αναπτυχθεί για σύγχρονες κατασκευές, επομένως παρουσιάζουν περιορισμούς όταν εφαρμόζονται στην καταγραφή και διαχείριση Μνημείων. Η πολύπλοκη γεωμετρία που αυτά παρουσιάζουν τόσο σχεδιαστικά όσο και κατασκευαστικά, απαιτεί αρκετά υψηλό επίπεδο εξοικείωσης με τα εργαλεία BIM ώστε να μην γίνει η διαδικασία σχεδιασμού προβληματική και χρονοβόρα.

Σημαντική εξέλιξη προς αυτή την κατεύθυνση θα ήταν η δημιουργία βιβλιοθηκών «έξυπνων» παραμετρικών αντικειμένων, που θα διαμοιράζονται εύκολα. Προϋπόθεση για κάτι τέτοιο εκτιμάται ότι είναι η ανάπτυξη αρχιτεκτονικών IFC, ως μία «κοινή γλώσσα» μεταξύ των διαφορετικών χρηστών.

Συμπληρωματικά στα παραπάνω αναφέρεται ότι η χρήση απλοποιημένων επιφανειών από το Revit® λειτουργεί ανασταλτικά. Όπως επιβεβαιώθηκε μέσα από αυτή την διπλωματική εργασία, μπορεί να αποδοθεί μόνο απλή υφή μέσω χρωμάτων ή έτοιμων μοτίβων που έχει το πρόγραμμα, ενώ δεν μπόρεσαν να αξιοποιηθούν δεδομένα όπως το ορθοφωτομωσαϊκό ή το μοντέλο υφής, προϊόντα που συναντώνται συχνά στην καταγραφή και τεκμηρίωση της Πολιτιστική Κληρονομιάς.

Ένα ακόμα σημείο προς διερεύνηση είναι η ουσιαστική αξιοποίηση του νέφους σημείων μέσα στο ίδιο το πρόγραμμα με καλύτερες προδιαγραφές για πιστότητα, καθώς τα Μνημεία είναι ένα θέμα ευαίσθητο. Για την Santa Maria τα γεωμετρικά δεδομένα προήλθαν από τα σχέδια που έγιναν στο AutoCAD® με το Cloudworx®.

Σε αυτό το σημείο πρέπει να επισημανθεί ότι οι παραπάνω επισημάνσεις αφορούν στο Revit® 2013, καθώς μόνο αυτό χρησιμοποιήθηκε. Επομένως, σημαντικός παράγοντας είναι και η ίδια η επιλογή του λογισμικού και η καταλληλότητα του καθενός για τέτοιου είδους project.

Τέλος, αξίζει να σχολιαστεί ο ρόλος του Τοπογράφου Μηχανικού και Μηχανικού Γεωπληροφορικής σε εργασίες καταγραφής και διαχείρισης Πολιτιστικής Κληρονομιάς με την βοήθεια του BIM. Αν και υστερεί σε γνώσεις Αρχιτεκτονικής και τρισδιάστατου σχεδιασμού, με την κατάλληλη βοήθεια και προσωπική προσπάθεια μπορεί να ανταπεξέλθει επάξια στις απαιτήσεις αυτών των εργασιών. Ούτως η άλλως, λόγω ειδικότητας έχει καλή αντίληψη του χώρου και μπορεί να διαχειριστεί και να αξιοποιήσει ορθά το πλήθος των ετερογενών δεδομένων. Έτσι μπορεί να αποτελέσει σημαντικό μέλος μίας διεπιστημονικής ομάδας που έχει στόχο την ουσιαστική ανάγνωση και διαχείριση των Μνημείων.

INTRODUCTION

The 3D digital construction and documentation of existing heritage buildings is a complex undertaking that typically involves a hybrid approach to visualization of heterogeneous datasets such as survey data, CAD drawings, photographs, and 3D non-contact imaging data, such as e.g. laser scanning, photogrammetry etc. (El-Hakim et al. 2005; Remondino et al 2009).

During the past decade, a growing number of research projects have provided a wide range of workflows, from the digital acquisition of buildings to the display of high-fidelity 3D models and animations. High visual fidelity, metric accuracy, and the integration of multiple media types have been the primary consideration in heritage documentation. In recent years, however, heritage documentation has taken a turn towards intelligent data, as it pertains to the cultural analysis and maintenance of existing buildings (Pauwels et al. 2008; Attar et al. 2010).

As Fai et al. (2012) argue Building Information Modeling's (BIM) recognition has played an important role in this turn, as a technology that addresses the growing demand for a multi-disciplinary knowledge base essential to the management of life-cycle processes such as operation, renewal and development of the growing inventory of heritage sites. In addition, there is a growing recognition in the potential for BIM to contribute to the collation of the complex relationships between tangible and intangible heritage.

Main purpose of this diploma thesis is the development of a BIM model for the Catholic Church of Santa Maria (Scaria, Italy), while researching its capabilities in the field of built Cultural Heritage. For this to be done, the cooperation of an interdisciplinary group was necessary, as well as the knowledge of the architectural elements of the church.

In the following chapters the whole procedure is described, from data collection through the geodetic and the photogrammetric survey until the final results (orthophotos, BIM model), along with the first specifications and conclusions derived from it.

More specifically, the *first chapter* is an introduction for the reader to what BIM is, by presenting definitions as well as some critical aspects of it that are under constant research, like interoperability, and its evolution until today. Some advantages and disadvantages of it are also presented, which at the same time define its functionality, capabilities and limitations.

In the *second chapter*, a brief overview of BIM in modern AEC industry is made and then follows the case studies that constitute characteristic examples of the research undertaken in the field of BIM's contribution in projects related to Cultural Heritage.

The *third chapter* refers to the case study of Santa Maria's church. Firstly, there is a brief reference to the village of Scaria and the church's history. Then, the geodetic and photogrammetric part of this thesis is presented – the survey, the data processing and the final results. The rest of the chapter is about the development of the architectural BIM model with Revit® 2013, the more simplified one (also with Revit®) and its energy analysis with Green Building Studio® (GBS), the decisions that had to be taken through the design process and the final results.

Finally, in the *fourth chapter*, the first specifications and conclusions of BIM's value in Cultural Heritage projects are presented, as derived from the case study of this diploma thesis.

1. BUILDING INFORMATION MODELING (BIM)

1.1 Introduction

The buzzword BIM- Building Information Modeling appears more and more often in articles and conferences the last years. It is also true that it is gaining the attention of organizations involved in the Architecture -Engineering- Construction (AEC) industry, as well as the owners and operators. The vast evolution in the usage of Information and Communication Technology (ICT) for describing and managing construction projects led to the elaboration of BIM for describing buildings and building information according to their different composing elements.

Goal of this chapter is mainly to familiarize the reader with the BIM concept. Firstly, includes a basic conceptual background with definitions of it and also other concepts that are strictly connected with, like *Life Cycle Management* (LCM) and *interoperability.* In addition to that, after a brief historical retrospective of how the AEC industry moved towards BIM, some advantages and disadvantages of BIM are highlighted. At that point special reference to its role in Cultural Heritage documentation and management is made, as the aim of this diploma thesis is to explore the capabilities and limitations of BIM in that field.

1.2 Definition of BIM

Put simply, a Building Information Model (BIM) is a 3D representation of a facility that apart from its geometry and the spatial relations of its parts, contains the properties and qualities that characterize all individual elements (walls, columns, stairs etc). This includes material (wood, concrete, metal etc), their function (structural, architectural etc) and their behavior. In other words it constitutes a way of object-oriented parametric designing of facilities, which subsequently leads to an improved decision making process during the life cycle of the facility , adding new parameters like cost estimation and energy efficiency and making the BIM (the product) in reality a n-dimensional model.

In the following sections some formal definitions of BIM are quoted for the reader to be able to form as complete an idea as possible for this new ICT tool.

The USA NBIM Standard Project Committee defines Building Information Modeling as *a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition* (NBIM US Committee, 2007).

According to Eastman et al. (2008) *Building Information Modeling is one of the most promising developments in Architecture, Engineering and Construction (AEC) industries. BIM simulates the construction project in a virtual environment. With BIM technology, an* ***accurate virtual model*** *of a building is digitally constructed. When completed, the computer-generated model contains precise geometry and relevant data needed to support the construction, fabrication and procurement activities required to realize the building*.

Additionally, *a Building Information Model is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and to improve the process of delivering the facility* (Associated General Contractors US-AGC, 2005).

But in order to understand better the value of BIM and how it has changed (and is still changing) the AEC industry, some other concepts like *integrated project delivery (IPD)*, *interoperability* and *building life-cycle management (BLM)* need to be presented:

Integrated project delivery (IPD), *is a collaborative alliance of people, systems, business structures and practices into a process that harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction* (American Institute of Architects, 2007).

It is a fact that the AEC industry is highly fragmented and hence integrated ways of working have always been a vital need for the industry. The Integrated Project Delivery (IPD) approach reflects the perspective on the future of project life-cycle management and project delivery. BIM has emerged as an essential tool for achieving the high level of collaboration that IPD encourages. The integration of IPD principles and BIM tools results in a more effective way of design and construction, reducing also the time needed. From an Integrated Project perspective BIM can be defined as:

"the information management process throughout the lifecycle of a building (from conception to demolition) which mainly focuses on enabling and facilitating the integrated way of project flow and delivery, by the collaborative use of semantically rich 3D digital building models in all stages of the project and building lifecycle"(Eastman at al., 2008)

Although BIM is the key enabler of the IPD process, BIM goes beyond the management of information in the IPD process: IPD concludes with the closeout stage following construction, while the BIM process continues even beyond the demolition (disposition) stage, i.e. as a process of knowledge management providing input to future projects.

Another important aspect of BIM is the level of *interoperability* that offers. Architecture, engineering and construction are three highly collaborative activities, so they require tools which enable the unhindered exchange of data between different professions and applications. James A. O'Brien and George M. Marakas define interoperability as *being able to accomplish end-user applications using different types of computer systems, operating systems, and application software, interconnected by different types of local and wide area networks.*

So, with simple words it is the ability of two or more systems or components to exchange information and to use the exchanged information. This is the crucial concept in the BIM process as interoperability is the essential requirement to allow a larger number of projects to be developed with an effective BIM methodology instead of a simplified object-based model using basically during the design stage. (Ossello, 2012)

There are three different levels of interoperability:

- interoperability between software from the same vendor, like embedding a Microsoft Excel spread sheet into a Microsoft Word document; or as far as BIM is concerned, working with models of different versions of Autodesk Revit
- interoperability between software from different vendors; for example the design of a building could be realized in ArchiCAD, but the specification could be completed with 'NBS create' plug-in
- interoperability through open data standards; the two well established data standards for transferring data are IFC (Industry Foundation Classes) and gbXML (Green Building XML), which are further analyzed in this chapter and in chapter 3.

The transition from paper-based exchange of design models to processes based around the use of digital models represents an important shift in the design and construction industry. Using digital models opens the possibility of automating a number of the analyses done during design, with important positive consequences for the speed and efficiency of the design process, and for the quality of the resulting designs. In an industry so heavily dependent on collaboration, challenges of interoperability must be addressed in order to maximize these benefits (Steel et al., 2009).

Until 1999 computer software for building design, analysis and maintenance could not usually exchange data, even when the same team used them. Buildings took more time to be designed and built; they were more expensive to construct and to operate. Hence the need for software environment in which computer programs could easily exchange data automatically, regardless of software and data collection, was compelling. Towards that goal the International Alliance for Interoperability (IAI) proposed a standard that specifies object representations for AEC products, the IFC.

The IFC data model is intended to describe building and construction industry data. It is a neutral and open specification that is not controlled by a single vendor or group of vendors. It is an object-based file format with a data model to facilitate interoperability in the AEC industry and is a commonly used format for BIM. The IFC model specification is open and available. (American Institute of Architects California Council, 2007, Lean Construction Institute Nov. 18, 2004). It is registered by ISO as ISO/PAS 16739 and is currently in the process of becoming the official ISO 16739.

In order for a real free flow of information to take place besides the exchange data format (IFC), a specification is also needed concerning which information to exchange and when (Information Delivery Manual-IDM) and a standardized understanding of what the information that is exchanged actually is (International Framework for Dictionaries –IFD).

The IFCs allow various data to be exchanged in various ways. If a receiver of information wants to be sure that he can utilize the information he receives, the sender and receiver need to agree on exactly which information to exchange. The Information Delivery Manual (IDM) specifies exactly which information is to be exchanged in each exchange scenario, while IFD is, in simple terms, a standard for terminology libraries or ontologies; it describes the objects i.e. their parts, properties, units etc. (BuildingSmart, 2007).

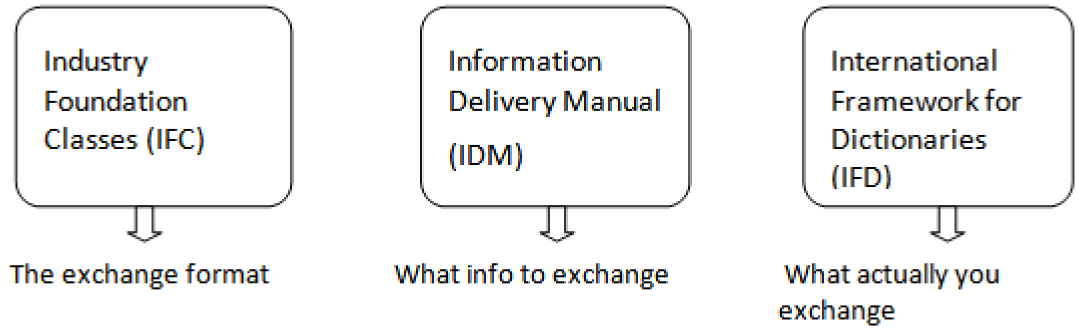


Figure 1.1.1: A schematic representation of IFC, IDM and IFD.

The multi-role of BIM in AEC industry includes also the use of it during the construction phase and for post-construction phases and facility management, going beyond the planning and designing phase of the whole project. Building lifecycle management is *the adaptation of product lifecycle management (PLM)-like techniques to the design, construction, and management of buildings*. Building lifecycle management requires accurate and extensive building information modeling.

During the building process the participants are constantly challenged to deliver successful projects despite tight budgets, limited manpower, accelerated schedules, and limited or conflicting information. The BIM concept envisages virtual construction of a facility prior to its actual physical construction, in order to reduce uncertainty, improve safety, work out problems, and simulate and analyze potential impacts. Sub-contractors from every trade can input critical information into the model before beginning construction, with opportunities to pre-fabricate or pre-assemble some systems off-site. Waste can be minimized on-site and products delivered on a just-in-time basis rather than being stock-piled on-site (Smith, 2007).

Moreover, BIM can bridge the information loss associated with handing a project from design team, to construction team and to building owner/operator, by allowing each group to add to and reference back to all information they acquire during their period of contribution to the BIM model. Dynamic information about the building, such as sensor measurements and control signals from the building systems, can also be incorporated within BIM to support analysis of building operation and maintenance (Liu, et al., 2009).

1.3 Evolution of BIM

This section is mainly based on the article "BIM history", by Bergin, M.. (http://www.architectureresearchlab.com/arl/2011/08/21/bim-history/)

The beginnings

In early years the AEC industry relied on drawings to represent all the necessary data for the design and construction of each artifact. Over the years, as the needs of representation were changing and becoming more complex, the 2D and 3D drawings evolved too, in order to assist the designer: many technological achievements have been realized during the last 50 years in computer science and the present era is characterized by the transition towards the use of highly structured 3D models that are seriously changing the role of drawing in the AEC industry.

The term BIM, which may also be found under different names like *virtual building, product model* and *intelligent object model*, has been developed only in the last 20 years, so it is impossible to understand its history without starting much earlier.

The conceptual underpinnings of the BIM go back to the earliest days of computing, as early as 1962: Douglas C. Englebart in his paper *Augmenting Human Intellect* suggests object based design, parametric manipulation and a relational database; dreams that would become a reality several years later.

"The architect next begins to enter a series of specifications and data–a six-inch slab floor, twelve-inch concrete walls eight feet high within the excavation, and so on. When he has finished, the revised scene appears on the screen. A structure is taking shape. He examines it, adjusts it… These lists grow into an ever more-detailed, interlinked structure, which represents the maturing thought behind the actual design."

There is a long list of design researchers whose influence is considerable including Ian McHarg (who developed a parallel track with GIS) and Christopher Alexander (who influenced an early school of object oriented programming), but as thoughtful these systems may have been, they could not become a reality without the appropriate graphical interface for the user to interact with such a Building Model.

Visualizing the Model

Ivan Sutherland's Sketchpad® program (1963) and SAGE graphical interface were the basis for solid modeling software, which refer to easy creation and editing of solid shapes and were separately developed at Cambridge University, Stanford and the University of Rochester since 1973. The two main methods of displaying and recording shape information that began to appear in the 1970s and 1980s were Constructive Solid Geometry (CSG) and Boundary Representation(B-Rep). The CSG system defines each geometry as a volumetric system, by using Boolean operations. On the other hand, B-Rep shapes are represented using the limits: a solid is represented as a collection of connected surface elements, the boundary between solid and non-solid.

Another milestone in this brief history between the late 1970s and the early 1980s is that CAD systems were developed and among their basic functions and they adopted the 3D solid modeling by allowing the creation of building models. The aerospace and manufacturing companies recognized the potential and started collaborating with software companies in order to implement the systems, despite the high cost and the fact that some aspects of production were not already fully developed. Meanwhile, the AEC industry did not see those capabilities, but adopted architectural drawing editors, such as AutoCAD® and Microstation®, moving towards the digital representation of conventional 2D drawings. This transition of course improved the designing progress, but focused only on that and not on the whole process of construction.

Database Building Design

The first attempt to handle buildings from the perspective of a database was made by Charles Eastman with the project Building Description System (BDS) (Eastman, 1979). It was the first software to describe individual library elements which can be retrieved and added to a model. This software used a graphical user interface, orthographic and perspective views and a sortable database that allowed the user to retrieve information categorically by attributes including material type and supplier. BDS was an experiment that would identify some of the most fundamental problems to be tackled in architectural design over the next fifty years. Eastman's next project, GLIDE (Graphical Language for Interactive Design) created in 1977 at CMU, exhibited most of the characteristics of a modern BIM platform.

A lot of systems were developed during that time (early 1980s) and gained attraction but the founding of the Center for Integrated Facility Engineering (CIFE) at Stanford in 1988 by Paul Teicholz marks another landmark in the development of BIM as this created a wellspring of PhD students and industry collaborations to further the development of 'four-dimensional' building models with time attributes for construction. This marks an important point where two trends in the development of BIM technology would split and develop over the next two decades: On one side it was the development of specialized tools for multiple disciplines to serve the construction industry and improve efficiency in construction. On the other side was the treatment of the BIM model as a prototype that could be tested and simulated against performance criteria.

Virtual Building

While the developments were happening rapidly in the United States, the former Soviet Union had two programming geniuses who would end up defining the BIM market as it is known today. Leonid Raiz and Gábor Bojár would go on to be the respective co-founder and founder of Revit® and ArchiCAD®. Using similar technology as the Building Description System, the software Radar CH was released in 1984 for the Apple Lisa Operating System. This later became ArchiCAD®, which makes ArchiCAD® the first BIM software that was made available on a personal computer.

ArchiCAD® was considered to be revolutionary software as for the first time architects and engineers were able to store large amounts of data within the 3D building model, such as the building geometry and spatial data, as well as all the properties and quantities of the components that the building consisted of.

Not long after Graphisoft® began to sell the first installations of Radar CH, Parametric Technology Corporation (PTC) was founded in 1985 and released the first version of Pro/ENGINEER® in 1988. This is a mechanical CAD program that utilizes a constraint based parametric modeling engine. Equipped with the knowledge of working on Pro/ENGINEER®, Irwin Jungreis and Leonid Raiz split from PTC and started their own software company called Charles River Software in Cambridge. The two wanted to create an architectural version of the software that could handle more complex projects than ArchiCAD®. By 2000 the company had developed 'Revit', which was written in C++ and used a parametric change engine, made possible through object oriented programming. In 2002, Autodesk® purchased the company and began to heavily promote the software in competition with its own object-based software 'Architectural Desktop®'.

Revit® revolutionized the world of Building Information Modeling by creating a platform that utilized a visual programming environment for creating parametric families and allowing for a time attribute to be added to a component to allow a 'fourth-dimension' of time to be associated with the building model. This enables contractors to generate construction schedules based on the BIM models and simulate the construction process.

Towards a Collaborative Architecture

The use of a big variety of programs by architects and engineers makes the collaboration between them difficult. Different file formats contribute to loss of fidelity as they move across platforms, especially in BIM models as the different objects are modeled and stored in an object-oriented structure, using several proprietary file formats. To overcome the problem of interoperability in order to achieve further simulation, evaluation and analysis, the International Foundation Class (IFC) file format was developed in 1995 by buildingSMART® (International Alliance for Interoperability, IAI) and has continued to adapt to allow the exchange of data from one BIM program to another. This IFC file format is created as a highly interoperable information structure, which tries to guarantee that the information in this IFC format can be browsed and queried on an object-oriented and semantically rich basis.

Summarizing all the above, it is clear that huge progress has been made since the first approach of the conceptual background of BIM (Figure 1.2). Nowadays, the BIM buzzword is really popular, but the AEC industry has only begun to understand the potential and the benefits of BIM models.

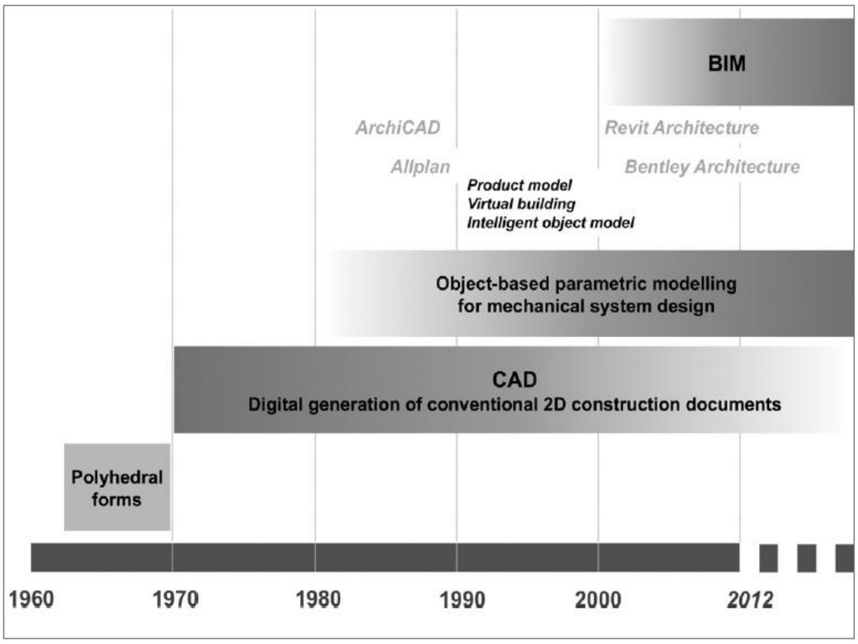


Figure 1.2: A schematic representation of BIM's evolution (Osello, 2012).

1.4 Advantages and Disadvantages

BIM is rapidly gaining acceptance as it is a new approach of working and managing information of buildings with many advantages, both for the design teams and the clients.

First of all, the models that BIM offers are a direct 3D visualization of what is designed or constructed, so it makes it easier for the users to understand space, especially for those who are not professionals but just users. It is true that the masses in general are always looking for something tangible and clear to see and a 3D model is probably the best way to achieve that.

But the visualization capabilities of BIM do not stop to the 3D model. The contemporary BIM platforms give the opportunity to extract independent 2D and 3D views, like sections, plans, elevations and easily jump from 2D to 3D and vice versa. In addition these drawings are not just graphical entities like e.g. lines, arcs etc., but contain smart objects defined in terms of building elements and systems (walls, columns, beams) combined with non- graphical information like specifications and schedules.

Another big advantage of BIM is that all the views (which in reality are different drawings) are completely coordinated: every change that is made in any element in any view is automatically done to all the other views, as all the information comes from the same file. This reduces tremendously the time needed to edit and manage the project, while at the same time diminishes the errors of correspondence of floor plans, sections and perspective.

This up-to-date data-rich model does not only minimize the error during input of information, but in general is a better overall solution for project teams, as different members of it can use it simultaneously in contrast with the traditional 2D workflow. In this way coordination and speed of workflow are improved, while team trust, efficiency and productivity increase.

Last but not least it should be mentioned that these models can be used to demonstrate the entire building life-cycle (Bazjanac, 2006). They contain material inventories, requirements, design, construction and operational information for making also cost estimates and project schedules. For example if repairs or upgrades are contemplated, the model can be used to analyze their compatibility and cost-effectiveness as well as provide visual representations of any improvements or major changes. Hence, they become shared knowledge resources to support decision-making about a facility from earliest conceptual stages, through design and construction, its operational life and eventually its demolition.

On the other hand, BIM has some disadvantages too. Its inherited data-richness creates really big files that need to be managed from a big number of collaborators as well. As the AEC industry has just made the first steps towards the BIM adoption from CAD-based logic, the shift in fundamental data management is really essential. Furthermore, as it is a new technology and the data sharing involves different professions with different backgrounds, any 'weak link' of the team could endanger the whole project. The fact that BIM systems are a new state of the art means also that their implementation requires - besides training- software and hardware upgrades, which are costly and it takes a lot of time to implement them into an existing process.

Since every product from a BIM procedure is extracted from the model, any mistake in the initial design is reflected in all the other drawings too, making it more difficult to be detected. Any small miscalculation could lead to bigger problems that would be costly.

As Gerald and Jordan (2007) aptly mention *if and to the extent that design documents are intellectual property that are capable of copyright, BIM raises issues of ownership* (U.S.C.

federal copyright law § 101). *BIM models can (on some projects) be opened and edited by other parties and used by other parties to derive new models, both of which can blur a model's ownership. As other commentators have noted, intellectual property issues related to design documents are not unique to BIM, but the importance of the issues is heightened because of the potential value of BIM models (Larson and Golden, 2010).The GSA solves this problem by designating BIM models as project deliverables and vesting ownership in the owner (GSA guide, 2005). American Institute of Architects' (AIA) documents and other standardized contracts typically lag behind real-world developments as contract drafters wait to incorporate emerging business patterns and practices into standard-form contracts. This is true with BIM, as new standard-form contract documents are emerging, including those that allocate the ownership of and the right to use BIM models (AIA, 2008). Nevertheless, parties should be aware of the intellectual property issues presented by the use of BIM.*

Though BIM has its disadvantages, it has also the potential to become the leading technology of the AEC industry. Looking towards the future, the more BIM systems are used, the more the users will master this new way of working. Hence, the adoption of BIM will be only but beneficial for all the stakeholders of the projects.

Although the adoption of BIM in Cultural Heritage management is still a field under research, it has already shown some quite beneficial aspects. Since one of its most important features is parametric modeling, BIM design process may help to significantly lighten the load of future work, as new and alternative forms can be easily reproduced or modified just by changing the parameters, while also libraries of these objects may be created.

Moreover, the different plug-ins that support several exports (IFC, external DB link, gbXML, Google Earth®, Rhino® etc) facilitate the integration of BIM software with other, towards a more complete result. For example a BIM model could be connected with an external database containing manuscripts or images, meaning that heterogeneous data collected could be interrelated. But, "full" interoperability for now exists only in theory and it is a crucial aspect of BIM that is under research by many experts. The data exchanged by the different software may differ in quantity, quality or in how they are exchanged. An example for that is mentioned by Murphy (2012): in order for a BIM model to be imported in CityGML, it firstly needs to be converted by Google® SketchUp®; the geometry is automatically converted but semantic information could be lost if not assigned in an appropriate layer.

Last but not least it should be mentioned that BIM models are 3D models that also contain information about the materials or the construction methods and phases; information that is usually essential for the professionals that are involved with Cultural Heritage management and conservation. BIM software has been developed mainly for modern constructions, a fact that often makes the design process of complex elements problematic and time consuming, as most of them need to be modeled from scratch and sometimes even with ways that may undermine the projects' reliability.

This theoretical evaluation of BIM' s role in AEC industry and in Cultural Heritage is tested and confirmed by the case study of this diploma thesis

2. STATE OF THE ART OF BIM

2.1 Introduction

It has recently been noticed that several changes within the domain of architectural design have been strongly affected by information and communication technologies (ICT). The transition from CAD to BIM in AEC industry is already underway (Eastman et al., 2007), while, at the same time, the documentation and management of architectural heritage has barely benefited from this technological innovation (Gaiani, 1999). The applications of BIM in new projects prove that BIM is not only a powerful modeling tool, but also provides inherent semantic data pertaining to structural, material and operational information (Gaiani., 2007). Therefore BIM is expected to be a central database supporting comprehensive data input for life-cycle management and, where multiple data are collected, stored and retrieved for various motivations (Apollonio et al., 2012).

"Modern BIM design tools […] define objects parametrically. That is, the objects are defined as parameters and relations to other objects, so that if an object changes, the related one will also change accordingly. Parametric objects automatically re-build themselves according to the rules embedded in them. The rules may be simple, requiring a window to be wholly within a wall, and moving the window with the wall, or complex defining size ranges, and detailing, such as the physical connection between a steel beam and column" (Eastman, 2009). From these characteristics it is clear that classical building composition and construction and parametric BIM are closely linked and BIM will be an excellent technique to build knowledge-based architectural system (Apollonio et al., 2012).

The main purpose of this chapter is to give a first overview of the role of BIM by given examples of BIM implementation in Cultural Heritage documentation. They differ in the methodology they propose due to the variance of their specific object of research. Nevertheless, all of them aim to the evaluation of BIM's role in facilitating the documentation and conservation process of Cultural Heritage monuments and to trigger further research, which is also the last part of this chapter.

2.2 Overview of BIM Implementation in Modern Construction Projects

As it has been mentioned previously, BIM gains the interest of the AEC industry with more companies every day to adopt it in their workflow. What BIM offers has been described in Chapter 1, so these paragraphs aim to present how BIM is used in practice with some examples from Revit®-made projects (which is also the software used for this diploma thesis).

The construction of a building is a multidisciplinary procedure and requires the cooperation of different parties: architects, civil engineers and MEP engineers join forces to obtain the final result. All of them are able to work simultaneously, each one to the field they subject while they are being informed of what the other parties do.

So, BIM is a "multitasking tool". More specifically in BIM software is possible to design the elements (architecture feature), to define and visualize the structural reinforcement and the analytical model of the structure (civil engineering), to design the MEP systems (MEP engineering), to control the fabrication of the project and finally have projects with enhanced visualization (renderings etc.). In the following pictures some examples of BIM models built in Revit® can be seen (see Appendix, p.117 for color images).

Figure 2.1: Architectural Design in Revit®.

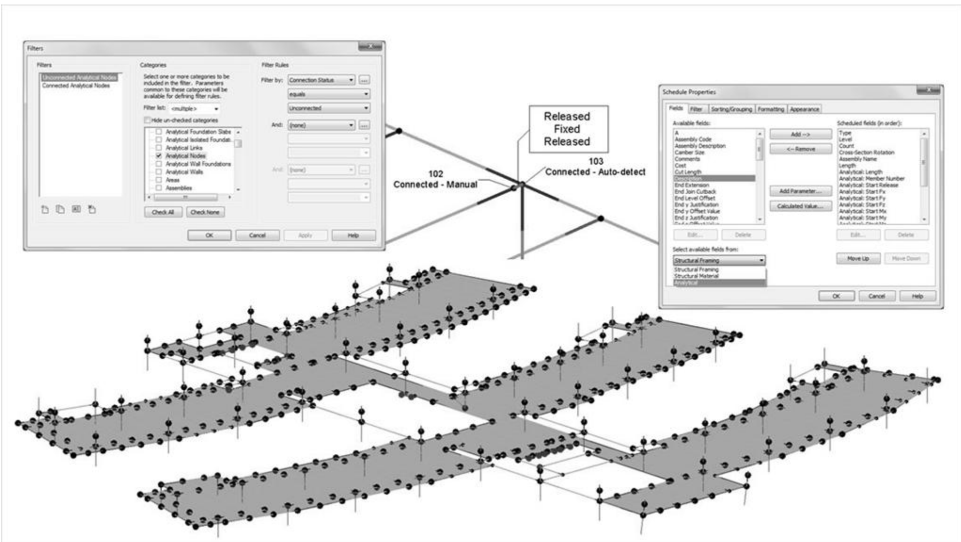


Figure 2.2: Example of an analytical model.

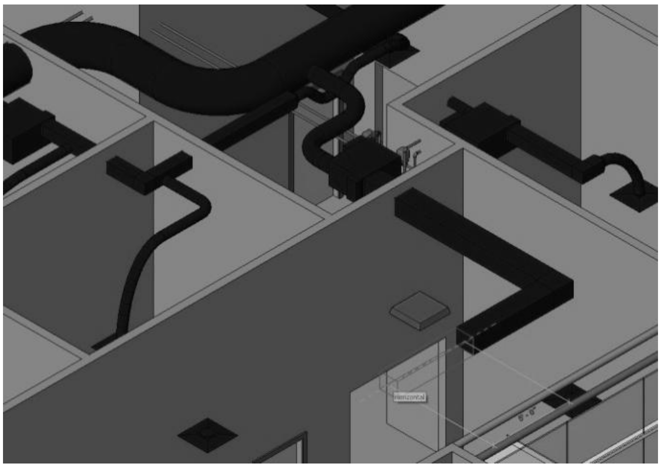


Figure 2.3: Part of a MEP system.

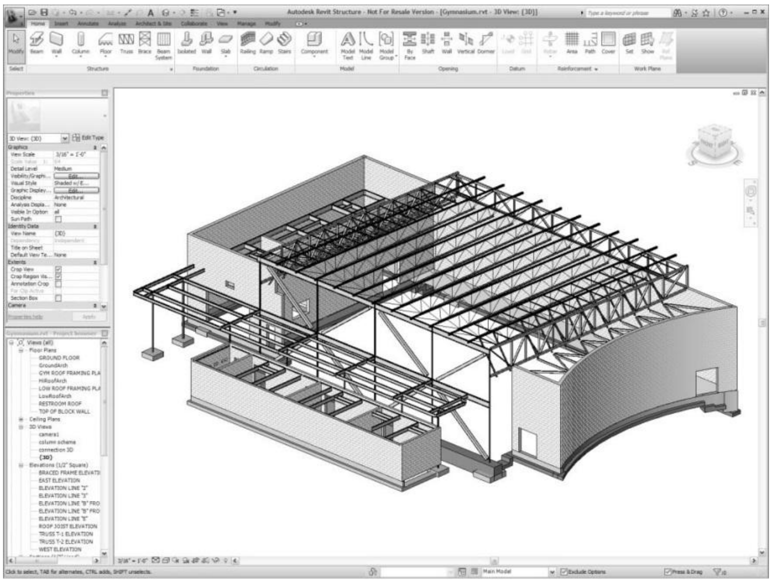


Figure 2.4: Modeling with multiple materials.

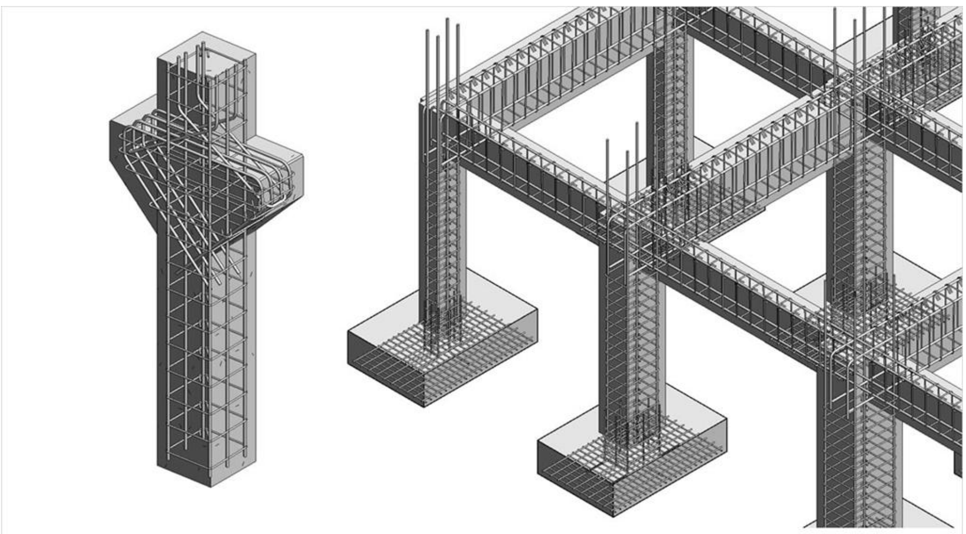


Figure 2.5: Overview of concrete's reinforcement in Revit®.

Finally it should be mentioned that most BIM software has the ability to connect with other applications, usually cloud-based, for further analysis of the structure or the building's behavior from the point of energy, giving in this way a full solution of conceptual design and LCM.

2.3 Case Studies of BIM Implementation in Cultural Heritage

Despite a trend to adopt BIM for the design and life-cycle management of new and modern buildings, very little research has been undertaken to explore the value of BIM in the documentation and management of heritage buildings and cultural landscapes (Fai et al., 2012).

One of the most common aspects of research found in the relevant literature is finding a way to automate the design of complex architectural elements, while also applying to them both quantitative assets (intelligent objects, performance data) and qualitative assets (historic photographs, oral histories, music etc).

One characteristic example of integration of contemporary technology and BIM approach in the field of Cultural Heritage documentation is the Historic Building Information Modeling (HBIM), developed by Murphy et al. (2009, 2011). It functions as plug-in for BIM and it is a novel prototype library of parametric objects built from historic data and a system for mapping the parametric objects onto a point cloud and image survey data. The proposed methodology for HBIM is described by the following steps:

- collection and processing of laser/image survey data
- identifying historic detail from architectural pattern
- production of parametric historic components/objects
- correlation and mapping of those objects onto the data acquired from the laser scanning process
- final production of engineering survey drawings

The final product is a full 3D model of the object that also provides information about its construction method and material make-up. Moreover, HBIM contributes significantly to the conservation of historic buildings and environments, as it produces automatically complete engineering drawings for that purpose (3D documentation orthographic projections, sections, details and schedules for energy, cost etc.), adding in this way intelligence to image based and laser scanning surveys.

Considering the plotting of parametric objects onto laser and image-based surveys within HBIM, the library of parametric objects is designed as a plug-in for existing modeling platforms with the addition of a set of procedures and a framework for mapping these objects. The point cloud is segmented in order to provide floor plans, elevations and sections as a map for the library objects (Figure 2.1).

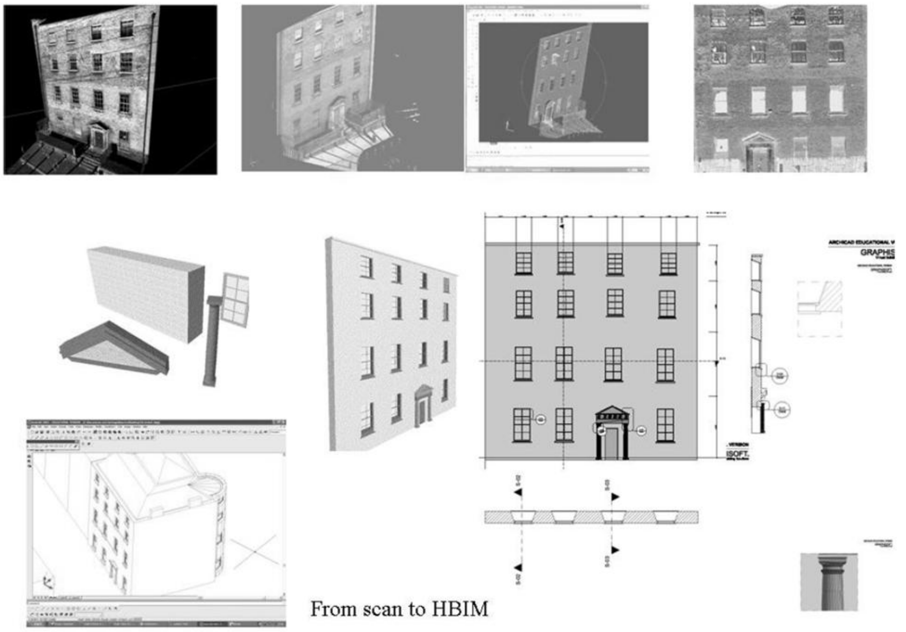


Figure 2.6: Mapping parametric objects into survey data- automated engineering drawings.

The design of the parametric architectural elements is based on the manuscripts ranging from Vitruvius and Palladio to the architectural books of the 18th century. The renaissance architects formulated scientific rules for the production of architectural elements, which support the design of the parametric elements. The historic data provide also the detail behind the object's surface that refers to the methods of construction and material make-up.

For the design and construction of a parametric library of objects the BIM platform ArchiCAD® (Graphisoft®) was used together with the open script based language which is embedded in it, the Geometric Descriptive Language (GDL). The scripting in GDL allows for sharing and editing of the parametric objects at different levels, which are specifically constructed for one or many uses and carry the required parametric information for the object's function. The case study refers to documentation of Henrietta Street in Dublin.

Objects are scripted with parameters making them dynamic objects that can be reused. A bottom-up approach is adopted, which starts with the smallest building objects such as ornamental mouldings and profiles. These uniform objects are created from a shape vocabulary of 2D shapes and rules that allow for all configurations of the classical orders (Figure 2.7). These shapes are stored as individual parametric objects or combined to make larger objects such as columns, pediments, walls, windows or roofs.

The library objects along with the plotted survey products were imported to ArchiCAD®, making the complete HBIM model (Figure 2.8). Walls were extruded from the floor plan and the objects' parameters were defined from the survey data.

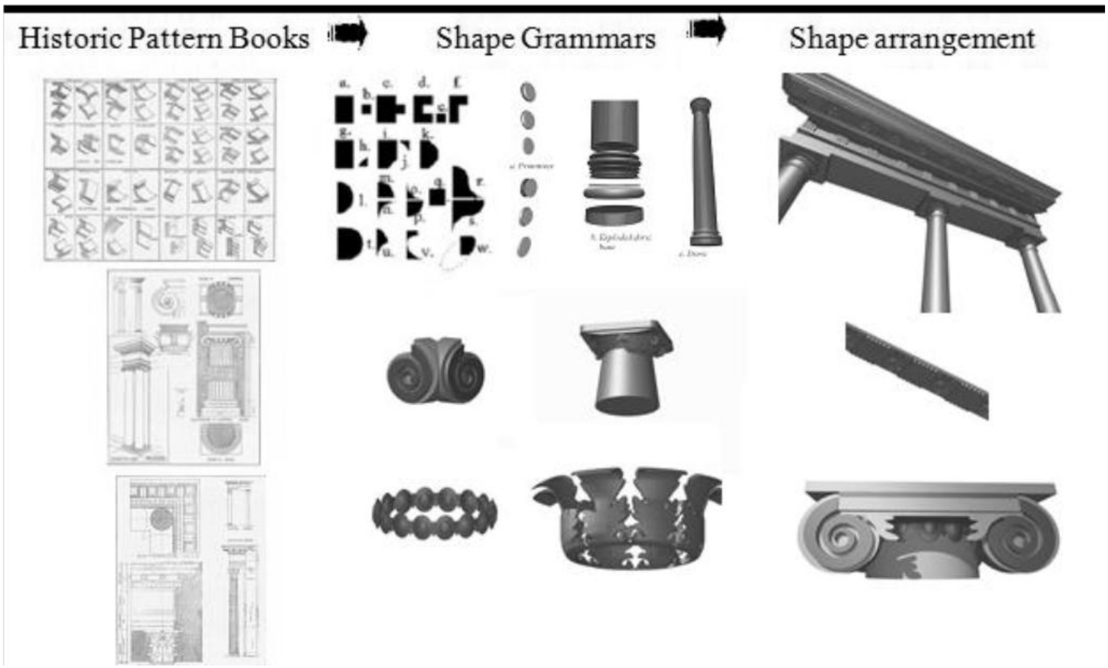


Figure 2.7: Historic data and shape grammars for classical orders.

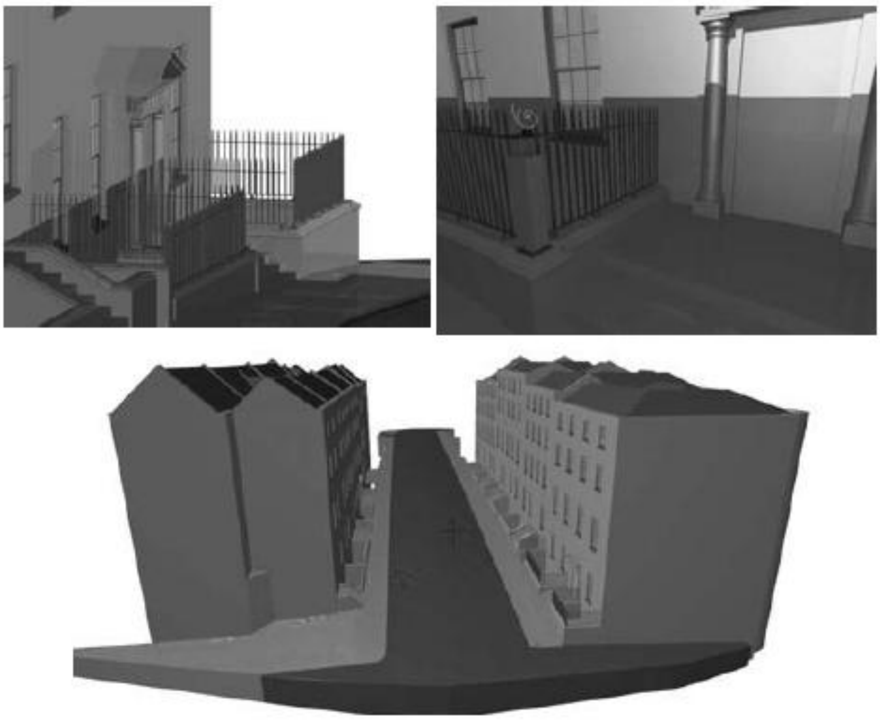


Figure 2.8: The final HBIM model.

The final step for this case study was the conversion of the HBIM model into CityGML for further analysis and management, while giving special care to integration between BIM and 3D GIS applications. CityGML is and open standard 3D data format, with a detailed semantic framework, more focused on city modeling. The HBIM model was imported into Google® SketchUp® were geometry and semantic classes were converted for CityGML (Figure 2.9, see Appendix-p. 118 for the color image). Missing attributes due to the different level of semantics were added manually by Murphy et al. (2012), while the model can be imported into several GIS platforms for further analysis on geometry, semantics, external references and topology.

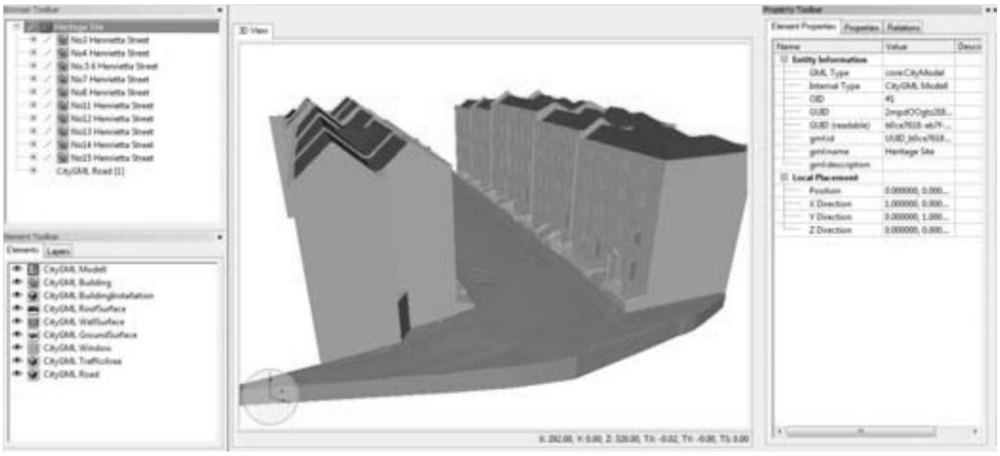


Figure 2.9: CityGML model showing semantic classes.

In the research area of BIM implementation in Cultural Heritage management, Pieter Pauwels (Pauwels et al., 2008) has proposed an expanded approach to BIM through the development of Architectural Information Modeling (AIM). AIM is quite similar to the so called procedural modeling, that has been a point of interest in the recent years in Cultural Heritage research. It is a grammar-based procedural method already used in several application domains, such as urban modeling (Parish and Müller, 2001) and modeling for virtual heritage application (Müller et al., 2006), but further reference to that technique is not an objective of this thesis.

The methodology of AIM is demonstrated through the case study of the *Casino* in Ghent (Boydens, 1986). A BIM model of the casino has been made with Autodesk Revit® Architecture 2008 as seen in Figure 2.10 (see Appendix-p. 118 for the color image)..

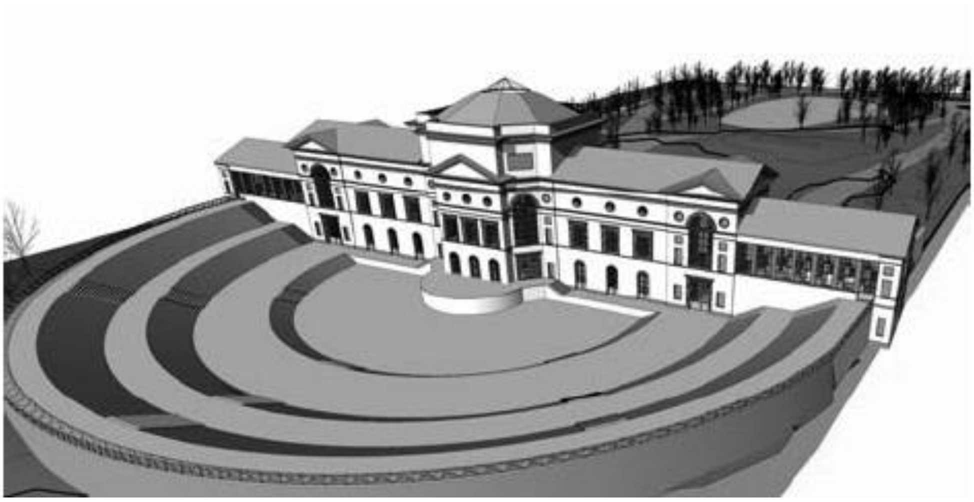


Figure 2.10: Exterior view of the BIM model of the Casino in Ghent.

This technique is mainly based on the BIM approach, but has the difference that uses more historical, theoretical and abstract information, instead of component-based building information of the present BIM approach. A network of spaces is used to describe the building structure of the Casino and not the composing elements like walls, doors, windows etc., creating in this way an abstract spatial structure. The modeling of this structure in 3D space makes the AIM model (Figure 2.11, see Appendix-p. 118 for the color image), where every building block, like in this case the ‘central hall’ is divided into several underlying spaces depending on the historical information (Figure 2.12, see Appendix-p. 118 for the color image).

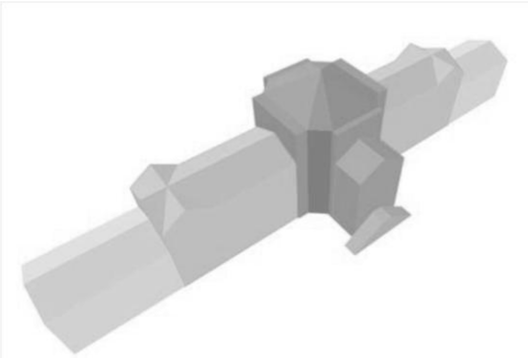


Figure 2.11: Architectural information model, showing the Casino’s overall spatial structure.

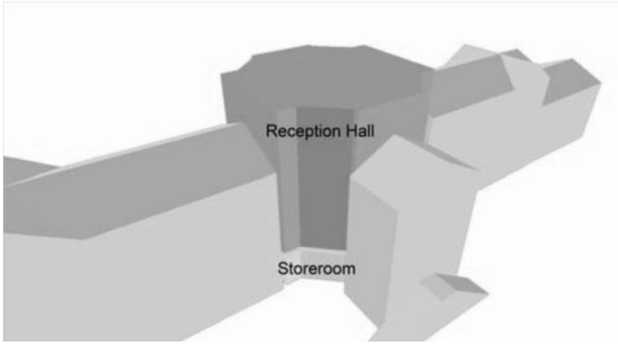


Figure 2.12: ‘Central hall’ is divided ‘storeroom’ and ‘reception hall’.

Each part of information is linked to the correspondent part of the AIM model, covering the actual geometric descriptions of the structure. The added information refers to the actual building block and its components (Figure 2.13, see Appendix-p. 118 for the color image). This information refers to more abstract theoretical and historical knowledge such as references to historical plans or other documentation that was found in the historical research project, even possible relations between spaces and typological annotations. The resulting information model contains for almost every part of the building its documentation and information, directly bound and visualized to the actual element it belongs to (a space, an abstract typology, a wall or floor, an historical reference, etc.).

Figure 2.13 : Geometric building components that are annotated to the 'central hall' of the Casino in Ghent.

Another interesting example is the methodology followed in the case of a reconstruction project, built on knowledge of previous research upon other Viennese synagogue reconstructions at KU Vienna (Boeykens et al., 2012). It was combined with a resource organization methodology developed at KU Leuven and was carried out by using the BIM platform ArchiCAD® 15 (Graphisoft®). One of the initial goals of the project was to make full use of the power of BIM and create intelligent, parametric objects applying ArchiCAD®'s GDL scripting language (Nicholson-Cole, 2000) that could be re-used in other similar reconstructions, but the size of the project proved to be too vast to actually achieve this with more complex objects.

The Vinohrady synagogue was demolished, so the integration of data such as laser-scanning generated point clouds was not an option, while the implementation example of BIM refers to the façade of the building in the custom wall patterns. If possible, the pattern of the new materials can be straightly deducted from on site photographs, but since no high quality pictures were available, simple geometric shapes were drawn with 2D polygons and saved as vectorial hatches that can be applied to an existing standard ArchiCAD® material to deliver an added dimension.

Figure 2.14: Materiality of the model (left) elevation showing off the custom materials (upper right) original photograph (lower right) custom materials seen with the internal 3D engine.

Even though the methodology that was implemented during the reconstruction gives the model a factual backbone, the repetitive visual assessment that was part of the reconstruction process remains very subject to interpretation if there is no physical evidence left of the building as it once was. In addition because all original photographs were black-and-white, they were compared with the renderings to assess the lighting quality and overall ambience (Figure 2.15 & 2.16, see Appendix-p. 119 for the color images).

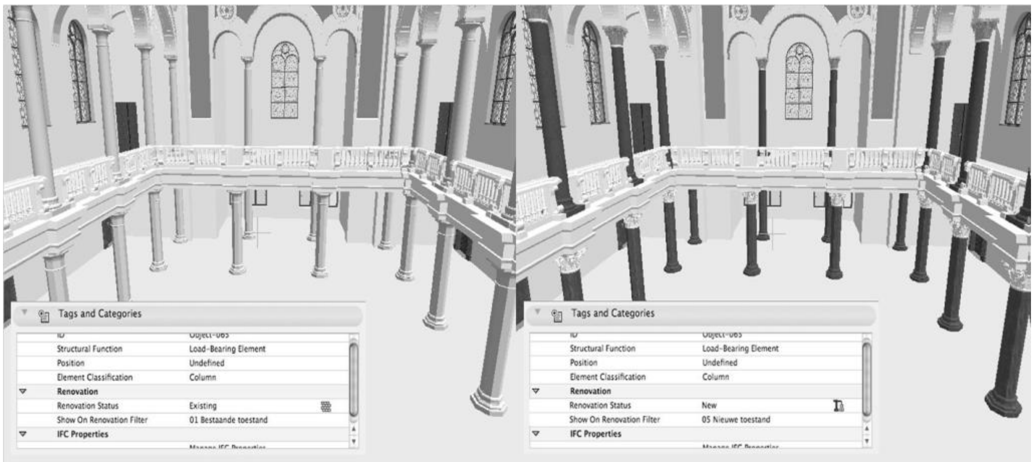


Figure 2.15 : Visualization of assumptions.

Figure 2.16: Comparison between historical photograph and interior rendering.

Last but not least, one noteworthy case study that explores and highlights the advantages of BIM from the Cultural Heritage aspect is that of the Batawa project, which refers to a shoe factory (part of the whole project) in Canada (Fai et al., 2010). An expanded role of BIM was considered, combining heterogeneous data, applying different kind of attributes (from geometrical to historical) and producing a time based representation to document the chronology of the site. At the same time any change that will be made in the future it can be added in a later stage.

The context of their research is a redevelopment proposal for approximately 600 hectares of land that includes this former factory town with its rich history of modern architecture and town planning. Architectural and planning documents, paper and digitized photographs and both digital and paper based texts were the diverse sources of information.

In contrast to existing methods that primary focus primarily on geometrical description of heritage buildings; they employed BIM as a platform to incorporate information pertaining to material assembly and construction (Figure 2.17). While this level of detail is common in design documentation of new construction projects, its application in heritage documentation typically involves a reverse engineering and analysis of existing conditions based on disparate heterogeneous data sets.

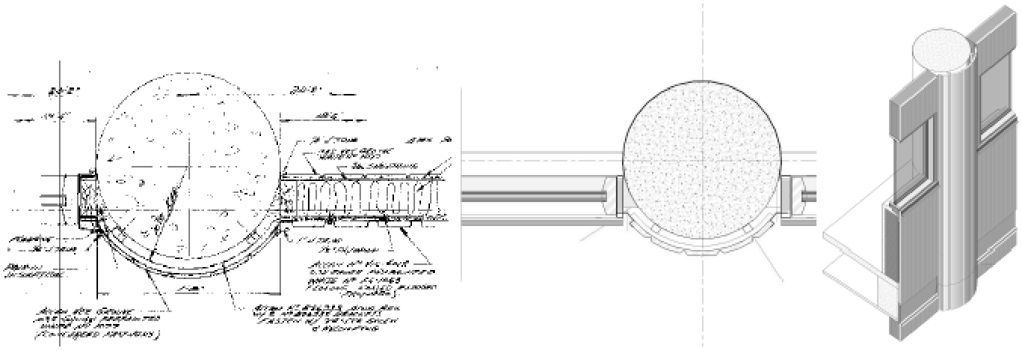


Figure 2.17 : Original shop drawings (plan) for iteration of the factory re-cladding and Revit reconstruction (plan and axonometric).

During this project a timeline of the construction phases of the shoe factory was created using Navisworks®, a robust project management tool that is able to integrate the diverse software required for the project (AutoCAD®Civil 3D, SketchUp®, Revit®), while retaining the intelligence of the objects and incorporating intangible heritage (e.g. historical texts).

Figure 2.18 : (Top to bottom) Factory timeline as viewed within Navisworks.

The latest development in the field of research towards BIM adoption was presented in *3D ARCH* 2013 conference in Trento, Italy (http://www.3d-arch.org/) . A plug-in for Autodesk® Revit® named *GreenSpider* was developed and presented by Garagnani (Garagnani and

Manfredini, 2013), aiming to introduce a methodology destined to process point cloud data in a BIM environment with high accuracy.

The plug-in imports vertexes of interest only from the cloud, considering them as discrete, selectable snap points to reproduce accurate components with precise extensions. *It is still in its infancy, so it only has two commands· the first one "GSpoints" imports the vertex point cloud, while the second "GScurves" traces a spline interpolation among imported vertexes, in order to build surfaces with accuracy. This way the plug-in allows an easier modeling capability to Revit, which considers points as vertices of simple parametric primitives pertaining to native families. The generated shapes can therefore be imported in master models as smart masses, with semantic metadata embedded, allowing hyperlink presence to multimedia contents, self-conscious topology, and lighter memory consumption and so on.*

Complex point clouds can be simplified using planar sections and then they can be used to produce smart objects, by a semi-automatic way as there is the need of an operator who will select the most appropriate locations of the sections. Figure 2.19 shows the workflow of this methodology:

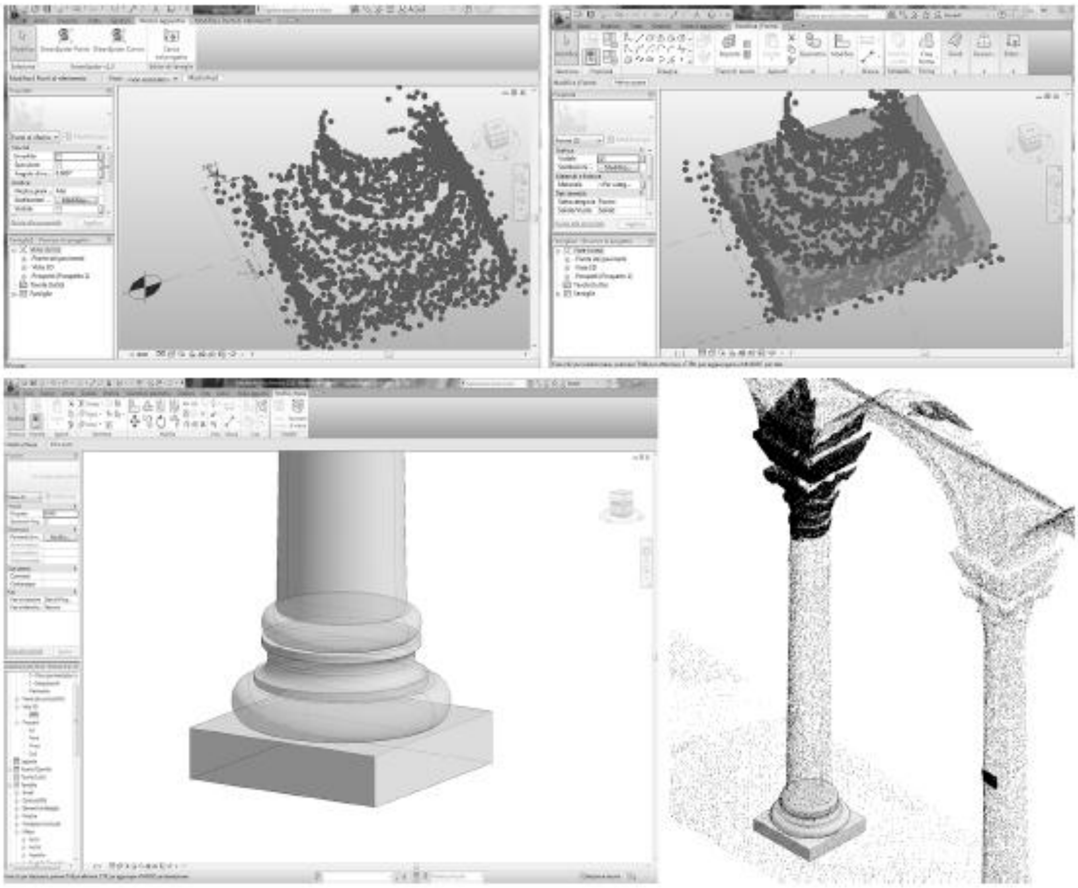


Figure 2.19: GreenSpider plug-in for Autodesk Revit 2012, developed by S. Garagnani in order to import selected vertexes from unstructured,relevant point clouds as native reference points. This way "*smart*" BIM elements can be traced out with accuracy obtaining parametric objects, which can be semantically segmented.

Despite the different methodologies that were followed, the goal was common: how to take leverage of the ICT tools, using the BIM approach, in order to document, manage and emerge Cultural Heritage buildings and sites. While all the projects described previously are remarkable, the conclusions reached by the research made are probably even more, from the point of view that they are directly associated.

A problem that needs to be overcome is the fact that most BIM tools are exclusively focused on contemporary building practice (Boydens et al., 2012). Murphy refers to the probability of constructing “AIM IFCs” to deal with the distinction of the concrete building information and the more abstract and theoretical, while also Fai highlights the integration between tangible and intangible heritage to a single parametric object.

Another aspect of interest that is strictly related to what is described above is the exchange of data between those that use the BIM for Cultural Heritage purposes. Fai (Fai et al., 2011) underlines the need of a web based resource for IFC/BIM data related to materials and methods of construction specific to heritage documentation.

A similar proposal is made also from Murphy (Murphy et al., 2011), about a cloud that the users could use to share custom objects. As most of them are project-specific but they could profit from parameterization so that small alterations to parameters could make the object suitable to use in a different, yet similar project (i.e. synagogue reconstruction). Tools like that, would make the work of designing architectural elements much easier and quick, while the sharing of knowledge between different professions that follow different methodologies could improve significantly our expertise.

3. CASE STUDY: THE CHURCH OF SANTA MARIA (SCARIA, ITALY)

3.1 Introduction

This chapter refers to the documentation works carried out in the Catholic church of Santa Maria (Scaria, Lanzo d' Intelvi, Italy) as a sample case study for BIM implementation in Cultural Heritage objects, while precedes a brief reference to the history of the church.

The chapter can be divided in three parts:

In the first part, the work progress and the methodologies followed for the geometric documentation of the church, with contemporary geodetic and photogrammetric methods are presented. During the period March - April of 2012 two series of surveys were performed in the church: the first one included the geodetic measurements of the network and the GCP points and a laser scanning survey, while the other comprised the image acquisition mainly for the vault system and the photo documentation of the whole church.

In addition in this chapter data processing from the laser scanning survey and the DSM generation are also described, up to the production of an orthomosaic of the vault system, while also the methodologies implemented in Greece in order to improve the final result, i.e. a part of the orthomosaic are also presented. Finally, the results are presented and a comparison between them is made, as well as some observations and conclusions for the whole process.

The second part deals with the BIM approach towards the documentation of cultural heritage monuments, using Autodesk® Revit® 2013. It contains thorough description of the steps followed in order to design the BIM model of the church inside a Revit® project and the progress of decision making of how to organize the elements of the church and their attributes by leverage the BIM capabilities to the maximum, leading eventually to the reconstruction of the final BIM model.

The third part refers to the Building Performance Analysis (BPA) performed for the church of Santa Maria and the parochial house as a "building system". BIM has many aspects to be explored in general, but also particularly for Cultural Heritage applications. In this case study it was decided that BPA would be that aspect and it is an effort to explore the contribution of BIM in life-cycle building management and energy efficiency. As explained in the following paragraphs, this procedure includes the creation of a new simplified model with the necessary elements for BPA in Revit® and the analysis of it with Green Building Studio® web-based software (Autodesk®).

3.2 Brief History of Santa Maria's Church

The village of Scaria belongs to the municipality of Lanzo d' Intelvi, in the province of Como and the region of Lombardy. The village of Scaria is 1 km far from San Nazaro and 2,13 km far from the same town of Lanzo d'Intelvi to which it belongs.

Figure 3.1: The geographic position of Lanzo d'Intelvi

Figure 3.2: The geographic position of Scaria, relatively to San Nazaro and Lanzo d' Intelvi.

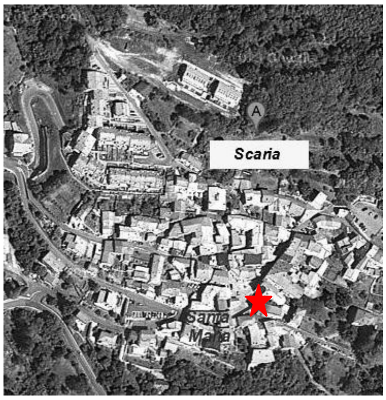


Figure 3.3: The position of the church in Scaria.

The parish church of St. Maria in the center of the town of Scaria introduces one of the most beautiful churches of the Intelvi's Valley, as architecture, sculpture and painting come together in perfect harmony. Santa Maria's church has a size of about 23 x 10 m and a height of approximately 12 m. The bell tower next to it is about 4x4 m and 20 m high.

The church consists of three spaces (naves) that are divided with an arch and demarcated with columns that are placed on each corner. Each nave has a vault. The vaults are decorated with exquisite paintings and connect to the walls with spherical triangles, that also have paintings and stucco decorations. Moreover there are three little chapels and a baptistery, as seen in Figure 3.4. In the last nave, on the west wall there is also a decorated apse. As for the façade, it is also decorated with stucco and has two little statues. At this point it should be mentioned that also the rest of the church is similarly decorated, and that is one of its main characteristics. Lastly, the bell tower is connected to the east side of the second nave through a door.

The church has been under constant motivations during the years. The first documentary that speaks of Santa Maria dates back to 1564 and mentions that the church existed since 1470. The first description of the church is found in a bishop's note of 1593 and shows that it was slightly different from its present day form. The shape was basically the same: divided in three spaces with the vaults, the two chapels close to the baptistery and the bell tower, but with no detailed information about their shape. In addition, all the walls where covered with frescos and some of them are still visible today. The first chapel on the right is not mentioned until 1635.

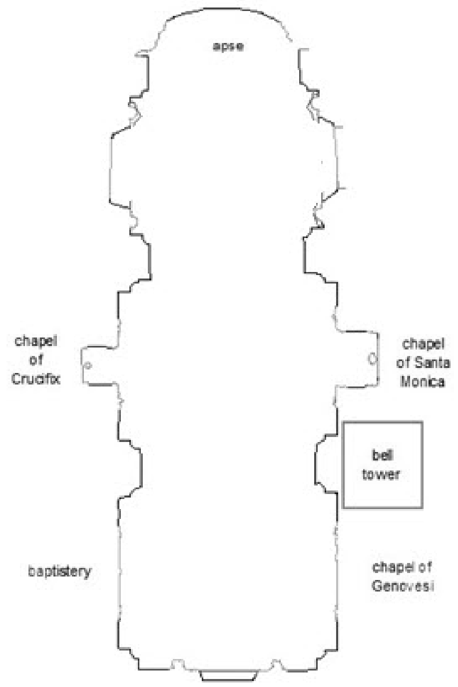


Figure 3.4: Floor plan of the church with the relevant positions of its characteristic elements.

Around 1708 renovation works started, by the Carloni family of local craftsmen- Diego and Francesco Carlo Innocenzo Carloni. They were artists specialized in paintings and stucco decorations, notorious in several European courts. The periods that they returned to Scaria, they committed themselves in making that church the baroque jewel that it is today in order to honor their birth-town. That is why in such a small village like Scaria there is a church so decorated like Santa Maria, which consists a characteristic example of Baroque style.

Figure 3.5: A characteristic example of the decorations and paintings made by Carloni.

During the period of Carloni's works on the church, that lasted almost fifty years, the apse was rebuilt and made bigger (Figure 3.6), which indicates that the third vault is also newer than the other two. The different phases of construction are visible also when comparing the three vaults, as they differ in shape (Figure 3.7).

Figure 3.6: Part of the apse as it is now.

Then from 1850 to 1960 the church was restored many times, while the parochial house was built in 1963 (Figure 3.8).

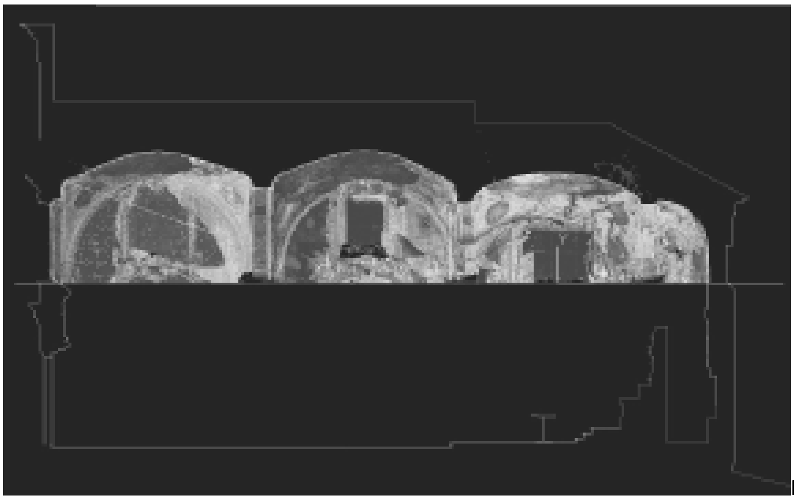


Figure 3.7 : Part of the point cloud in section, where the differences between the three vaults can be seen.

Figure 3.8: The church and the parochial house today.

Based also on the bibliographic research of Anna Raimondi.

3.3 Data Acquisition and Processing

3.3.1 Geodetic and laser scanning data acquisition and data processing

The geodetic survey of the church was performed using *Leica®'s TS30* total station which has an accuracy of 0.5'' in angles' measurement and ±1mm±1ppm with a prism and ±5mm±3ppm in reflectorless mode. The geodetic network that was used to geo-reference the project is a local reference system and consists of nine stations; two of them are inside the church and the rest of them outside, as seen in Figure 3.9.

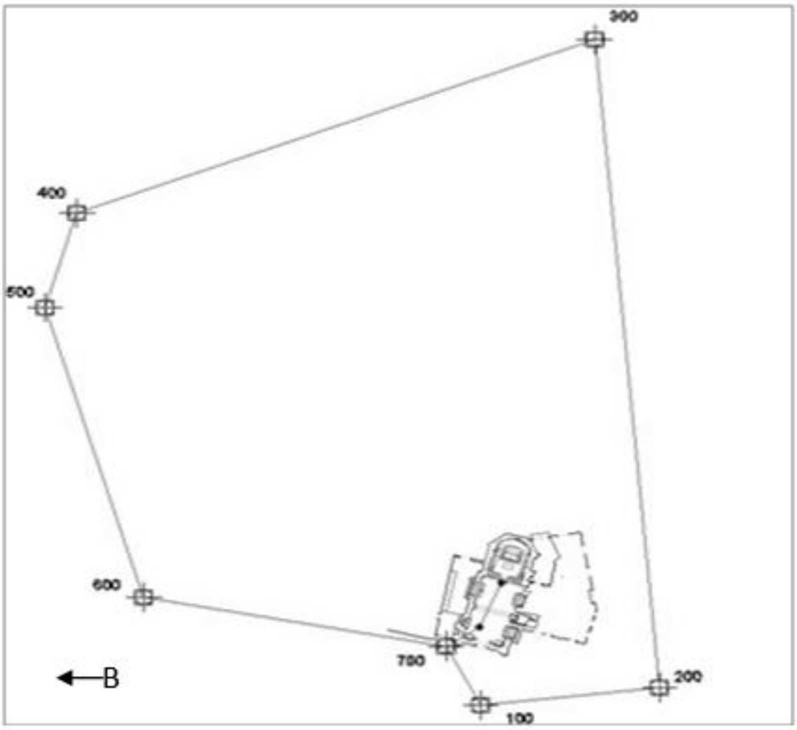


Figure 3.9: The geodetic network- distribution of the stations of the TS inside the church.

The GCPs for referencing the photogrammetric images were measured with the total station in reflectorless mode. Special care was taken while choosing the position of the GCPs on the vault system, in order for them to be distributed properly from a geometrical point of view on the complex surface of the vault system. Unfortunately, some points have been excluded from the first vault during the adjustment phase; therefore their coordinates were not calculated (Figure 3.10).

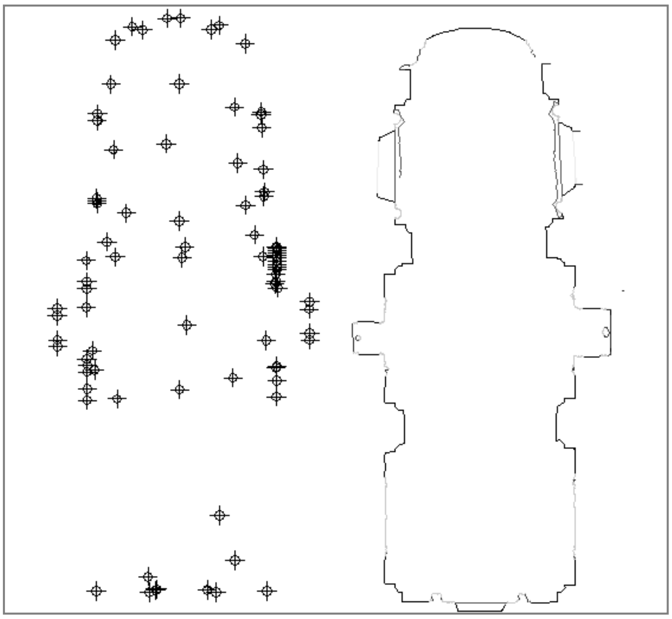


Figure 3.10: The distribution of the GCPs relatively to the floor plan of the church.

As for the laser scanning survey the phase-shift terrestrial laser scanner *Leica HDS6000* was used both for the interior and the exterior of the church. Like in most cases of cultural heritage documentation, the church of Santa Maria was too large to be scanned from only one scan position. Therefore, multiple scanning positions were required. It was decided that 4 scans would be necessary in the interior, in order to achieve a highly dense point cloud and extract as many details as possible. For the exterior, 4 scans were also necessary (Figure 3.11). Black-and-white targets were placed inside and outside of the church in order to enable the registration of the individual scans. The laser scanner's resolution was set to 1 mm in 25 m.

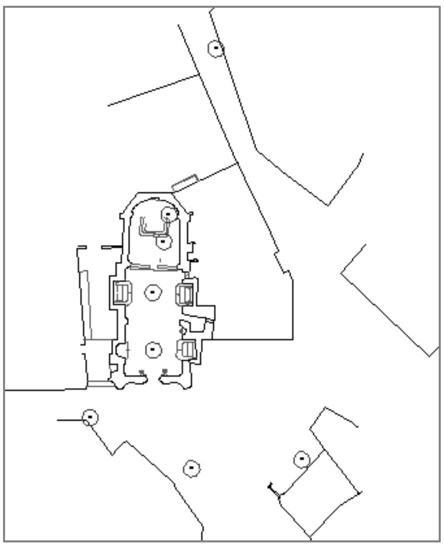


Figure 3.11: T he laser scanner positions.

The targets were measured and coordinated with the total station in the common geodetic reference system. The scans were done from the stations that can be seen in Figure 4. The scans of the interior were firstly registered together and then unified, in order to be seen from the software as a single point cloud; the same procedure was followed for the exterior scans (it is an *indirect registration*, implying the use of artificial target features in the scene itself to align datasets.. Finally they were all registered to the geodetic network with a final registration error of 0.001 m.

3.3.2 Image block acquisition for photogrammetric purposes

For the acquisition of the image block of the vault system the DSLR camera *Canon EOS 1D Mark IV* was used. The camera frame is equal to 27.9x18.6 mm, i.e 2/3 of the full frame (36x24mm). We had at our disposal 2 lenses, a 20.4 mm and a 35.5 mm. The 20.4 mm was chosen, as with the 35.5 we would need to take more photos.

Since for a digital final product at a scale of 1:20 a groundel (Ground Element) of 2 mm is required, the GSD of the original images should be smaller than that. Indeed this is the case, as at an image scale of 1:300, the GSD is 5.7μm x 300 = 1.71mm.

After the determination of the basic parameters as described above, it was decided that for every one of the three vaults 2 strips of 4 photos were needed and also another strip with 4 photos for each of the two arches that separate the middle vault from the other two. An 80% overlap and a 20% side overlap were decided, while the approximate height of the vaults is about 9-10 m and the width between 7-10 m. The base was set approximately to 1.5 meters and the images were taken from a tripod with the camera axis facing vertically to the zenith. The direction of the photo “flight” was vertical to the main axis of the church. In addition, in order to fulfill the convergent photogrammetry principles and avoid any omission of valuable information, 2 more photos were taken for each tassel (the spherical triangles that are formed between two arches of the vaults). A total of 86 photos were taken.

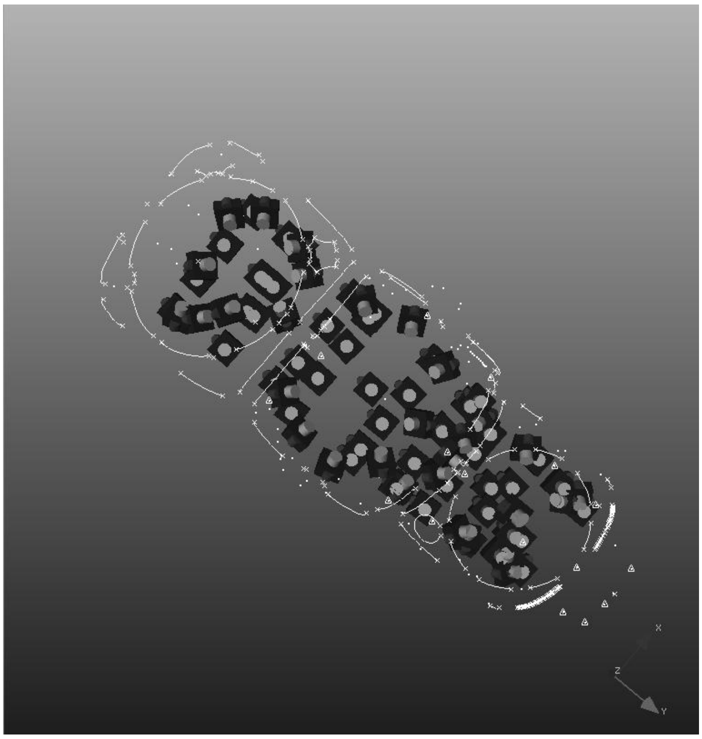


Figure 3.12: The camera positions – screenshot from Photomodeler Scanner.

3.3.3 Orthophoto production

The first thing that needed to be done was to make the registered point clouds easier to manage and refine them in order to extract the information needed. The noise was removed and the parts that were not needed in order to generate orthophotos of the vaults system were also removed. This means that only that part of the point cloud that refers to it was maintained, which was rotated and translated in *Innovmetric®'s PolyWorks®* and using *ERDAS® Imagine® 2011* a DSM was generated with a step of 6 mm.

After the laser scanning data improvement, the orientation of the photos acquired was necessary and for this purpose *Photomodeler Scanner 2012 (PM)* was used. The interior orientation was performed by inserting the parameters (position of principal point and radial distortion parameters) as a .pmr file. The exterior orientation was performed in two steps. Photomodeler uses the SIFT algorithm (Scale Invariant Feature Transform, Lowe 2004) in order to match the images (Smart Points Matching), so a big number of common points is determined (Figure 3.13).

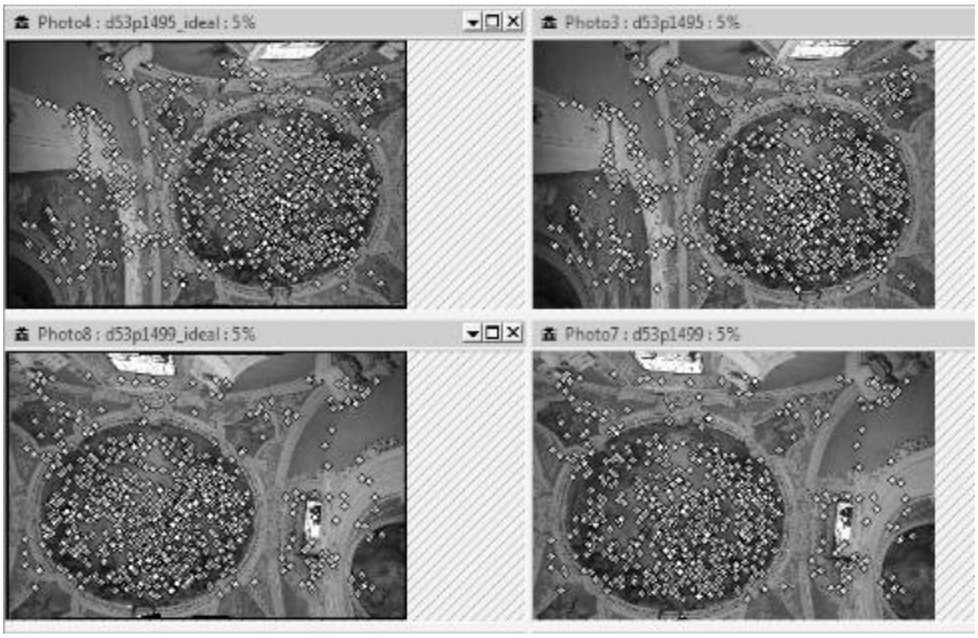


Figure 3.13: An example of Smart Points Matching.

Then all common GCPs were measured manually, while their geodetic coordinates were imported in PM with an accuracy of 1 cm as attribute and the images were oriented again, not all together but some of them at a time (not more than 2-3), because there were convergence problems in the bundle adjustment. The result was the exterior orientation parameters (Xo, Yo,Zo, ω, φ, κ) for each of the 86 photos that were oriented. Last step was the *Idealization* of the images oriented, i.e. the generation of distortion-free images. These images were used later, for the refinement of some orthophotos produced initially with different software, so the distortion's values from *Australis®* calibration software (the one used for camera's calibration) could not be used.

For the generation of the orthophotos of the vault system ERDAS Imagine 2011, and more specifically Leica®'s Photogrammetric Suite Tool (LPS®) was used. The camera and the exterior orientation parameters were imported from the PM project. After importing all the images and the parameters needed, the pixel size was calculated by using the width (W) and height (H) values from the Photomodeler project:

W in format size/ W in image size=5.91346 microns in Y direction

and

H in format size/ H in image size=5.91280 microns in X direction.

This calculation was necessary as the idealization procedure does a resampling of the image and in order PM to maintain all the original information it enlarges a little bit the final image (pixel size equal to 5.9 μm and not 5.7 μm, as the calibration sheet suggests).

Finally, as DTM source the DSM that was generated from the laser point cloud was chosen, while the output cell was set equal to 2 mm matching the project's requirements.

Composotion of the Orthomosaic

In order to create the mosaic of the orthophotos of the vault system *ArcGIS® 10 (ESRI®)* was used, and in particular *ArcMap® 10*. All the orthophotos that were made in LPS were imported as .img files into ArcMap. Then, a shape file was used in order to clean every orthophoto from the black limits that they had and cut them in a way that would make the process of making the mosaic easier. With this shapefile (.shp) as extent limits every photo was 'cleaned' by using the *Clip* function from *ArcToolbox*. Then, the orthophotos were all exported in .tiff format, which provides no compression and the highest quality.

In the case of this project, differences in colors and light exposure were clearly visible. For correcting these problems *Adobe® Photoshop® CS4 (PS)* was used. For every vault the photo that its colors represent in the best way the real ones was chosen to be used as reference for the editing of the rest. By using the Levels tool (a good balance between the most bright and most dark pixels was achieved. Also, by changing the light Exposure of the photos, some of the overexposure issues were solved. At the end, with Color Balancing the yellowish tone that the colors of the vaults seemed to have was removed. With the new images a mosaic was made in *ArcMap® 10*, by using the *Blending* utility as it was requested. The final product is shown in Figure 3.14 (see Appendix-p.120 for color image) :

Figure 3.14: The orthomosaic produced with ArcMap .

Refinement of the Problematic Parts in the Orthophotos

In order to overcome the problems of creating an orthophoto without 'floating' pixels in cases of complex anaglyph (e.g. arches between the vaults, stucco decorations), a different approach was decided. The DSM created by LPS was not appropriate, as LPS is a photogrammetric suite and hence it does not form the proper triangles during TIN creation, even if we insert correct breaklines where needed.

For that reason an example area of the vault system was chosen to work with and more specifically the second half of the first vault, the first half of the second vault and the connecting arch in between, as it is shown in the relevant screenshot (Figure 3.15, see Appendix-p.121 for color image).

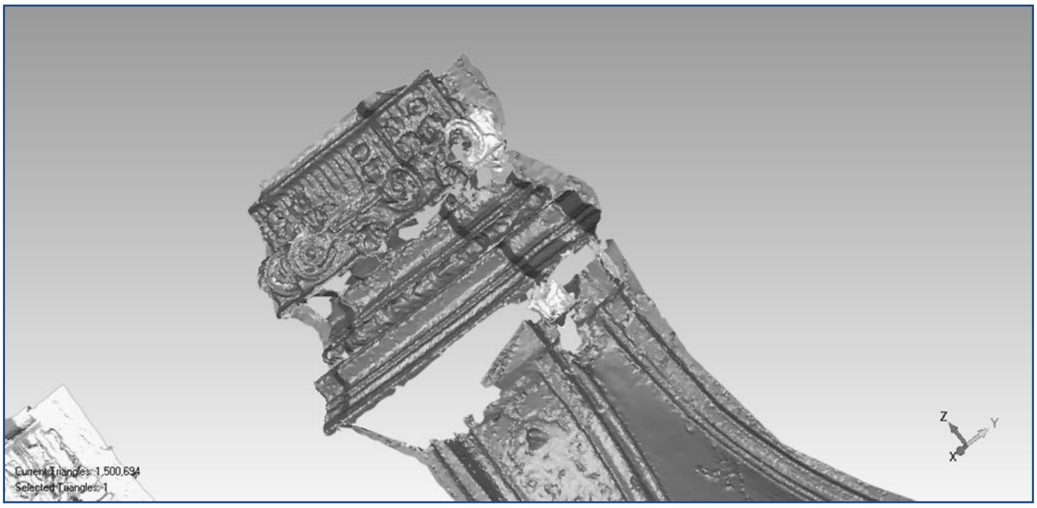
Figure 3.15: The example area to be refined.

3D Surface

The first step was the generation of a surface which would be a full 3D representation of the anaglyph. The raw data that were used is the point cloud (the high resolution one) obtained from the laser scanner survey in a *dxf* format. This dxf file was inserted into *Geomagic Studio® 2012*, in order to be edited.

The point cloud, after been inserted into Geomagic®, was cut and only the area of interest was maintained. The noise was removed *(Noise Reduction)* and the number of points was reduced *(Uniform command)*, in order to make the file smaller and more easily manageable. Then the TIN was created by the *Mesh command.*

After the creation of the mesh two things need to be fixed: the holes (due to lack of data) and the back-flipped triangles (yellow color) that were created. Where there was lack of information due to occlusion the geometry was lost when the holes were filled (Figure 3.16). Moreover in cases of back-flipped triangles (Figure 3.17), the problematic part was detached and processed separately, and when corrected, it was replaced in its original position.



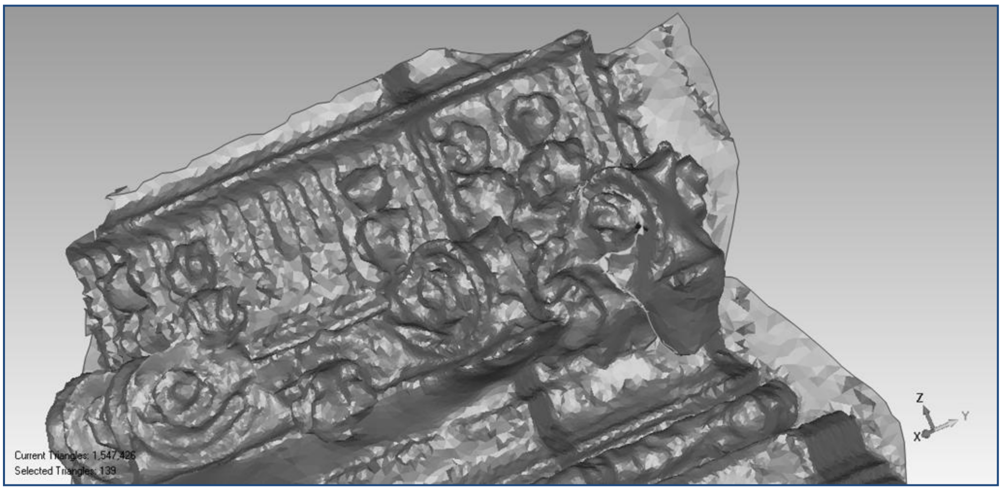


Figure 3.16: The connection between the arch and the capital before (above) and after the hole filling (below).

Orientation of the Photos and Orthophoto Creation

For the orientation of the photos that represented the sample area, *Topcon®'s Image Master®* was used. Nine photos that 'covered' the sample area were chosen to be orientated, so eight stereopairs were created. The interior orientation parameters of the camera and the file with the GCPs' coordinates were also imported.

After the measurement of all the points needed (tie points and GCPs) in each stereopair the orientation was calculated with bundle adjustment and the results were fulfilling the accuracy requirements. The first results show how 'well' the relative orientation of the images was done as they refer to the y-parallax that remained, which was above 1 pixel (which is the limit in our case) on all the images/pairs. The second results are about the errors of the calculated coordinates from the bundle adjustment, as we had a layer of control points (the GCPs).The errors are just some millimeters, which is acceptable.

After the orientation of the photos, the TIN from Geomagic® was imported into Image Master® as a shape file. An orthophoto was produced from each one of the nine photos with a ground resolution of 0.015 m, which is a little bit smaller of the 0.002 m that we wanted.

Finally, a new orthomosaic (Figure 3.17, see Appendix-p.121 for color image) was produced using Adobe® Photoshop® CS4: the best part from every orthophoto was kept and they were all combined to form the final result. Some color adjustments were also performed, using the tools provided by the software (brightness, contrast etc.) while unwanted objects were removed (e.g. the bar between the first and the second vault).

Figure 3.17 : The new orthomosaic of the example area.

It is clear that while dealing with problems on areas of intense anaglyph this procedure was much more efficient as there are much less 'floating pixels', even on the decorations of stuccos which have a complex geometry or in the edge of the arch, where the neighboring pixels (vault) have quite a different z value (Figure 3.18, see Appendix-p.122 for color image).

Figure 3.18: Part of the arch on the orthomosaic from LPS (above) and Image Master (below).

Textured 3D Model (VRML)

As mentioned before, Image Master® can produce textured models. Several views from the TIN were used and were combined with the corresponding photos. Each view is a different VRML file. At the end all the different VRMLs were connected inside Geomagic Studio®, in order to obtain the final 3D model. The TIN was also *relaxed*, for obtaining a smoother textured surface (Figure 3.19, see Appendix-p.122 for the color image) eventually in a *wrp* format (Geomagic Studio®'s file). It will be tested if this vrml file is possible to be handled inside the BIM software, as it will be described later.

Figure 3.19: The textured model of the example area.

3.4 Development of a BIM Model for Santa Maria's Church

3.4.1 Introduction to Revit® 2013

Based on Autodesk®'s User's Guide 2013

As mentioned in an earlier chapter Revit® was first introduced by the Revit Technology Corporation in 1997 as Revit software and then acquired by Autodesk® in April of 2002. From that time Autodesk® expanded this BIM platform and created three Revit® products; Architecture, Structure and MEP. All of them use .RVT files for storing BIM models. In version of 2013 (which was used in the case of this diploma thesis) all features for architectural design, MEP and structural engineering, and construction are included in one suite.

Typically, a building is made using 3D objects to create walls, floors, roofs, structure, windows, doors ductwork, electrical systems and other objects as needed. These parametric objects— 3D building objects (such as windows or doors) or 2D drafting objects (such as fasteners)— are called "families" and are saved in *.RFA* files, and imported into the RVT database as needed.

A Revit® model is a single database file represented in the various ways which are useful for design work. Such representations can be plans, sections, elevations, legends, and schedules. Because changes to each representation of the database model are made to one central model, changes made in one representation of the model (for example a plan) are propagated to other representations of the model (for example elevations). Thus, Revit® drawings and schedules are always fully coordinated in terms of the building objects shown in drawings.

When a project is shared between several users, a central file is created which stores the master copy of the project database on a file server on the office's LAN. Each user works on a copy of the central file (known as the local file), stored on the user's workstation. Revit manages permissions on objects by locking them in the central file, ensuring that only one user has rights to them at a time. Users can periodically synchronize their changes back to the central file and receive changes from other users.

Multiple disciplines working together on the same project make their own project databases and link in the other consultants' databases for verification. Revit can perform collision checking, which detects if different components of the building are occupying the same physical space. When setup correctly schedules can also provide information to verify the functional aspects of a building. For example the level of occupancy for the room area, as well as electric and ventilation loads.

Revit is one of many varieties of BIM software which support the open XML-based IFC standard, developed by the buildingSMART® organization. This file-type makes it possible for a client or general contractor to require BIM-based workflow from the different discipline consultants of a building project. Because IFC is a non-proprietary and human readable format, it is archivable and compatible with other databases, such as facility management software. (Wikipedia Autodesk)

The following paragraphs refer and describe briefly the basic terms of Revit® that will be used consequently, while presenting the implementation of BIM approach with Revit® for the case study of the church of Santa Maria:

Project

In Revit, the project is the single database of information for your design—the building information model. The project file contains all information for the building design, from geometry to construction data. This information includes components used to design the model, views of the project, and drawings of the design. By using a single project file, Revit makes it easy for you to alter the design and have changes reflected in all associated areas (plan views, elevation views, section views, schedules, and so forth). Having only one file to track also makes it easier to manage the project.

Level

Levels are infinite horizontal planes that act as a reference for level-hosted elements, such as roofs, floors, and ceilings. Most often, you use levels to define a vertical height or story within a building. You create a level for each known story or other needed reference of the building; for example, first floor, top of wall, or bottom of foundation. To place levels, you must be in a section or elevation view.

Category

A group of elements that you use to model or document a building design. For example, categories of model elements include walls, windows, columns, and beams. Categories of annotation elements include dimensions, tags, and text notes. Categories are organized into families of elements with similar purposes and characteristics. Families are further organized into types, as shown.

Family

It is a class of elements in a category. A family groups elements with a common set of parameters (properties), identical use, and similar graphical representation. Different elements in a family may have different values for some or all properties, but the set of properties (their names and meaning) is the same. For example, a family of concrete round columns contains columns that are all concrete and round, but of different sizes. Each column size is a type within the Concrete Round Column family.

- **Loadable** families are families used to create both building components and some annotation elements. Loadable families create the building components that would usually be purchased, delivered, and installed in and around a building, such as windows, doors, casework, fixtures, furniture, and planting. They also include some annotation elements that are routinely customized, such as symbols and title blocks.
- **System families** contain family types that you use to create basic building elements such as walls, floors, ceilings, and stairs in your building models. System families also include project and system settings, which affect the project environment and include types for elements such as levels, grids, sheets, and viewports. System families are predefined in Revit Architecture and saved in templates and projects, not loaded into templates and projects from external files. You cannot create, copy, modify, or delete system families, but you can duplicate (copy) and modify the types within system families to create your own custom system family types. You can delete all but one system family type in a system family, because you need at least one type per family to create new system family types.

Type
It is a subdivision within a family of elements. For example, the family of Concrete Round Columns is further divided into types such as Concrete Round 18”, Concrete Round 24”, and Concrete Round 30”.

Instance
Instances are the actual items (individual elements) that are placed in the project and have specific locations in the building (model instances) or on a drawing sheet (annotation instances). Each instance belongs to a family and, within that family, a particular type.

Levels
Levels are finite horizontal planes that act as a reference for level-hosted elements, such as roofs, floors, and ceilings. You can resize their extents so that they do not display in certain views.

Constraints
Constraints are non–view-specific elements that can function independently of dimensions. Constraint elements appear in all views in which their references are visible; dimensions are view specific. You can modify and delete constraints independently of dimensions or remove them when you delete dimensions. Constraints appear as green dashed lines in project views. You create constraints by placing dimensions and locking them or by creating equality constraints.

In projects, Revit uses three types of elements:

- **Model elements** represent the actual 3D geometry of the building. They display in relevant views of the model (Walls, windows, doors, slabs, ramps, and roofs etc)
- **Datum elements** help to define project context. For example, levels and reference planes are datum elements.
- **View-specific elements** display only in the views in which they are placed. They help to describe or document the model. For example, dimensions are view-specific elements.

Figure 3.21 depicts a chart of the hierarchy of the various Revit® elements. Datum and view-specific elements are the same for all Revit® templates, while Model and Host elements differ in each case.

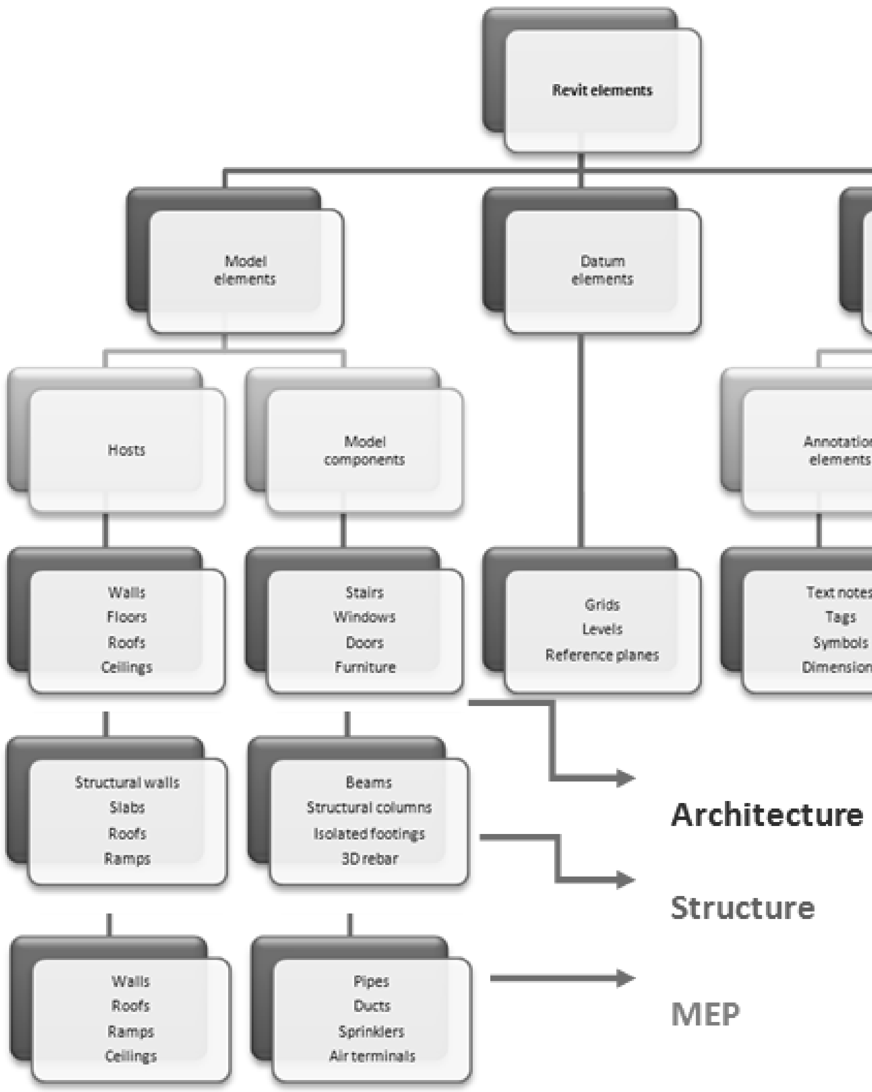


Figure 3.20: Hierarchy of elements in Autodesk® Revit®.

3.4.2 Building the BIM model

The main aim of this diploma thesis is to explore and highlight the capabilities of BIM in Cultural Heritage documentation, and more specifically in built CH as the object under research is the Catholic church of Santa Maria. In this part of the case study chapter, the approach of modeling the church inside the BIM software Revit® is thoroughly described. It is a fact that sometimes it was necessary to depart from the usual way of modeling in Revit® in order to serve the particular case's purpose, due to the complexity of the objects - e.g. creating different families for elements architecturally similar but geometrically different, that could not be handled as unique parametric objects.

Firstly the drawing of the floor plan (Figure 1) in scale 1:50 (.dwg file)was inserted to be used as a "guide", at Level 0, which was set as the ground level of the church. Several levels were created at characteristic elevations in order to position the different elements correctly and improve the design process, as they are presented on the left part of Figure 3.22. At this point it must be mentioned that all the geometric information (i.e. the dimensions and positions of the elements) derive from the drawings made based on the laser scanning survey.

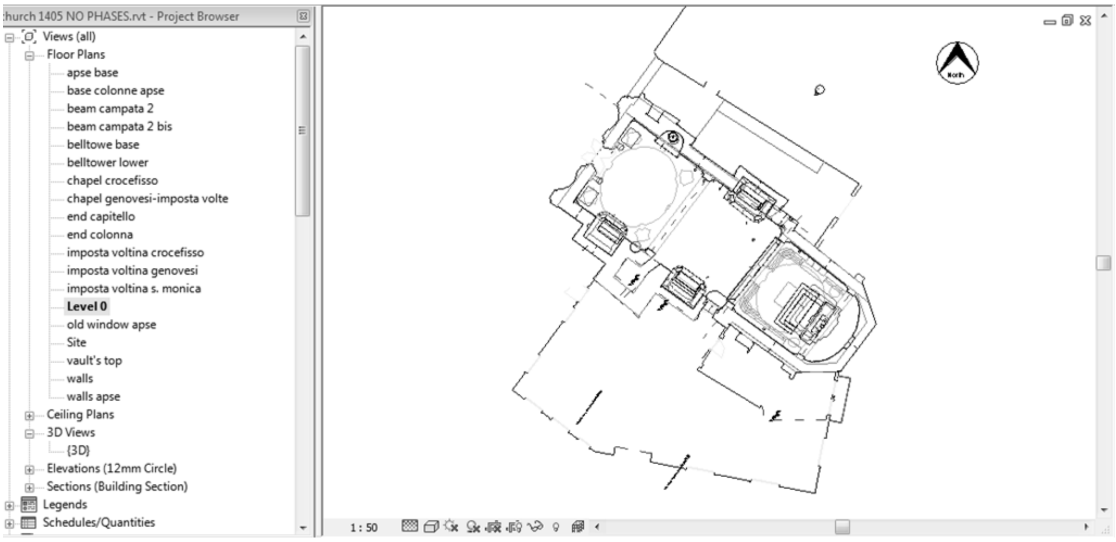


Figure 3.21: Screenshot from Revit® - the inserted floor plan in zoom view and the *Project Browser* with the different floor plans.

The walls of the church were not all of the same thickness, and in addition some of them did not have the same thickness themselves as they presented some irregularities in shape. It was decided that the family *Basic Wall* would be used for all of the walls with a different thickness (e.g. 700 mm, 670 mm, etc.), which is the parameter that defined the different types of the family – as well as their position (i.e. façade, surrounding, bell tower wall) for characterizing them, and then the irregular parts would be added. In table 3.1 the different types of the family *Basic Wall* are presented:

Category: Walls		
Family: Basic Wall		
Type:		
perimetral wall 700	perimetral wall 640	bell tower wall 1000
perimetral wall 670	perimetral wall 885	bell tower wall 1261.2
perimetral wall 623.2	perimetral wall 600	façade
perimetral wall 487.7	perimetral wall 480	

Table 3.1: The types of *Basic Wall family* used in the project.

The thickness and the height of each wall were determined from the drawings produced by A. Raimondi from the laser scanning point cloud.

Where the wall had irregularities, they had to be modeled separately. The irregularities needed of course to be properly attached to the wall, so a *Column* family was used, as it is a wall-based family (Figure 3.23). In this way any geometric inaccuracies in position were avoided. At the end, four different families had to be created (*irregularity wall 1, 2, 4 inside* and *irregularity wall 3 outside*- Figure 3.24).

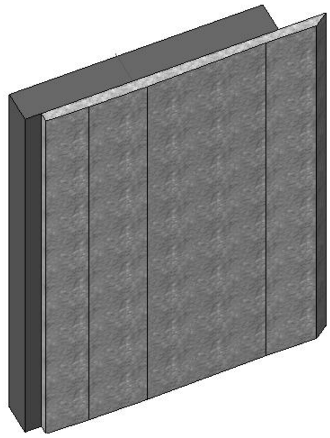


Figure 3.22: Screenshot from Revit® - the irregular part of the wall (front) and the base-wall (back).

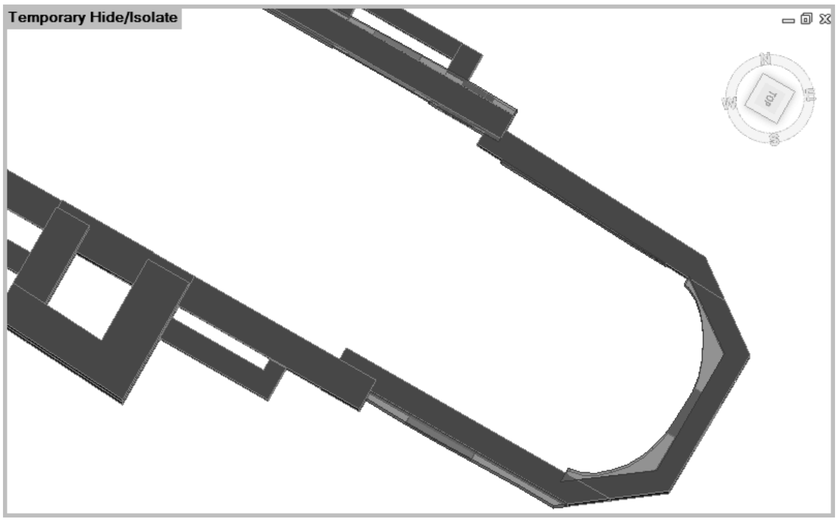


Figure 3.23: Screenshot from Revit® - the irregularities of the walls (in blue color).

On the walls of the church there are also some old windows and openings that are now closed and form part of the wall, so *In-place* families inside the category *Walls* (like *Basic Wall* previously) were used for each one of them. In-place elements are custom elements that you create in the context of a project. An in-place element (Figure 3.25) has a unique geometry that it is not expected to be reused or geometry that must maintain one or more relationships to other project geometry (Autodesk®'s *Wikihelp*).

Figure 3.24: Screenshot from Revit® - one of the old openings of the church, designed as a simple extrusion.

Table 3.2 complements table 3.1 with the six more in-place families that were created as described above:

Category: Walls
Family (in-place):
old opening 1
old opening 2
old opening 3
old window
old window apse
old window apse 2

Table 3.2: The *Wall*-based *In-place families* used in the project.

After the creation of the walls, the windows had to be modeled. In the Windows Category two kind of families were created, one that contained the old window that now is closed on the apse and one that included the rest of them (five in total) as different types (table 3.3):

Category: Windows	
Family:	**Type:**
old window apse	-
windows	window crucifix
	window genovesi
	window presbytery left
	window presbytery right
	window santa monica
	window façade

Table 3.3: The *Window families* and *types.*

All the windows in that family (*Windows)* were similar differing in some of their dimensions, so it was decided that they would be modeled as different types. Figure 3.26 shows the floor plan of the *window presbytery right*, were the different dimensions are visible while Figure 3.27 shows the values of those dimensions, which change for each one of the types, becoming in this way *parameters*:

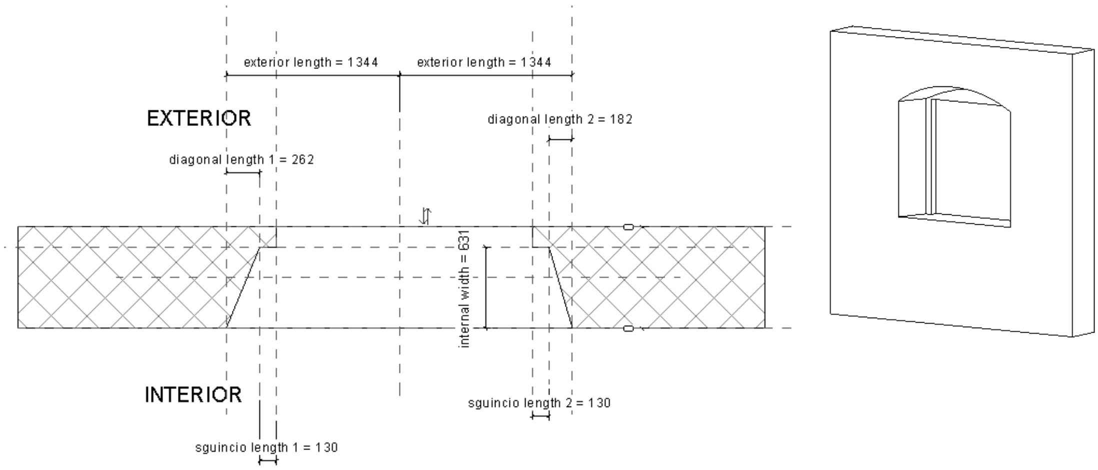
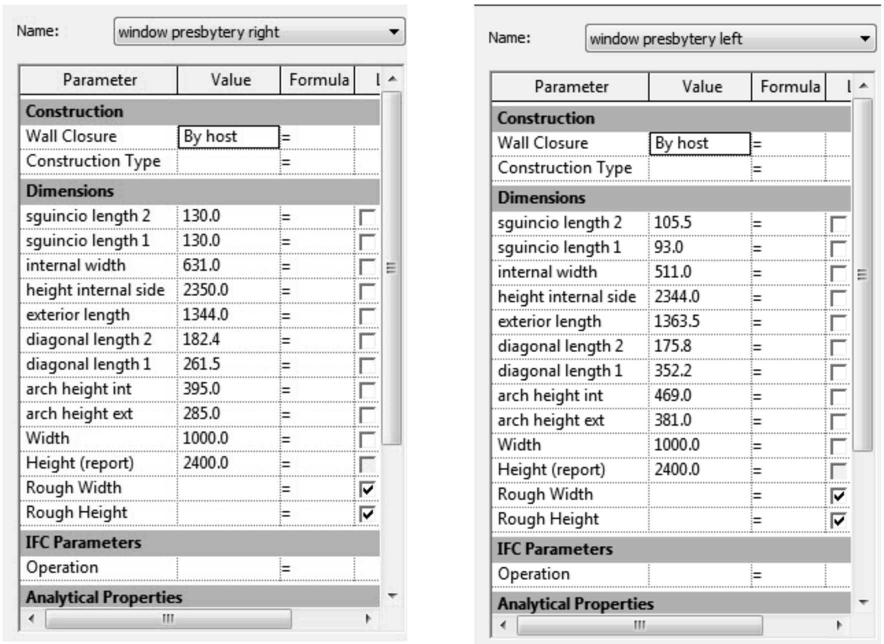


Figure 3.25: Screenshot from Revit® - the right window's of the presbytery dimensions in floor plan view and a preview of it inside *Family Editor* in 3D.



Name: window presbytery right

Parameter	Value	Formula	L
Construction			
Wall Closure	By host	=	
Construction Type		=	
Dimensions			
sguincio length 2	130.0	=	☐
sguincio length 1	130.0	=	☐
internal width	631.0	=	☐
height internal side	2350.0	=	☐
exterior length	1344.0	=	☐
diagonal length 2	182.4	=	☐
diagonal length 1	261.5	=	☐
arch height int	395.0	=	☐
arch height ext	285.0	=	☐
Width	1000.0	=	☐
Height (report)	2400.0	=	☐
Rough Width		=	☑
Rough Height		=	☑
IFC Parameters			
Operation		=	
Analytical Properties			

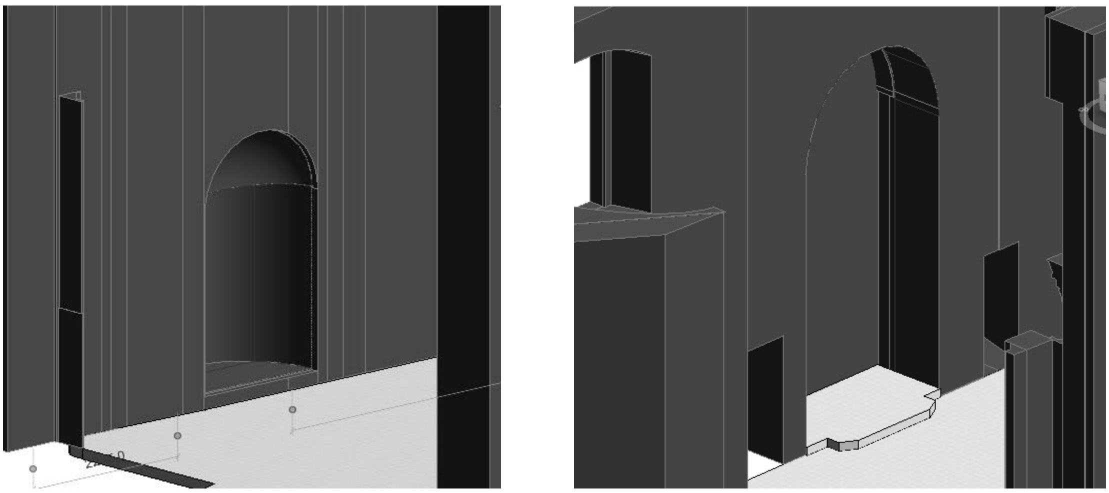
Name: window presbytery left

Parameter	Value	Formula	L
Construction			
Wall Closure	By host	=	
Construction Type		=	
Dimensions			
sguincio length 2	105.5	=	☐
sguincio length 1	93.0	=	☐
internal width	511.0	=	☐
height internal side	2344.0	=	☐
exterior length	1363.5	=	☐
diagonal length 2	175.8	=	☐
diagonal length 1	352.2	=	☐
arch height int	469.0	=	☐
arch height ext	381.0	=	☐
Width	1000.0	=	☐
Height (report)	2400.0	=	☐
Rough Width		=	☑
Rough Height		=	☑
IFC Parameters			
Operation		=	
Analytical Properties			

Figure 3.26: The differences between the two windows of the presbytery.

Moreover the church has three chapels and a baptistery, as seen in Figure 3.28, which are practically openings of the main walls. Those openings were modeled inside the *Door* family (Figure 3.29).

Figure 3.27: Examples of the church's openings- the baptistery and the chapel of Crucifix (from left to right).



a. b.

Figure 3.28: Screenshots of the baptistery (a) and the chapel of Santa Monica (b) modeled in Revit®.

The opening of the Crucifix's chapel was modeled as a *Nested family* inside the family of the irregular part of the wall, as it was the only one that was placed on an irregular part. A nested family, as the name implies, is a family inside another family and it is used for combined family geometry. So, instead of creating in-place void forms to create the openings, it was decided to follow that approach in order to have them also recorded as family elements. In this way the information about how exactly is the shape of the openings is documented. But, for making the virtual model more esthetically correct the entrance of the church and the one for the parochial house were also model as "true" doors inside predefined families of Revit® with the appropriate modification in their dimensions (Figure 3.30).

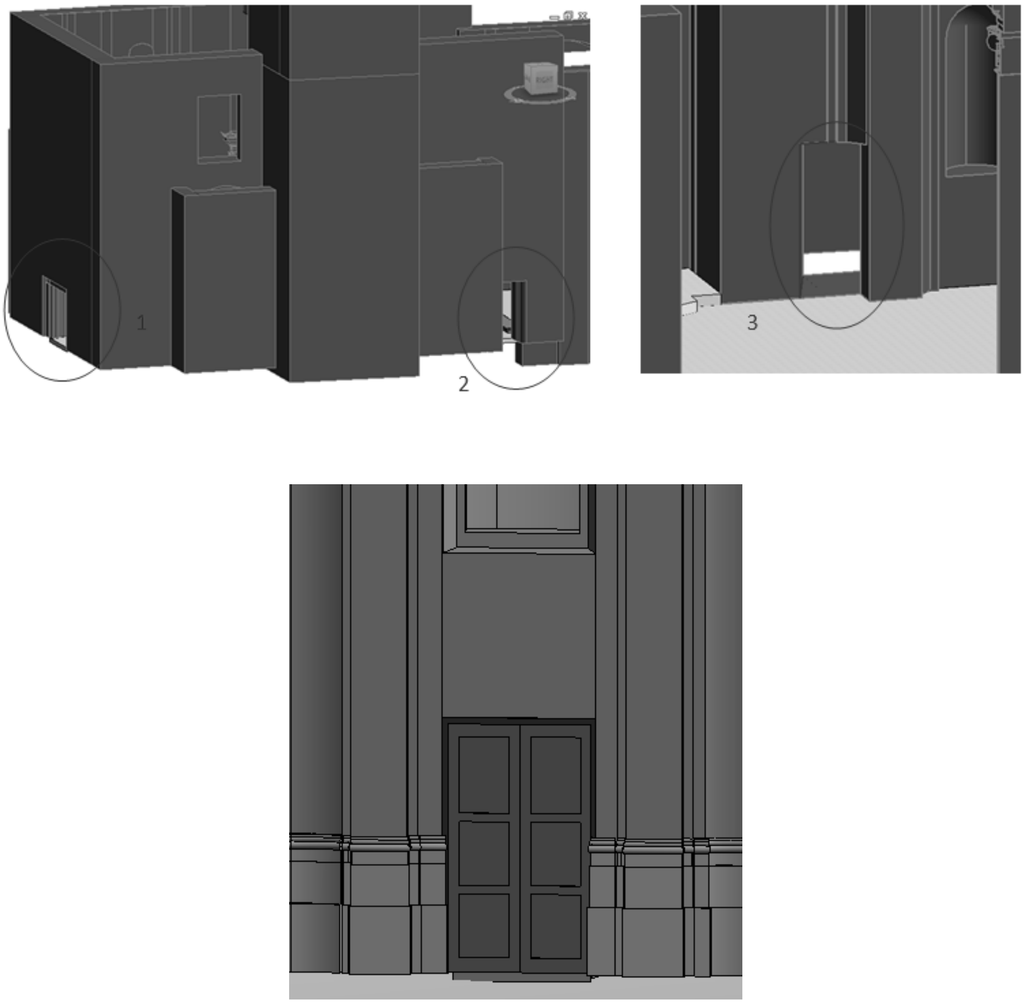


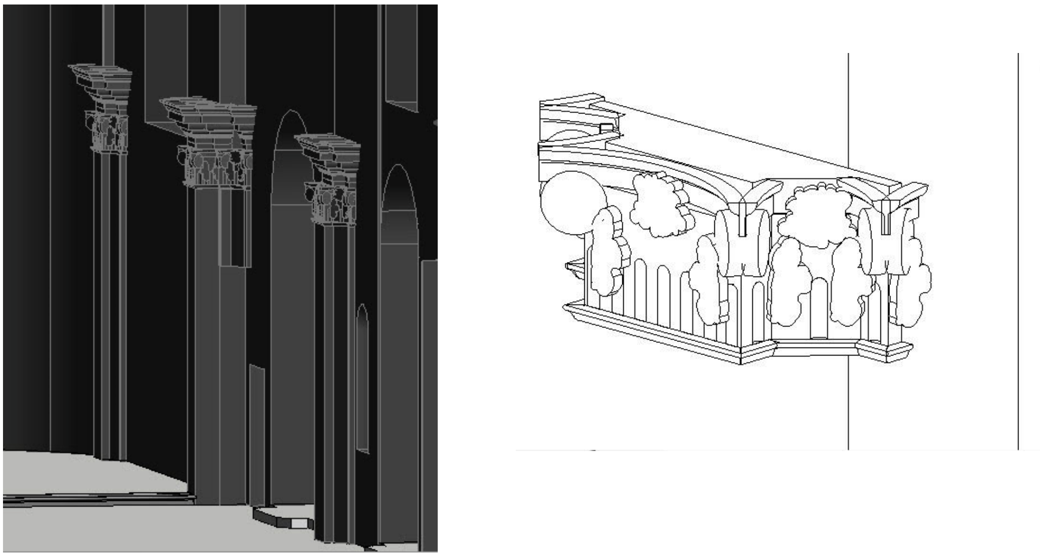
Figure 3.29: The entrance of the church (1) (below in realistic view), the entrance to the parochial house (2) and the bell tower door (3) - Screenshots from Revit®.

The openings that were modeled as “doors” but also the true doors could not be modeled as different types of the same family, as they were really different. Table 3.4 shows concisely the *Door families.*

Category: Doors		
Family:		**Nested Family:**
baptistry	door sacresty	chapel crucifix
chapel genovesi	entrance	old opening crucifix
chapel s. monica	IntSgl (type:belltower, parochial house)	
door belltower	M_double Panel (type: entrance)	

Table 3.4: The *Door families* of the project.

The elements that were modeled next were the columns with their capitals. They were modeled separately due to geometry complexity and in different categories -columns in *Columns* and the capitals were divided into lower and upper part, with the first modeled also in *Columns* and the second in *Generic Models category*. Regarding the columns, one family was created for each “couple” of columns with two types each (“right” and “left”) with different parameters. For the capitals the geometry was simplified in order to be modeled inside Revit®. The lower parts were modeled as a “column” in order to be attached to the wall and each one is a different family. The upper parts were model as *Generic face-based* models in order to attach them to the lower parts and they are divided in two families with two types each. All the parts of the columns were modeled as extrusions, while also void forms were used to cut the geometry were necessary.



a. b.

Figure 3.30: Screenshots from Revit® -Example of a column of Santa Maria modeled and placed inside the 3D model of the church (a) and detail of the upper capitals of the columns (b).

Table 3.5 contains all the column family’s elements: the “true” columns, the lower parts of the capitals and the irregular parts of the walls that were described previously. The upper parts of the capitals will be included later in the *Generic Models* family.

Category: Columns	
Family:	**Type:**
column 1	apse left 1
	apse right 1
column 2	apse left 2
	apse right 2
column 3	nave left 1
	nave right 1
column 4	type 1
	type 2
column 5	type 1

	type 2
column façade center	-
column façade right	-
column façade left	-
lower capital	-
lower capital 1	-
lower capital 2	-
lower capital 3	-
lower capital 4	-
lower capital 5	-
irregularity wall 1 inside	
irregularity wall 2 inside	
irregularity wall 3 outside	
irregularity wall 4 inside	
irregularity façade 1	
irregularity façade 2	

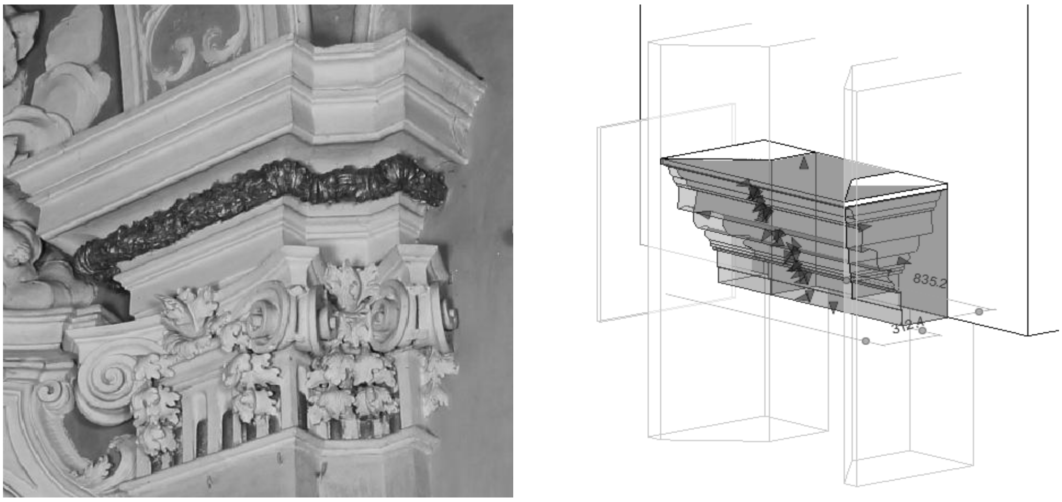
Table 3.5: The *Column* families.

As it has been already mentioned there is the family of the *Generic Models* that is used to create any generic model geometry. In this project Generic Models were used to create geometrically unique or complex elements like the upper part of the capitals but also the steps of the baptistery and the chapels.

The upper part of the capitals had to be placed above the lower part and at the same time to be attached on the wall, so the *Generic Models face based* family was chosen for that reason (Figure 3.32). It was decided that also the steps be modeled like different families, as they differed in section and the columns on the upper part of the façade (Figure 3.33).

<table>
<tr><th colspan="4">Category: Generic Models</th></tr>
<tr><th>Family:</th><th>Type:</th><th colspan="2">Family:</th></tr>
<tr><td rowspan="2">upper capitello face-based</td><td>upper capital</td><td>step apse</td><td>step s.monica</td></tr>
<tr><td>upper capitello right</td><td>step baptistery</td><td>upper façade column</td></tr>
<tr><td rowspan="2">upper capitello face-based larger</td><td>upper capitello</td><td>step crucifix</td><td>decoration roof</td></tr>
<tr><td>upper capitello right</td><td>step genovesi</td><td></td></tr>
</table>

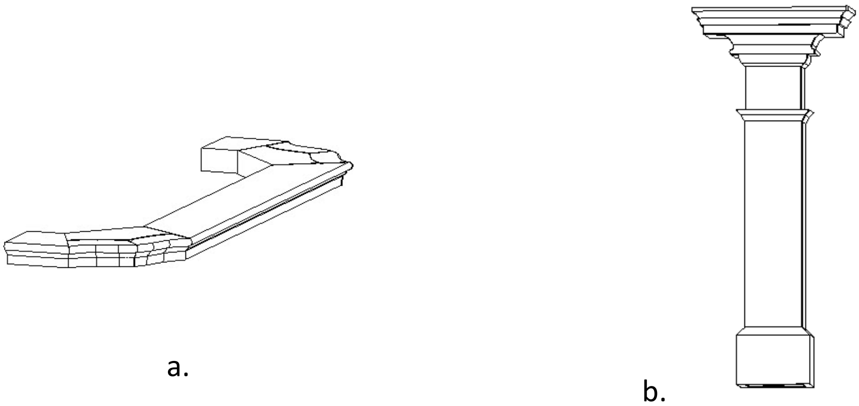
Table 3.6: The Generic *Models families.*



a. b.

Figure 3.31: The right capital of the apse (a) and how the upper part of it was modeled (b) –

Screenshots from Revit®.



a. b.

Figure 3.32: The step of Crucifix’s chapel (a) and the column on the upper part of the façade (b).

As for the modeling of roof’s elements, it was relied on a photo-based analysis but also on hypotheses made by A. Raimondi for some parts that were not visible. The roof is made from several types of beams that differ in shape, size and function (from architectural and structural point of view).

In Figure 3.34 it can be seen in the section view the analysis of the roof, which was the base of reconstructing the beams’ geometry:

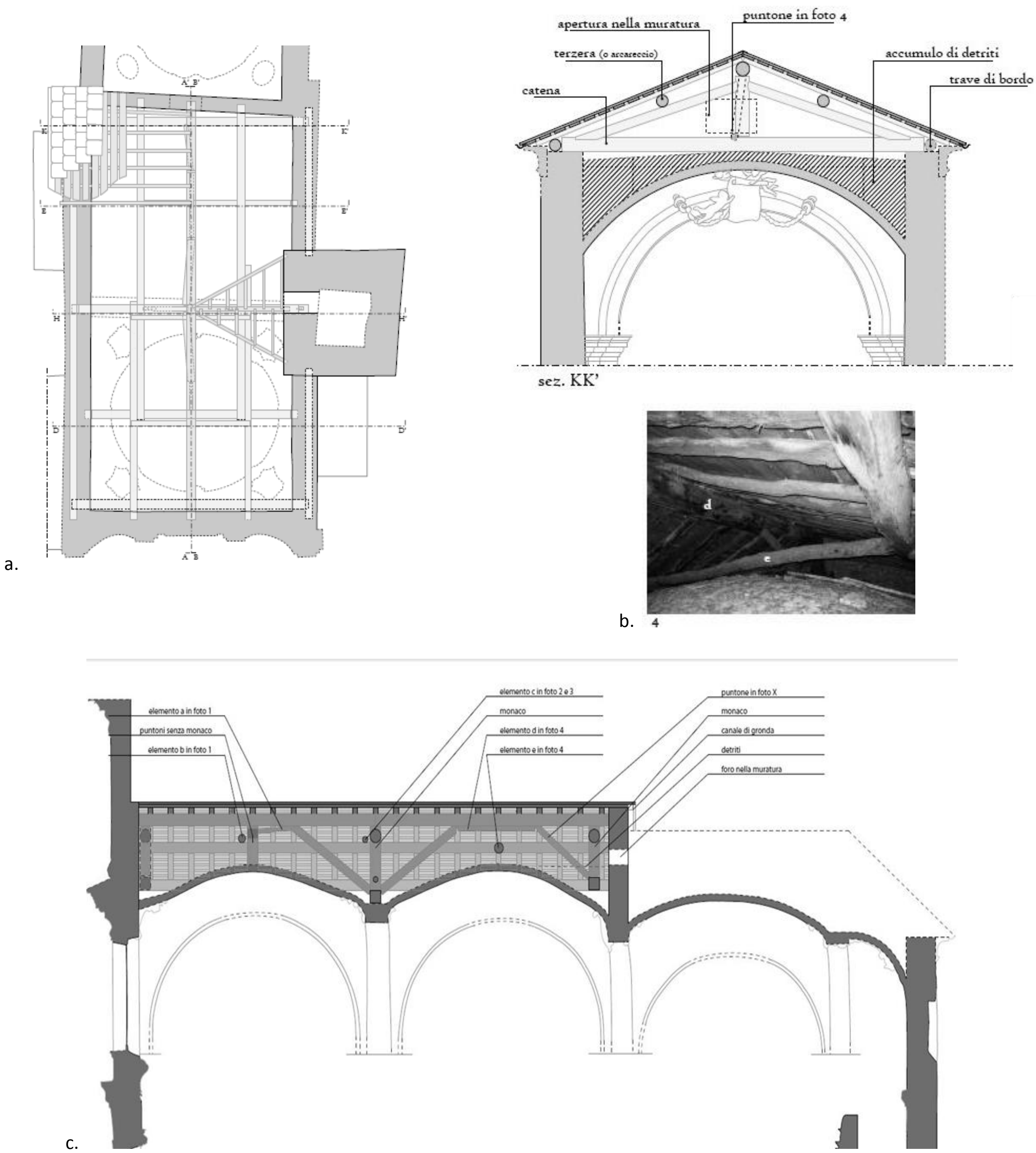


Figure 3.33 : Roof analysis in floor plan with indication of the sections' positions (a), in the cross section KK' (b) and in the longitudinal section AA' (c) - Screenshots from the work of A. Raimondi.

All the elements were created as extrusions with the proper dimensions. Only one element of the roof could be created parametrically, the tie beam, which was divided in two types with several parameters (Figure 3.35).

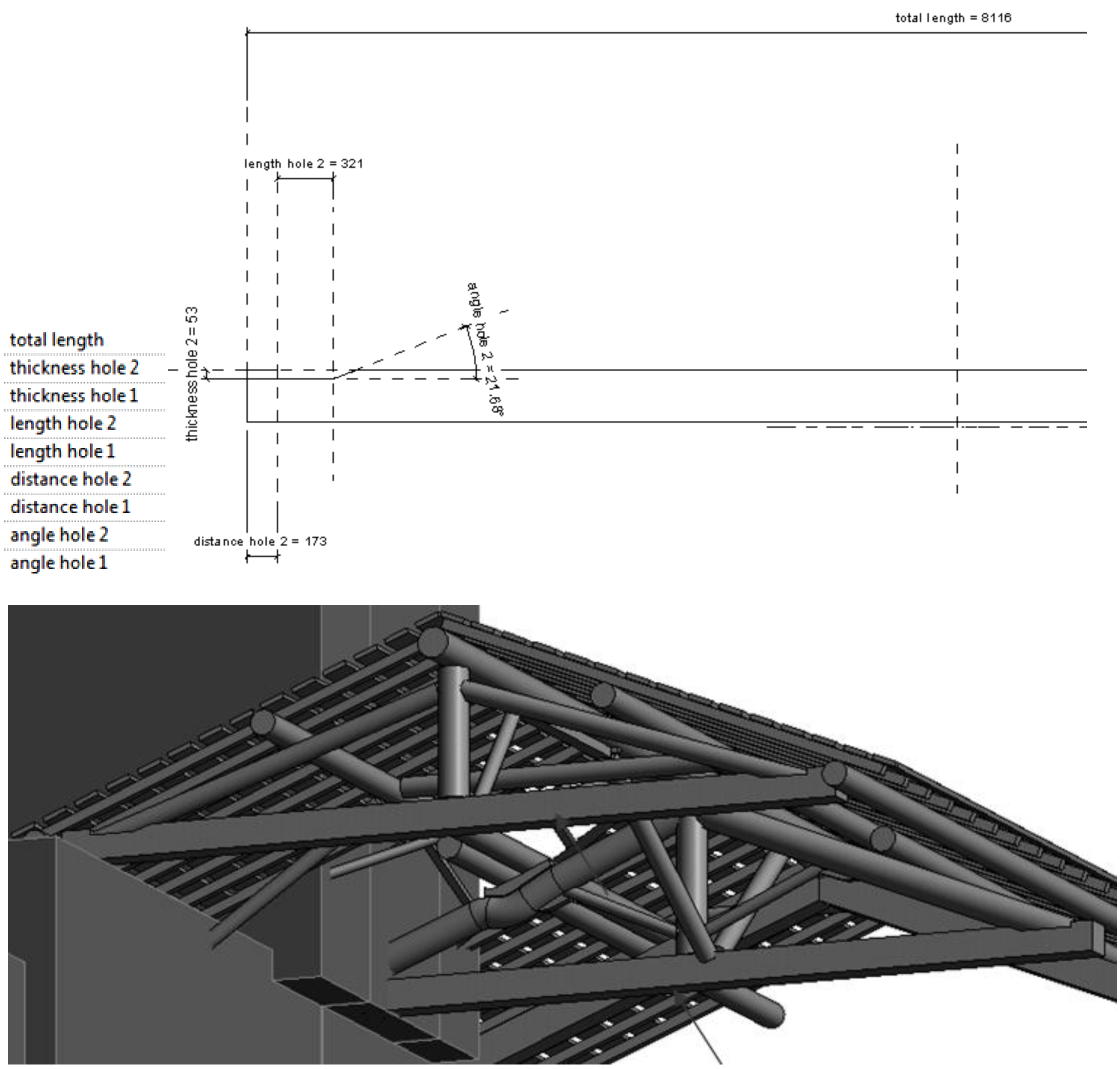


Figure 3.34: The parameters in list and some of them in floor plan (above) an dthe two types of catena in 3D (below)-Screenshots from Revit®.

Each element was designed separately, but some of them belong together with other elements from architectural or structural point of view (i.e. beam systems). For example in the case of the lath beams and the stud beams, one element was designed as extrusion and then duplicated and placed in the correct positions, with a modified shape in length when needed (Figure 3.36). All of these elements are included in *Structural Framing Category.*

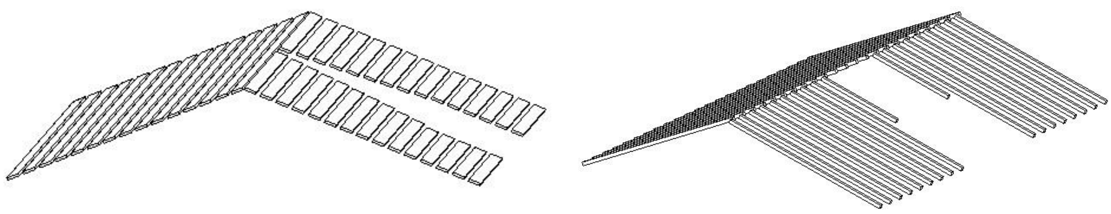
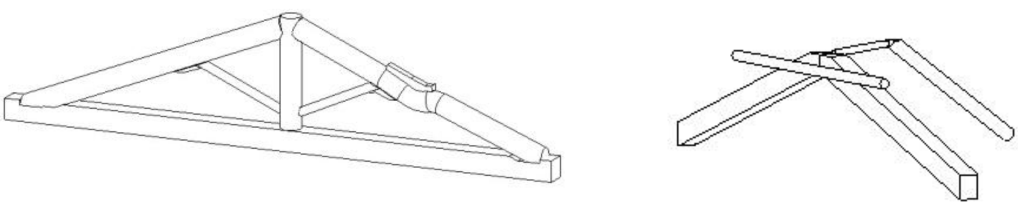


Figure 3.35: The lath beams (left) and the stud beams (right) modeled - 3D view.

Some of the elements were unified by using Assemblies, which refers to combined geometry. This means that Assemblies consist of different families, as it is visible in Table 3.7 while previews of all four assemblies are visible in Figure 3.37.

Category: Structural Framing		
Assembly:	**Family:**	**Type:**
roof truss 1	diagonal beams 2nd vault 1	-
	vertical strut 1	-
	tie beam	tie beam 1
	strut 2nd vault 1	-
roof truss 2	connection between 1st and 2nd bay	-
	strut 1st vault	-
	horizontal element beam	-
roof truss 3	diagonal beams 2nd vault 2	-
	vertical strut 2	-
	tie beam	tie beam 2
purlins and board	ridge beam	-
	side beams	-

Table 3.7: The Assemblies of the project with some of the Structural Framing families.



a. b.

Figure 3.36: Examples of the assemblies - (a) Roof truss 1 and (b) Roof truss 3.

In Structural Framing Category there are also the families described in Table 3.8:

Category: Structural Framing	
Family:	**Type:**
lateral beam 1	
lateral beam 2	
lateral beam 3	
connection roof-belltower	
connection between 2nd and 3rd bay	
generic element beam	bay 2a
	bay 2b
lath beams	
stud beams	
wooden element 4	
wooden element 5	
wooden element 6	

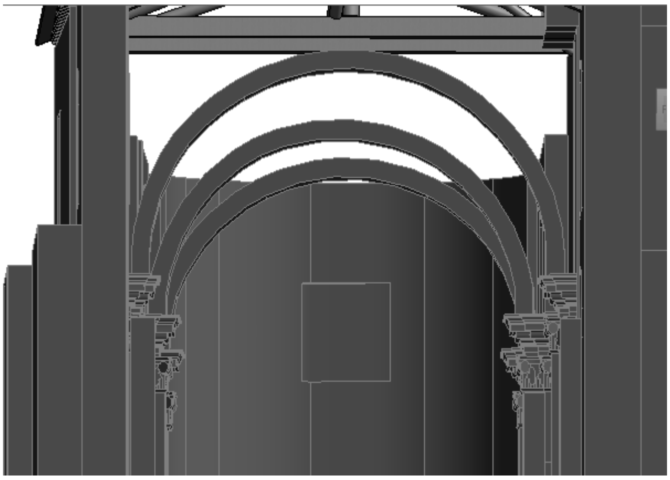
Table 3.8: The rest of the *Structural Framing* families.

In the church there are also three arches placed on the limits of the three rooms that consist the church (Figure 3.38 a, b). These arches along with the little vaults (Figure 3.38 c, d) of the three chapels with their external coverings were modeled by their profile and then the proper thickness was attributed.

Category: Roofs	
Family:	**Type:**
basic roof	little vault chapel
	generic 280 mm
	roof scaria

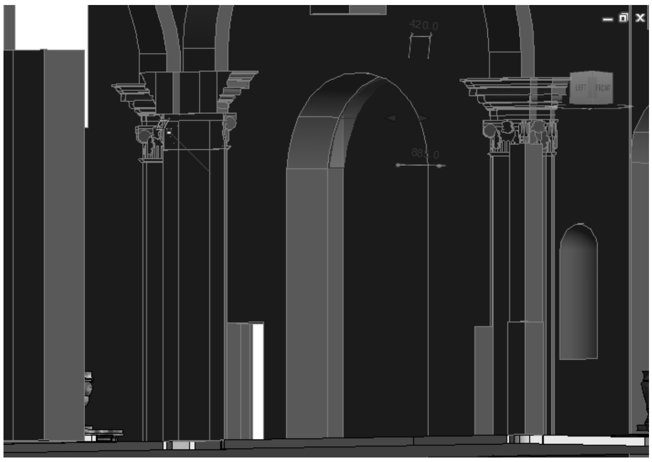
Table 3.9: The *Roof* families.

a.



b.

c.



d.

Figure 3.37: The arch between the 1st and the 2nd vault (1-a) and the 2nd and the 3rd vault (2-a), while (b) shows them modeled in Revit®- on (c) and (d) the little vault of the chapel "Genovesi".

A really important part of the roof elements are the three vaults, as it has been described in chapter 1. The information provided for the shape of these vaults is the laser point cloud and the hypothesis for their thickness and structure made by Anna Raimondi. One way to include the vaults inside the model was to import them as TINs, i.e. surfaces made in Geomagic Studio® imported into *Mass families.* In that case the result is not satisfactory enough, because it was not possible to add further information, e.g. its material, but also from esthetic point of view (Figure 3.39, see Appendix-p.123 for color image).

The second approach was made by using the *GreenSpider®* add-in (Garagnani et al., 2013). It was a time consuming procedure as the add-in requires that the points are imported in specific and separate .xyz files for each curve, which also should not be closed. GreenSpider® detected the curves from the points and then it was possible to create a *Form* with each two of them. Hence, the final form was created by copying the "semi-vault", based on the analogy that they present. The final result has also in that case some inaccuracies, but is deemed to be a better choice as it consists of Revit® elements (*Forms*). In this way it was possible to add the materials of the vault and to have a better visual representation (Figure 3.40, see Appendix-p. 121 for the color image).

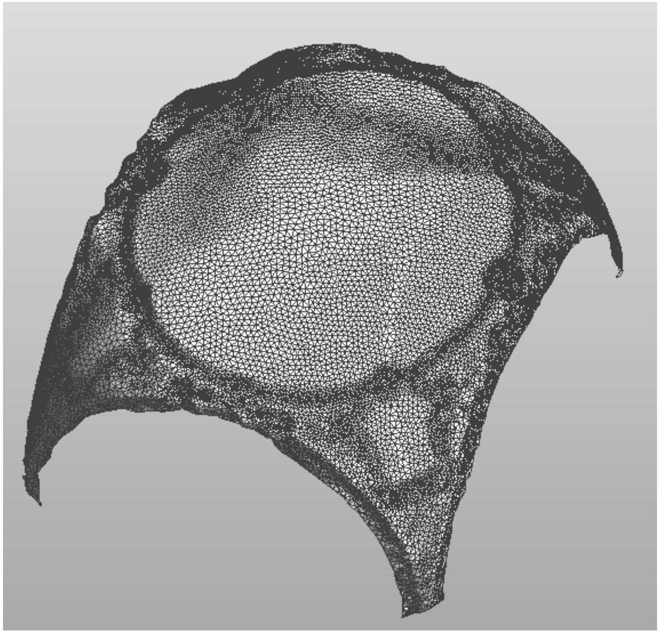


Figure 3.38: The TIN of the first vault imported inside a mass family.

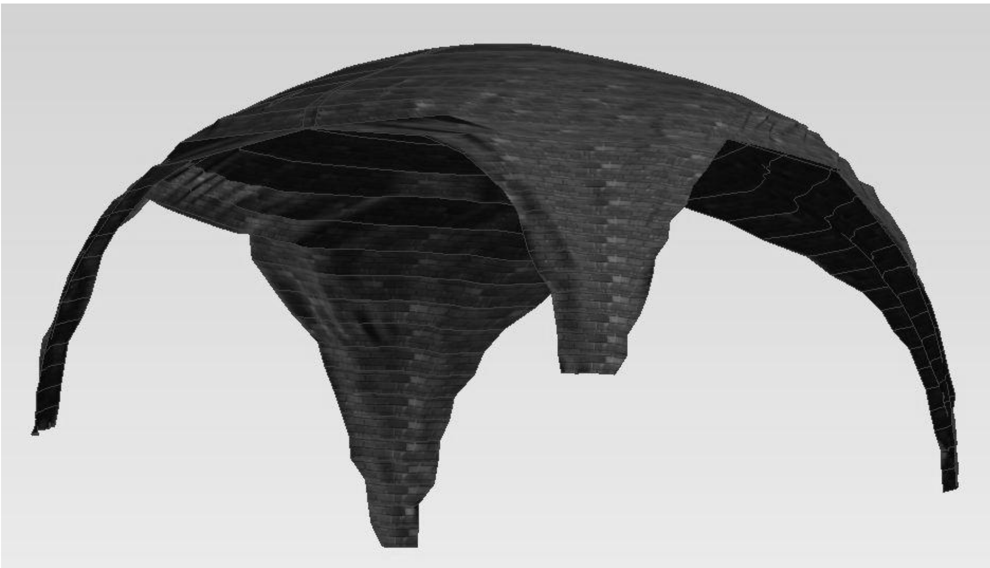


Figure 3.39: The first vault modeled with GreenSpider®.

Moreover, the altars and the baptistery were designed as different *Furniture* families (Table 3.10), while for the floor of the church a new type was created with a thickness of 130 mm, made of plaster and terrazzo.

As for the façade, a lot of the elements already designed for the interior were used also for the exterior, like some capitals. The rest of the elements were modeled like *Sweeps*, based on the profiles extracted from the drawings. The columns were designed from the beginning (they are included in Table 3.5). The façade had a lot of elements, hence sometimes simplification was needed (Figure 3.41).

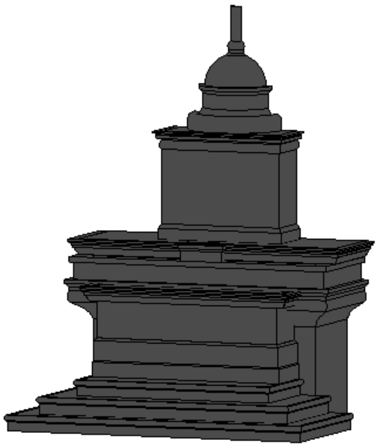


Figure 3.40: The altar of the apse.

Category: Furniture
Family:
altar apse
altar crucifix
altar santa monica
altar genovesi
baptistery

Table 3.10: The *Furniture* families.

Figure 3.41: Front view of the façade and the model (shaded view).

Material Assignment

One of the advantages of BIM is the fact that each element contains all the information that describes it, from the geometry to its material. The assignment of the materials in the church of Scaria was based on the hypotheses made by Anna Raimondi. This procedure could be divided in two parts: firstly, the determination of the material for each element or the layers of the materials when this was the case and secondly the choice of the visual graphics for each material, for a better representation.

Revit® offers a wide variety of predefined materials inside a library (Material Browser), where someone can review all their properties and choose the most appropriate one or create its own.

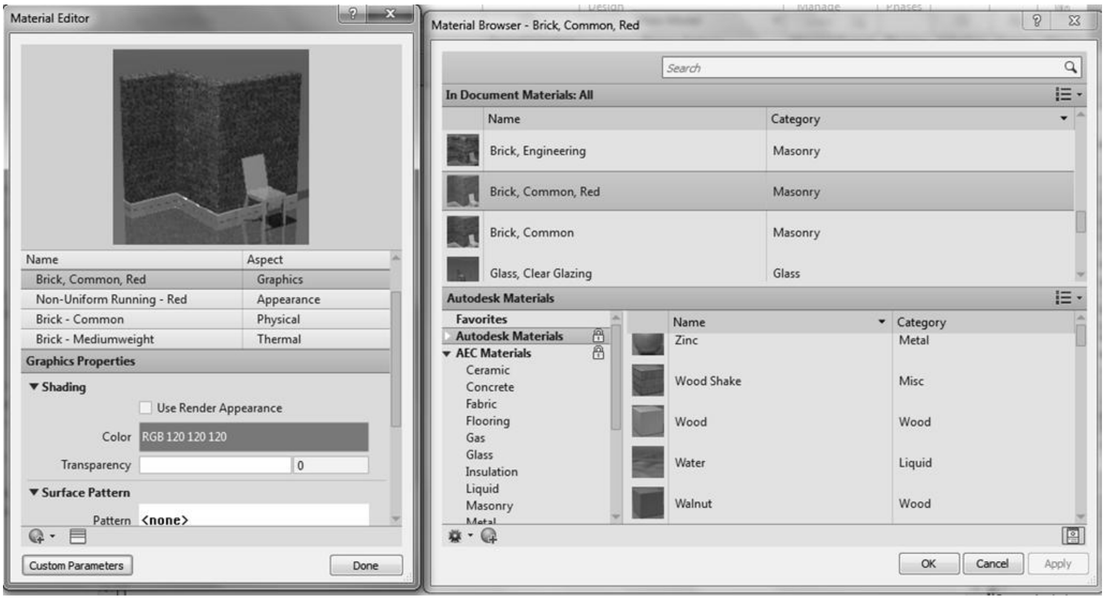


Figure 3.42: The Material Library and Material Editor inside Revit ®.

In this project most of the materials of the elements were modified, as they had multiple layers, usually one of stone and another of plaster (Table 3.11). In Figure 3.43 (see Appendix-p. 123 for the color image). an example of how Revit® handles materials can be seen.

Element	Inside	Thickness Inside	Outside	Thickness outside
walls	stone	Variable	plaster (outside and inside the church. In some cases just inside)	usually 2-3 cm
columns (central part)	bricks or stone	variable	plaster	usually 2-3 cm
columns (sides-smaller parts)	plaster	-	-	-
vaults	bricks	hypothesis dimensions	plaster	usually 2-3 cm

		bricks: 7x14x28 cm. In the vaults placed on the thinner side (so the thickness of the vault is 14 cm)		
old openings	bricks	hypotesis dimensions bricks: 7x14x28 cm	plaster (just inside the church)	usually 2-3 cm
doors	wood	-	-	-
floor	terrazzo	1-1,5 cm of terrazzo. Under it a layer of plaster(probably 10 cm)	-	-
roof (structure)	wood	-	-	-
roof (covering)	slate's sheets	sheets of max 1 cm, hooked by metal grapples	-	-
altars	marble	-	-	-

Table 3.11: The materials of Santa Maria’s church.

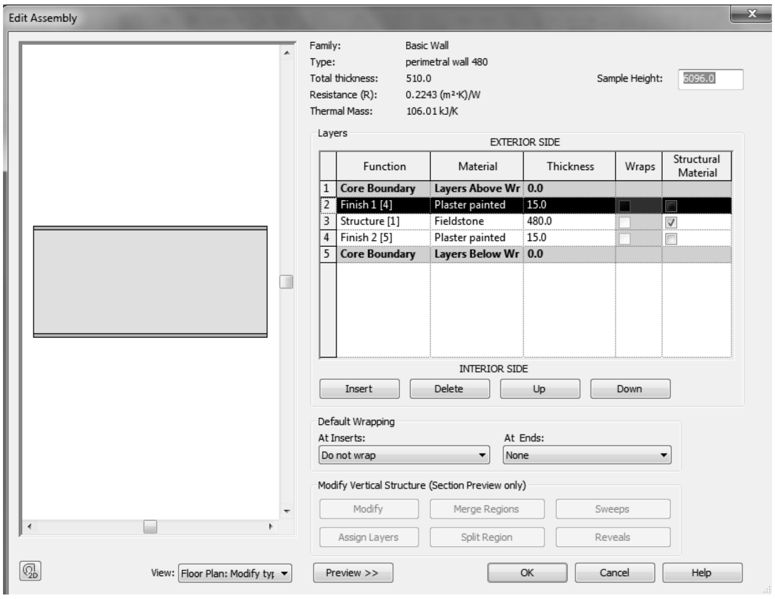


Figure 3.43: Modifying the material layers of the wall family “perimetral wall 480”.

After having applied the materials to all of the elements, it was decided that in order to obtain a better visual result texture of the images taken during the surveys would be used. Unfortunately Revit® does not support texture models (e.g. an .obj file), so when talking about texture we refer to the creation of a pattern based on sample images for each material. Sometimes the material remained the same, but for visualization purposes like when the plaster had a different color, a different sample image was used. This procedure was done with the Material Editor and the final result can be seen on the following figures (see Appendix-p. 124, 125 for the color images).

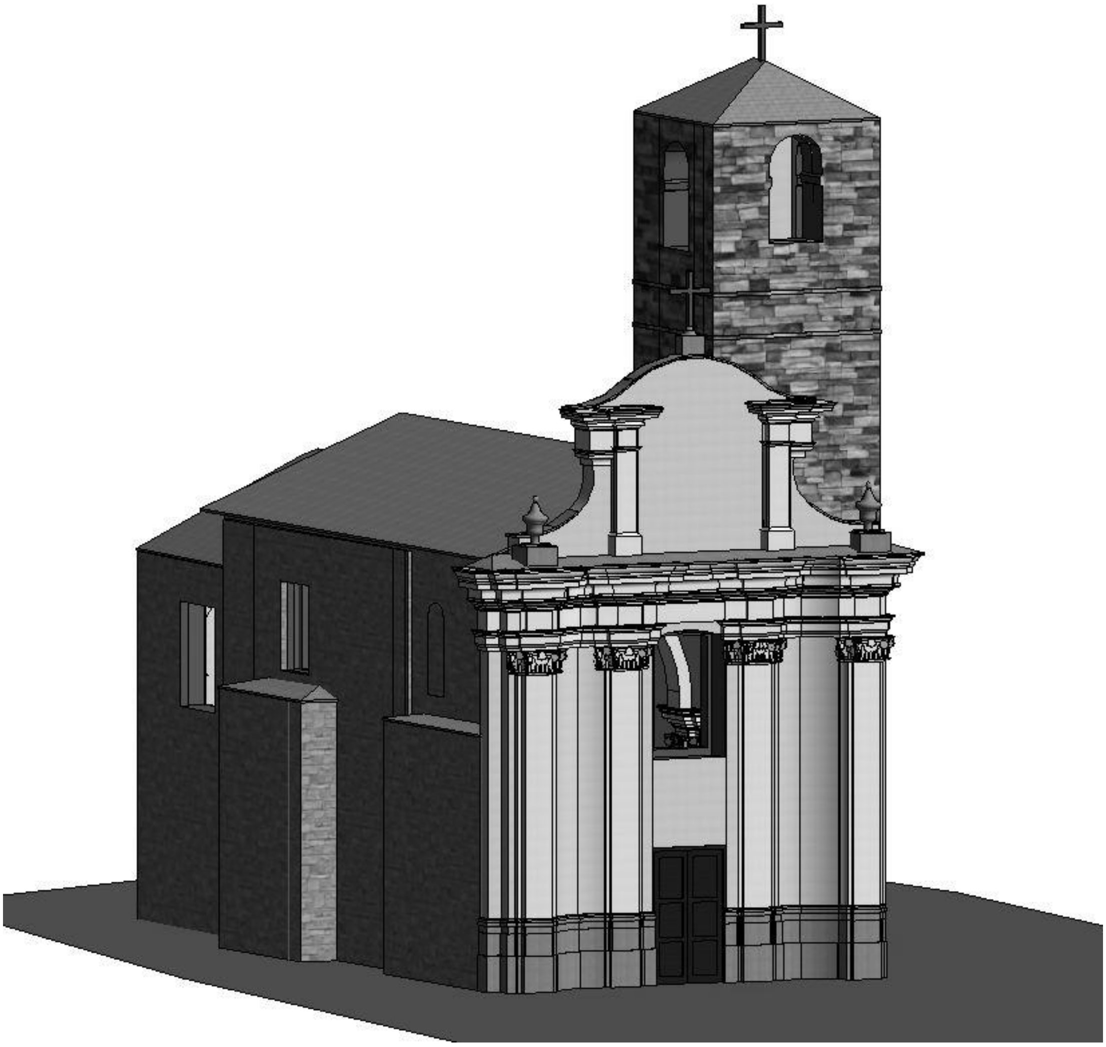


Figure 3.44: Exterior view of the church's BIM in its final form.

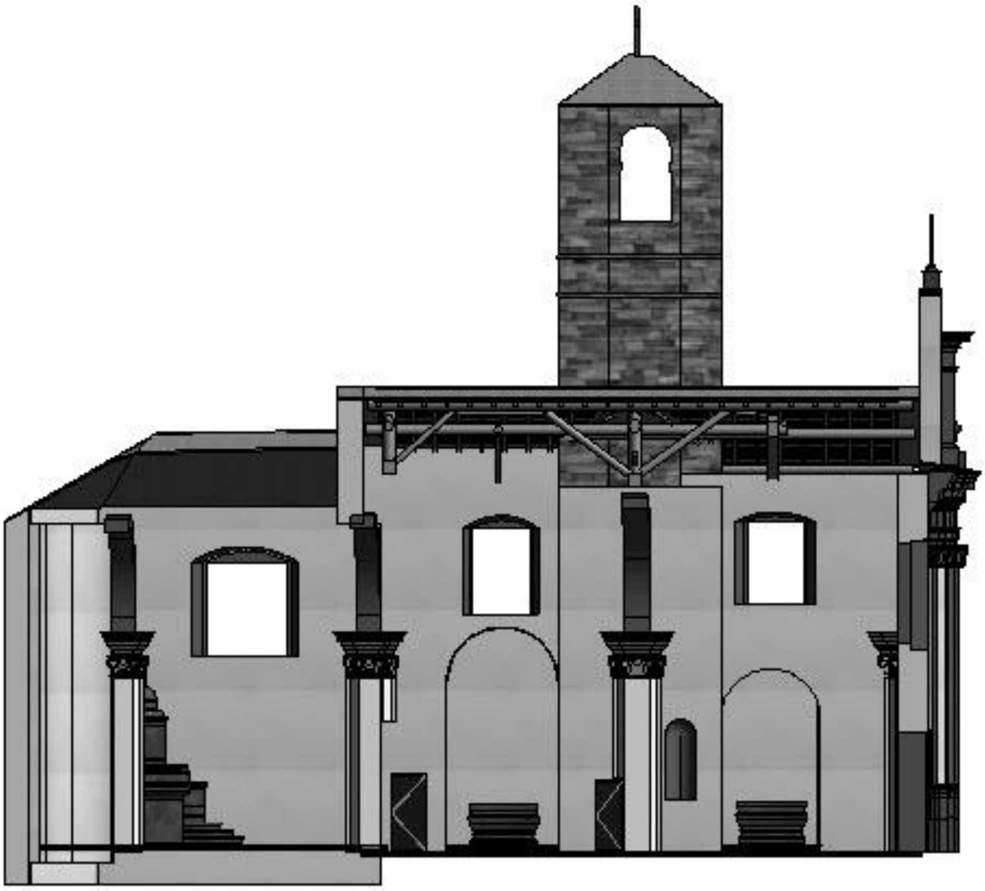


Figure 3.45: The interior of the church in EW section in its final form.

Phasing

One of the most important characteristics of Santa Maria's church is the fact that was completed after many different phases that refer not only to the structure of the church but also on its frescos and decorations. Therefore it was important that these phases were visible to the user by a color map. Revit® gives to the user the ability to create *filters* with the appropriate parameters that cover in each case their needs.

The phases were determined based on bibliographic research and testimonies and was decided that they would be synthesized in five (5) main phases chronologically, from the XV to the XIX century. The purpose of applying these phases was the creation of a "colored" model, where each color would indicate a different historic phase. For that to be done the stratigraphy analysis of Anna Raimondi was used as a guide (Figure 3.47, see Appendix-p. 125 for the color image).

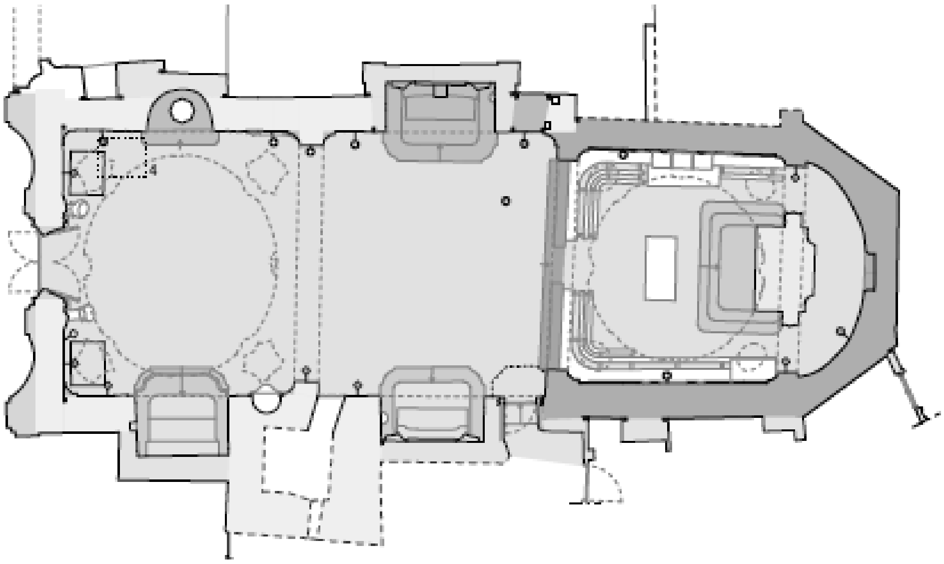
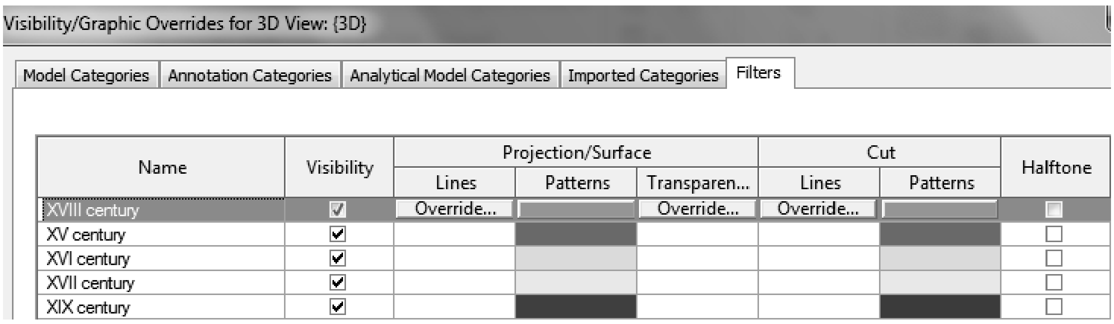


Figure 3.46: Part of the stratigraphy analysis were the different phases are visible in floor plan view–

screenshot from A. Raimondi's thesis.

In practice, through *Manage* menu a new *Project Parameter* named "history" was created, like a "text" parameter as each phase name would be defined by the user and was grouped under "phasing", as it would be used for determining different phases. Then the categories that this parameter would refer to were chosen.

For making the filters, inside the *Visibility/Graphics Overrides menu* a new filter was created for each one of the phases, by giving the name of the phase, selecting all the categories (the same like before) and applying the rule of the "history" parameter. Finally for each phase a different solid color was applied (Figure 3.48, see Appendix-p. 126 for the color image) and a "historic-colored model" was made (Figure 3.49, see Appendix-p. 126 for the color image).



Visibility/Graphic Overrides for 3D View: {3D}

Model Categories | Annotation Categories | Analytical Model Categories | Imported Categories | Filters

Name	Visibility	Projection/Surface			Cut		Halftone
		Lines	Patterns	Transparen...	Lines	Patterns	
XVIII century	☑	Override...		Override...	Override...		☐
XV century	☑						☐
XVI century	☑						☐
XVII century	☑						☐
XIX century	☑						☐

Figure 3.47: The filters for the historic phases.

Figure 3.48: Different views of the model after phases were applied.

3.5 BIM and Building Performance Analysis (BPA)

3.5.1 BIM and BPA integration

One of the major advantages of BIM, that has affected significantly the way AEC industry works, is its ability to produce models that can be analyzed from the standpoint of building life-cycle and energy efficiency. With BIM it is possible to iteratively test, analyze and improve a building design. This procedure is called *Building Performance Analysis* (BPA). As it has been already mentioned, the BIM models contain both geometric information and semantic characteristics of the structure. Therefore it is possible to estimate life-cycle energy costs, annual consumption, but also potential energy savings by using design alternatives.

The BPA performed in the case study of Santa Maria's church is a simulation with a lot of parameters taken as assumptions. The goal was to designate the potential BIM software, when used for energy analysis with the appropriate tools. This first energy analysis was performed with the integration of Autodesk's® Revit® 2013 and Autodesk's® web-basd energy analysis software Green Building Studio® (GBS) through *gbXML* format (Green Building Extensive Markup Language). GbXML is open schema helps facilitate the transfer of building properties stored in 3D building information models (BIM) to engineering analysis tools (gbXML Organization, 2000).

The concept of making the simplified model is based on some "rules" for the components that describe the Revit® Physical model, so that it is exported correctly like an Analytical model (Autodesk®, 2008). *Rooms* and *Spaces* are a fundamental element in the process of carrying out BPA: they dictate the majority of the geometry generated in the Analytical Model and also contain a great deal of the additional analysis parameters passed into the analysis software. If a Room is not accurate, then the analysis model will not be accurate too. Their difference is a matter of perception; architects use Rooms and focus to parameters like occupancy and engineers use Spaces and search for thermal loads. The extents of Rooms and Spaces are defined by the Elements that surround them. These Bounding Elements can be things like Walls, Floors and Roofs.

For this project Rooms and Spaces will be defined in the same way and the Analytical model will be based on Spaces. HVAC Zones (Heating, ventilating, Air Conditioning) were created automatically and respectively to the Spaces. This process is thoroughly described in the paragraphs that follow.

3.5.2 Building a Revit® model for BPA

It was decided that the proper way to make the energy analysis was the production of a simplified model of the church and the parochial house that was not designed before. For the parochial house, which is a modern construction, the floor plan of the ground floor was known and was assumed that it is the same for the other two floors (the one above and the other underground). In order to reconstruct the geometry, the floor plan made from the laser scans was inserted inside the Revit file as a design base.

The design process began by making the walls of the two constructions based on the floor plan above. Each wall needed to be characterized as exterior or interior, so different families were used. The interior walls refer only to the parochial house and it was decided to be a *Basic Wall- Generic 200 mm* family. By editing the family type the function of the wall was set to interior (Figure 3.50), while the construction material was maintained at its default value.

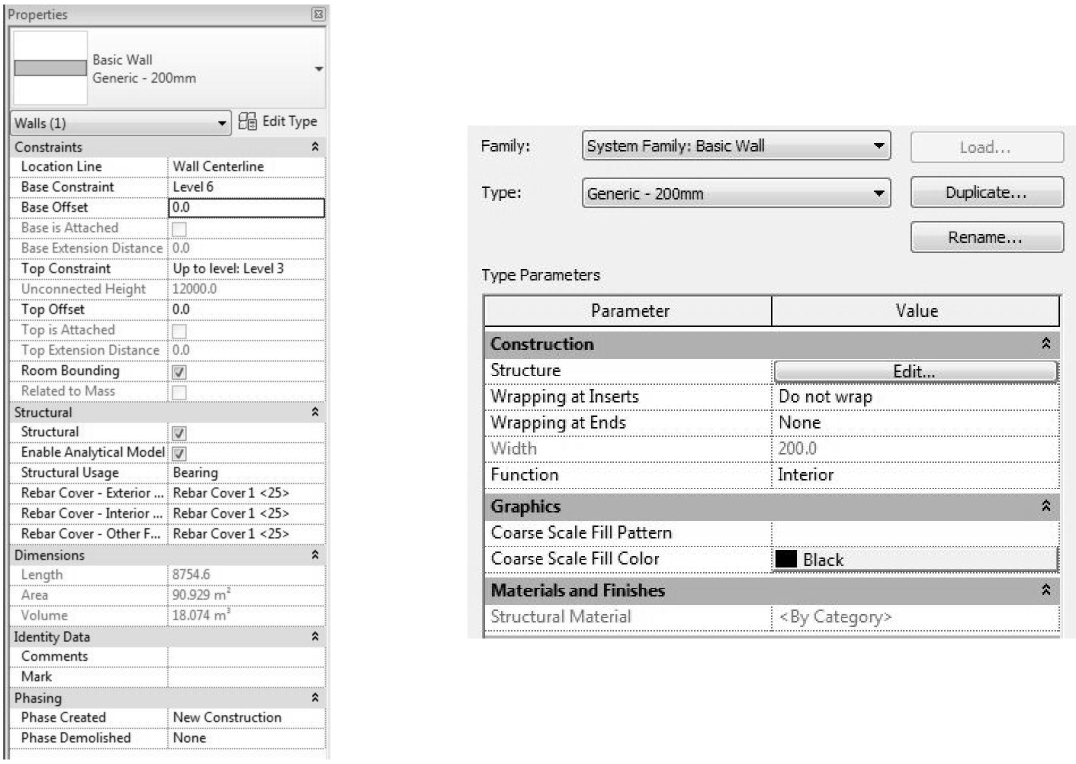


Figure 3.49 : The properties of the interior walls.

As imposed from the drawings of A. Raimondi, the thickness of the exterior and interior walls differs, but differs also between the two kinds of exterior. Those of the church are the old ones and have approximately a thickness of 700 mm, while they are made of stone and have also a layer of plaster. Those parameters needed to be changed so the family type *Exterior Scaria* inside the family *Basic Wall* was created. Similarly, another family type, *Exterior Scaria bell tower,* was made for the walls of the bell tower that differs from *Exterior Scaria* in the fact that there is no finish on the exterior part of the wall. For the external walls of the parochial house the predefined System Family and Type of *Basic Walls- Exterior Block on Mtl. Stud*, that has a thickness of 350 mm.

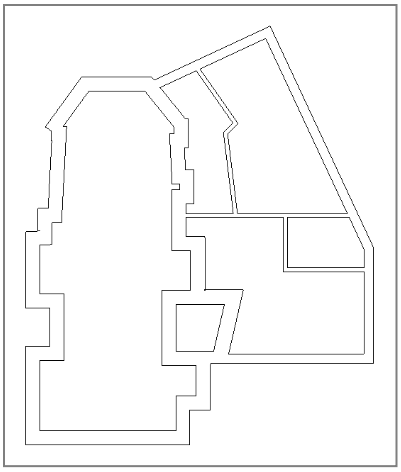


Figure 3.50 : The floor plan of the ground floor as designed in Revit® after the extrusion of the walls.

Then, ten levels (Figure 3.52) were made in order to be used as reference planes. They were used for adjusting the height of the church's and bell tower's walls and creating the two other floors of the parochial house. The height of the two first was known from the architectural drawings, while for the second it was set to 4 m based on a hypothesis (the common floor height in simple buildings). Two of these levels (red rectangular in Figure below) were set as *plenum levels*, so that the ceilings and floors are placed correctly as room-bounding objects, i.e. Rooms and Spaces are defined correctly.

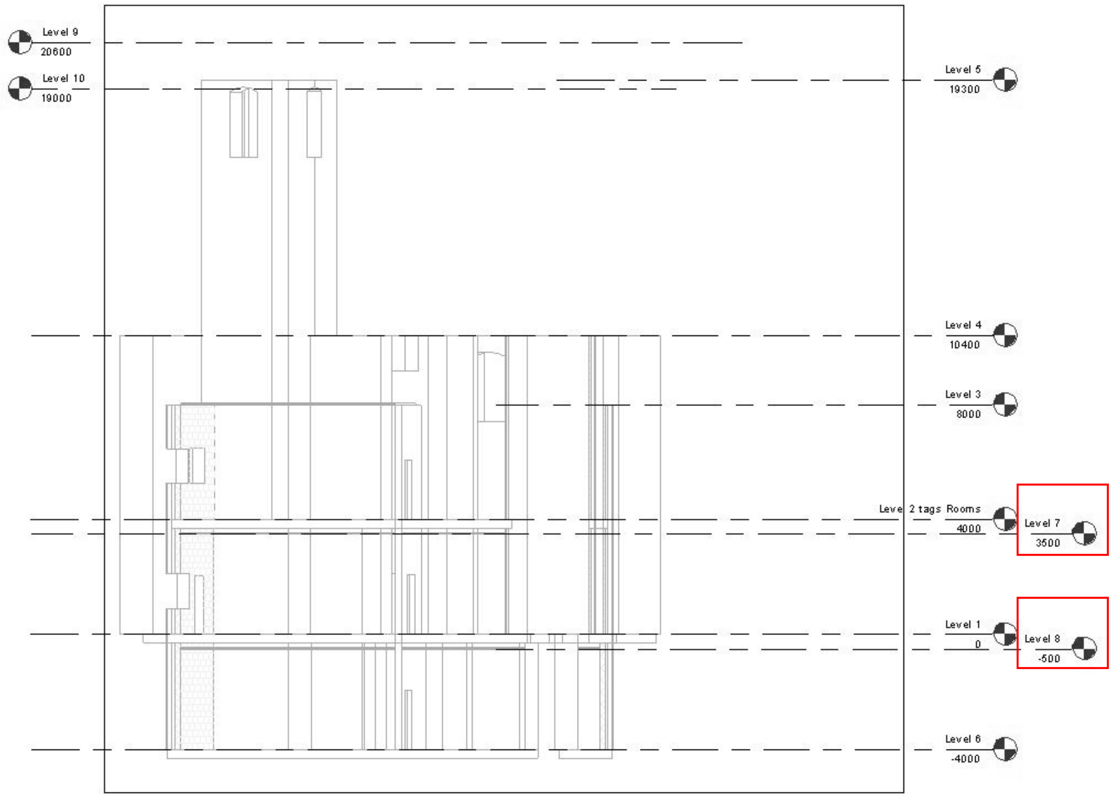


Figure 3.51: The levels of the project – section view.

After the levels' definition and the walls' reconstruction floors, ceilings and roofs could be created, each one at the proper height/level. Floors and ceilings were automatically created by selecting the boundaries i.e. the walls that form the different spaces. For the roofs, each footprint had to be drawn, which basically was the walls' axes of each building (Figure 3.53).

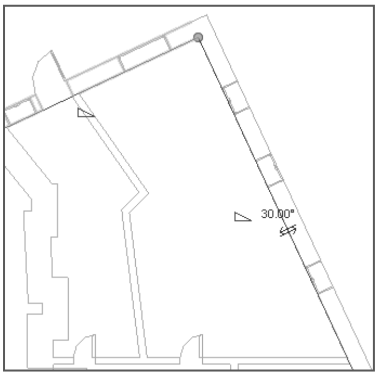


Figure 3.52: Screenshot from Revit®-Creating the footprint of the roof of the parochial house.

With all the bounding components of Rooms/Spaces created, their creation and tagging is pretty much automatic. Firstly, for each one of the floor plans of Levels 1, 3 and 6 two other floor plan views were created by duplicating the original. One of them was made for Room tagging and the other for Space tagging (e.g. *Level 1 Room tags, Level 1 Space tags etc.)*. From the *Architecture tab-Room command* an "X" cursor appears and Revit detects the boundaries of the Rooms on the floor plan of tags and with *Room tag command* the appropriate numbers and names were given. The same procedure was performed for Spaces, through the *Analyze tab-Space* and *Space tag commands.* Because Rooms were already created, Revit uses the same number and name to the correspondent Spaces. Figure 3.54 (see Appendix-p.127 for color image) shows Rooms' and Spaces' tags of Level 1 (ground floor), while the same procedure was performed for the upper and the underground floor of the parochial house.

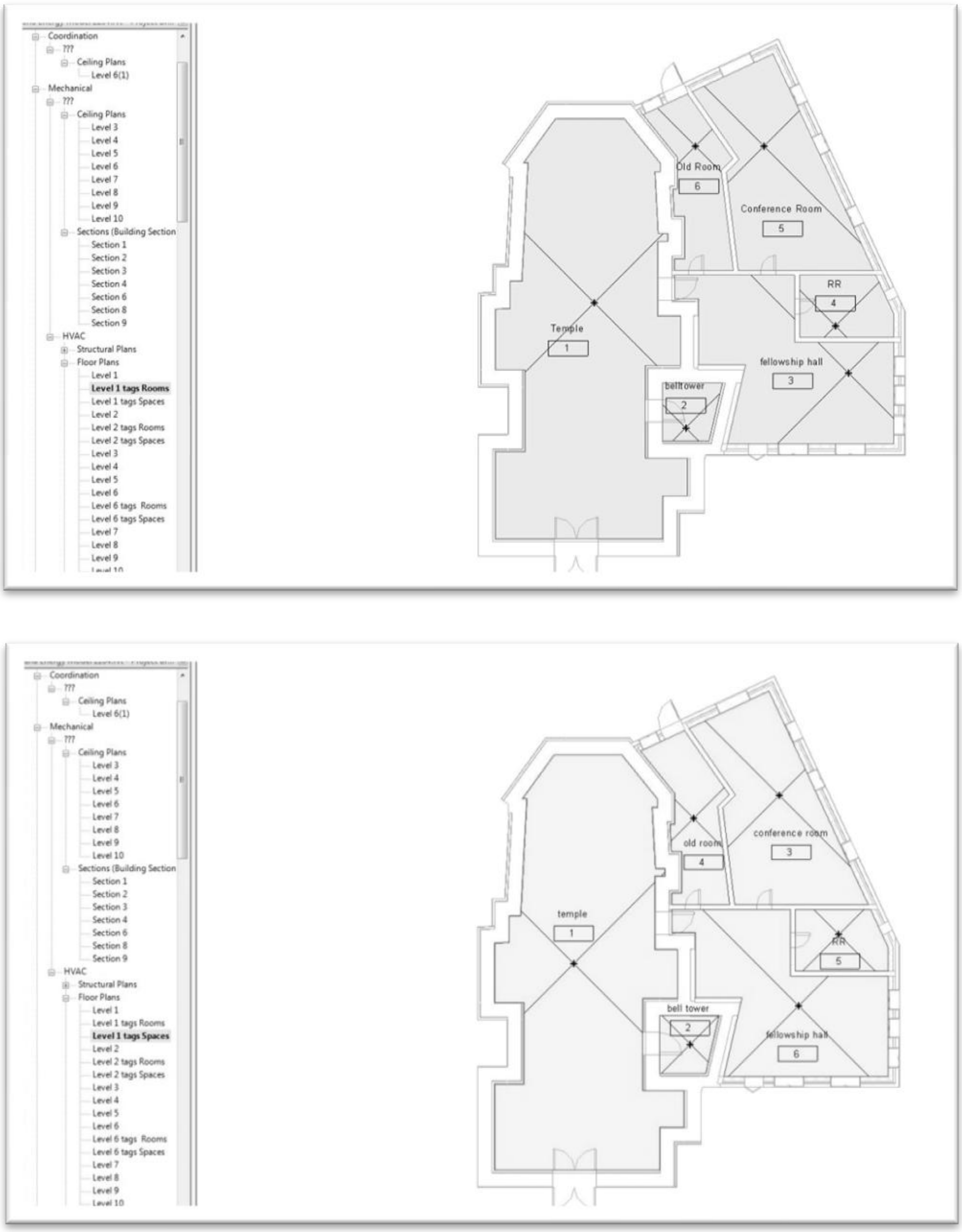


Figure 3.53: Screenshots from Rooms' (above) and Spaces' (below) tags.

The Rooms/Spaces “temple” and “bell tower” were defined only in Level 1 as it is their level of reference, while they have a *limit offset* a little bit higher of their construction height in order to include in the final *Volume Computation* the volume between the roof and that upper limit. The Rooms/Spaces of the underground and the ground floor had a limit offset equal to 4 m (common floor height) and the last floor’ s also with a limit offset a light bit more than the height of the building for the same reason.

The big advantage of Spaces is that they include information about the *Building Type* and from that more parameters can be applied to the model, even for each one of the spaces that consists of. In this project the Building Type was chosen from the list offered by Revit to be “Religious Building”. The other parameters that can be defined are:

- *Construction type*: It describes the materials of the components of the building and is set by the Building type, except if a new one needs to be made

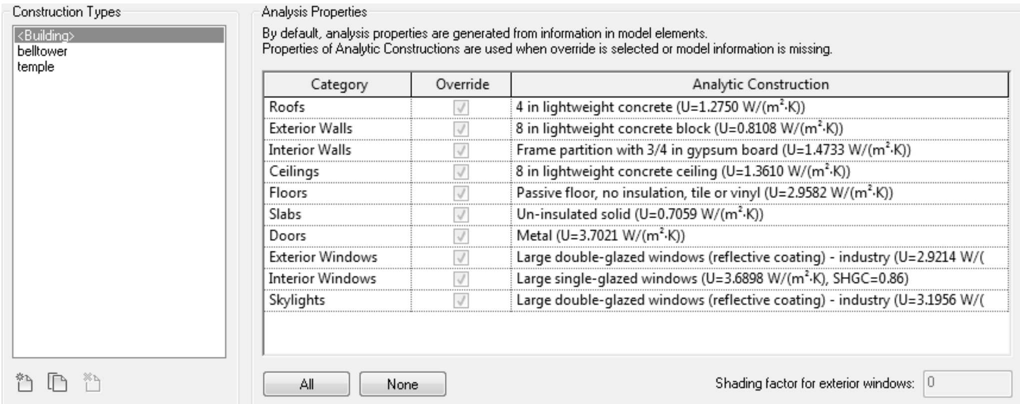


Figure 3.54: An example of *Construction Type – Religious Building* Analysis Properties.

- *Condition Type*: Defines the way a space is heated and cooled. The options are *Heated and cooled, Heated, Cooled, Vented, Naturally vented only.*
- *Occupiable - People*: If *Occupiable* box is checked then *People* field gets a value, either a default from Building type or the one that the user imposes
- *Electrical Loads:* Their values occur from all the above.

All of the parameters described above and much more can be shown in tables/schedules, which are easily created from the *Analyze* tab-*Schedule* command. Several categories can be scheduled from floors and ceilings to air terminals or spaces, and for each category a number of fields is assigned, and then added by the user in the schedule.

For example the following schedule contains the information about the spaces created in this project and provides an overview of characteristics that are crucial for the energy analysis, but also ‘check-points’ of their correct design like *Level* and *Limit Offset.*

Space Schedule 7									
Number	Name	Space Type	Construction Type	Condition Type	Number of People	Volume	Area	Level	Limit Offset
1	temple	Audience/Seating Area - Religious	<Building>	Heated and cooled	5	1084.97 m³	98 m²	Level 1	15000
2	bell tower	<Building>	belltower	Naturally vented only	0	99.75 m³	5 m²	Level 1	21000
3	conference room	Conference Meeting/Multipurpose	<Building>	Heated and cooled	5	117.66 m³	34 m²	Level 1	4000
4	old room	<Building>	<Building>	Naturally vented only	2	47.90 m³	14 m²	Level 1	4000
5	RR	<Building>	<Building>	Naturally vented only	2	31.24 m³	9 m²	Level 1	4000
6	fellowship hall	Fellowship Hall - Religious Building	<Building>	Heated and cooled	5	134.84 m³	39 m²	Level 1	4000
8	Conference Room	Conference Meeting/Multipurpose	<Building>	Heated and cooled	5	164.64 m³	34 m²	Level 2	6000
9	Room	<Building>	<Building>	Heated and cooled	2	63.89 m³	14 m²	Level 2	6000
10	RR	Restrooms	<Building>	Heated and cooled	2	43.81 m³	9 m²	Level 2	6000
11	Room	Active Storage	<Building>	Naturally vented only	0	117.66 m³	34 m²	Level 6	4000
12	Fellowship Hall	Fellowship Hall - Religious Building	<Building>	Heated and cooled	3	184.05 m³	39 m²	Level 2	6000
13	Room	<Building>	<Building>	Naturally vented only	0	31.24 m³	9 m²	Level 6	4000
14	Room	Active Storage	<Building>	Naturally vented only	0	56.86 m³	16 m²	Level 6	4000
15	Room	Active Storage	<Building>	Naturally vented only	0	137.60 m³	39 m²	Level 6	4000

Figure 3.55: Spaces' schedule of the project.

Next step was the placement of the windows. It was important to keep their relative size and shape. The interpretation of the photos taken outside the parochial house was necessary for verifying the windows' positions and shapes. For the windows of the church *M_Archtop with Trim-1830x2438mm* was used, a family that was suitable for our purpose. As for the bell tower openings, *M_Archtop with Trim-1220x2438mm* was modified in order to have that kind of opening on the bell tower but without the glass.

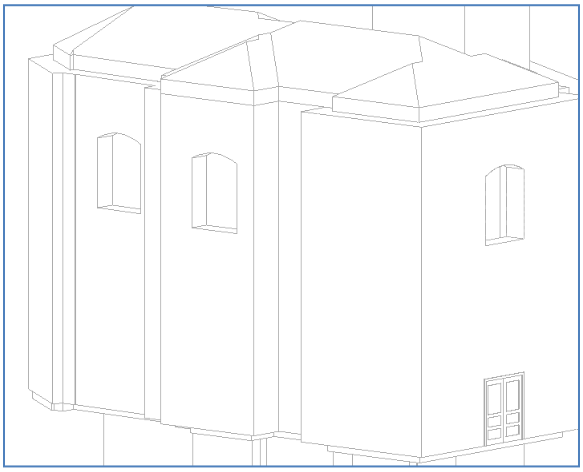


Figure 3.56 : Screenshot from Revit®- windows of the church

For the windows of the parochial house three kinds of windows were used, with reference to the photos for their size and position. All windows on the façade and most of the rest of the building were designed with the family *M_Casement DDL with Trim-812x1220* (while the two restroom windows with *M_Window Square Opening-400x600mm* (Figure 3.58, 3.60).

Figure 3.57: The façade of the parochial house, where the windows and the entrance are visible.

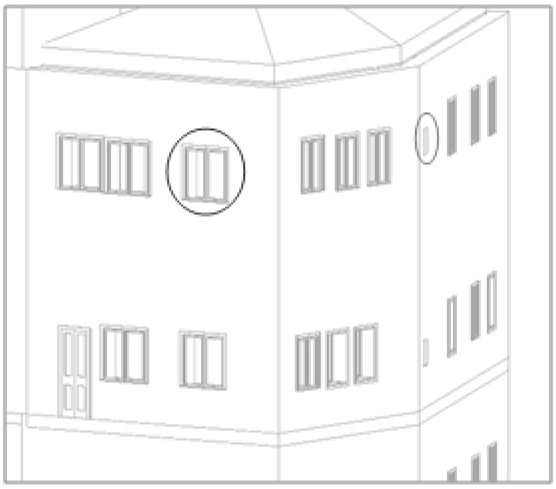


Figure 3.58: Screenshot from Revit®- windows and entrance of the parochial house designed by using the predefined families.

Figure 3.59: The bell tower of Santa Maria.

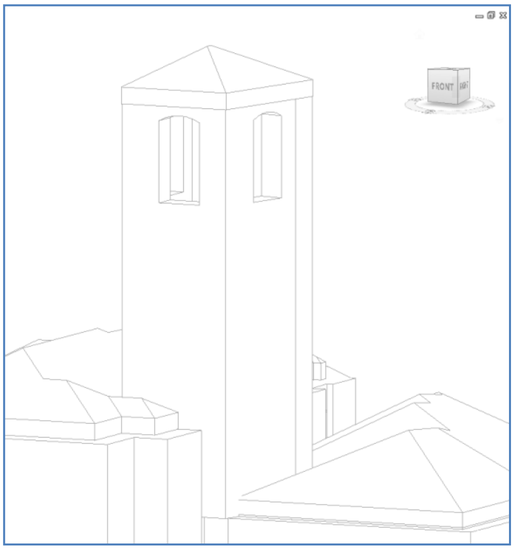


Figure 3.60: The bell tower in Revit® model.

Figure 3.61: The backside of the parochial house, where the windows and the two back doors are visible.

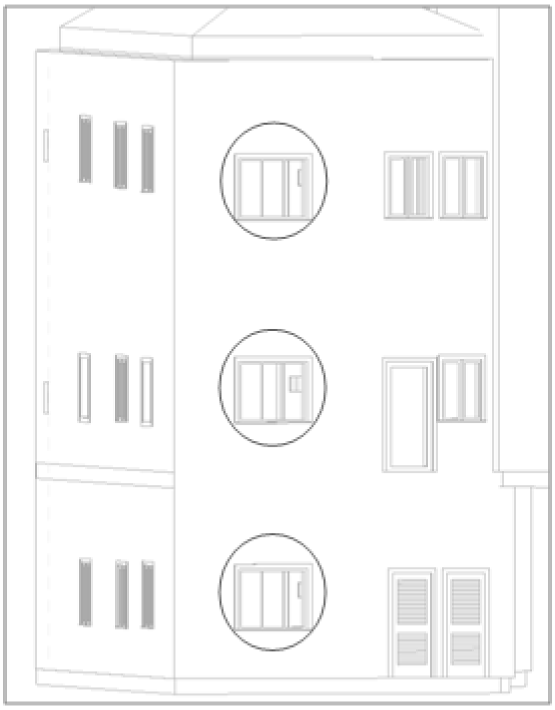


Figure 3.62: Screenshot from Revit®- the back side windows and doors of the parochial house.

With a similar approach, the necessary doors were placed inside the project. The church had one double door in its entrance and one interior door that connect it with the parochial house. For the church's doors *M_Double-Panel 1- 1730x2032mm* was used two times, one like as interior an done as exterior, while also the material was altered from metal (which was the default) to wood. The entrance door of the parochial house was placed like a *M_Bifold-2 Panel-762x2032mm*. The parochial house had also three exterior doors at the back side (Figure 3.61 & 3.62): one *M_Single Glass 1- 915x2134mm* and two *M_Single-Louvered- 762x2032mm*. For the interior door of the church and those of the parochial house the *M_Single-Cold Room- 610x2083mm* was chosen.

3.5.3 Performing BPA with Green Building Studio® (GBS)

Before exporting the model in gbXML format, it had to be checked that all the Spaces are formed correctly and that there are no gaps between them. In addition the model was orientated towards the north (approximately). The Export Menu gives a preview of the Spaces and the Analytical Surfaces of the model, as well as a full list of what is included (Figure 3.63 & 3.64, see Appendix-p.128 for color images).

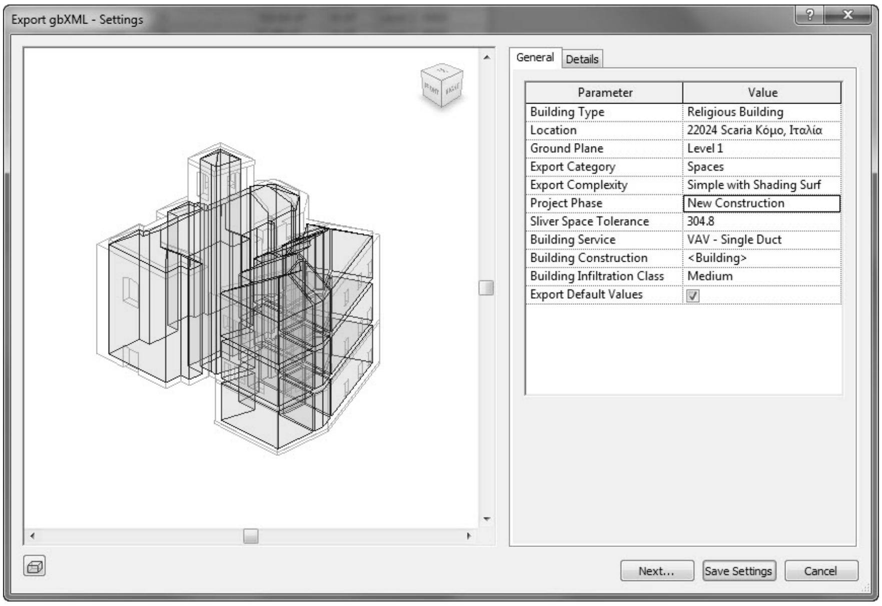


Figure 3.63: Screenshot from Revit®- Preview of the model's Spaces and some parameters of the BPA.

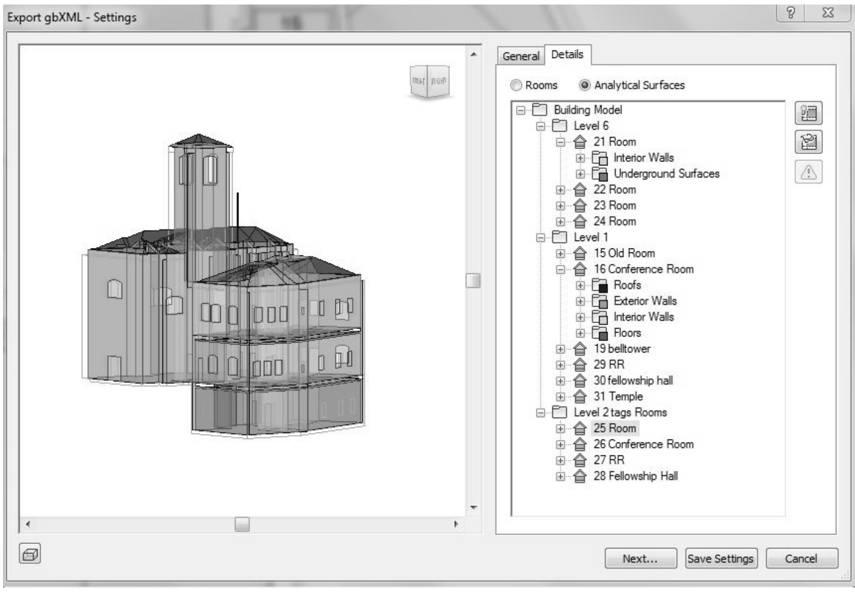


Figure 3.64: Screenshot from Revit®- Preview of the model's Analytical Surfaces.

GBS is easy software to perform a BPA with quite accurate results. In this case study, the purpose was to give an idea on how it could contribute in managing a religious facility from the standpoint of energy.

As mentioned before GBS was used for the BPA. In GBS few information need to be inserted: a name for the project, the type of the building (religious), the building schedule (worship), if it is an actual project and the location of the building from Google Maps®. Assumptions are made for the estimation of some values, which are presented above each result (example in Figure 3.67). Moreover CO_2 emissions are based on the on-site fuel use and the fuel sources for the electricity in the region and an equivalency using an SUV (driven 15,000 miles/year) is given to put the building's CO_2 emissions into perspective. From the location the appropriate weather data, the currency and the time zone are defined.

Detailed statistics, assumptions, and information on building constructions are also provided in *Building Summary* (Figure 3.65). This information allows the building designer to get an early assessment of code compliance and rough estimates of equipment sizing requirements for heating, cooling, and water heating, as well as window, wall, and floor area breakdowns when we refer to a building that is going to get built. For existing buildings this can be used as a quick overview.

Building Summary - Quick Stats

Number of People:	16 people ⬇
Average Lighting Power Density:	12.89 W / m² ⬇
Average Equipment Power Density:	8.31 W / m²
Specific Fan Flow:	3.8 LPerSec / m²
Specific Fan Power:	1.380 W / LPerSec
Specific Cooling:	12 m² / kW
Specific Heating:	6 m² / kW
Total Fan Flow:	1,489 LPerSec
Total Cooling Capacity:	33 kW
Total Heating Capacity:	63 kW

⬆ higher than typical value
⬇ lower than typical value

Figure 3.65: A summary of building 'energy' characteristics.

Roofs	4 in lightweight concrete U-Value: N/A	218 m²
Exterior Walls	8 in lightweight concrete block U-Value: N/A	1,051 m²
Interior Walls	R0 Metal Frame Wall U-Value: 2.35	661 m²
Interior Floors	Interior 4in Slab Floor U-Value: 4.18	349 m²
Underground Ceilings	8 in lightweight concrete ceiling U-Value: N/A	111 m²
Underground Walls	Basic Wall: Exterior - Block on Mtl Stud U-Value: 0.11	109 m²
	R0 8in (203mm) CMU UnderGnd Wall, assembly U-0.645 U-Value: 0.18	65 m²
Underground Slabs	Un-insulated solid U-Value: N/A	111 m²
Air Walls	Air Surface U-Value: 15.32	173 m²
Nonsliding Doors	R5 Door (14 doors) U-Value: 1.06	25 m²
Operable Windows	North Facing Windows: Large double-glazed windows (reflective coating) - industry (4 windows) U-Value: 2.92 W / (m²-K), SHGC: 0.13 , Vlt: 0.07	12 m²
	Non-North Facing Windows: Large double-glazed windows (reflective coating) - industry (33 windows) U-Value: 2.92 W / (m²-K), SHGC: 0.13 , Vlt: 0.07	41 m²
	Non-North Facing Windows: Large single-glazed windows (3 windows) U-Value: 3.69 W / (m²-K), SHGC: 0.86 , Vlt: 0.90	7 m²

Figure 3.66: A summary of building construction characteristics.

Base Run Hydronic Equipment		Note: this information should not be used for sizing purposes.
Domestic Hot Water	Average Demand	1,394

Base Run Air Equipment		Note: this information should not be used for sizing purposes.
Packaged Single Zone	Supply Fan Flow	1,436 LPerSec
	Annual Supply Fan Run Time	4,683 Hours
	Cooling Capacity	31
	Heating Capacity	61
Packaged Single Zone	Supply Fan Flow	52 LPerSec
	Annual Supply Fan Run Time	4,683 Hours
	Cooling Capacity	1
	Heating Capacity	2

Figure 3.67: Air and Hydronic equipment assumptions and characteristics.

It could be said that GBS provides two "groups" of information: the estimations of energy and the respective costs and what it could be changed towards a more "green" operation of the facility, and this how they are going to be presented consequently.

Energy and Carbon Results

Most building energy cost comparisons and early compliance decisions can be made using annualized energy cost and consumption information. Costs are estimated using statewide, territory, or country average utility rates (or even user-customized rates) and include both electric and gas consumption. CO_2 emissions are based on the on-site fuel use and the fuel sources for the electricity in the region. An equivalency using an SUV (driven 15,000 miles/year) is given to put the building's CO_2 emissions into perspective. The information provided with the perspective assumptions made, are shown in Figure 3.68:

1 Base Run

Energy, Carbon and Cost Summary	
Annual Energy Cost	€18,474
Lifecycle Cost	€251,621
Annual CO_2 Emissions	
Electric	6.7 Mg
Onsite Fuel	26.3 Mg
Large SUV Equivalent	3.3 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	1,732 MJ / m² / year
Electric	41,456 kWh
Fuel	527,554 MJ
Annual Peak Demand	17.8 kW
Lifecycle Energy	
Electric	1,243,679 kW
Fuel	15,826,629 MJ

Estimated Energy & Cost Summary Assumptions
30 -year life and 6.1 % discount rate for costs. Does not include electric transmission losses or the renewable and natural ventilation potential.

Figure 3.68: Estimated Energy and Cost Summary and the corresponding assumptions.

Energy End-Use Charts

Further breakdowns of estimated energy use for major electric and gas end uses, such as lighting, HVAC (Heating-Ventilation-Air Conditioning), and space-heating are provided in graphical format (Figure 3.69, see Appendix-p.127 for color image).

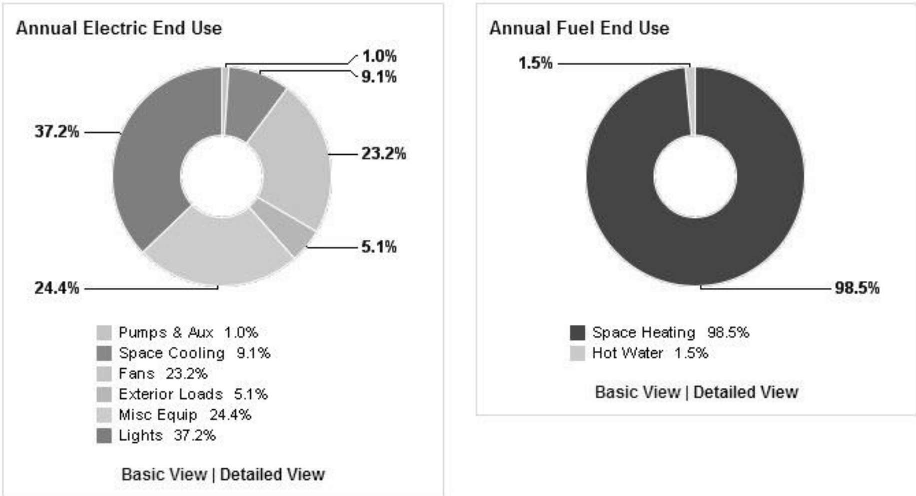


Figure 3.69: Charts of annual electric and fuel end-use.

Water Usage and Cost

A summary is given of the estimated water use in the building based on the number of people in the building as well as the building type. The water consumption is not related to the number of fixtures.

Water Usage and Costs

Total:	**1,830,332 L / yr**	**€1,969 / yr**
Indoor:	766,947 L / yr	€1,235 / yr
Outdoor:	1,063,385 L / yr	€734 / yr
Net Utility:	**1,830,332 L / yr**	€1,969 / yr

Source: AWWA Research Foundation 2000 Residential / Commercial and Institutional End Uses of Water.

Figure 3.70: Water usage and costs data.

Moreover, several charts for Monthly and Annual Data for Energy, Cost and Energy Use Intensity (EUI) are provided. EUI, or *energy use intensity*, is a unit of measurement that describes a building's energy use. EUI represents the energy consumed by a building relative to its size (Commercial Building Energy Consumption Survey -CBECS, 2003). An example of those charts is seen on the Figure 3.71 (see Appendix-p.129 for color image):

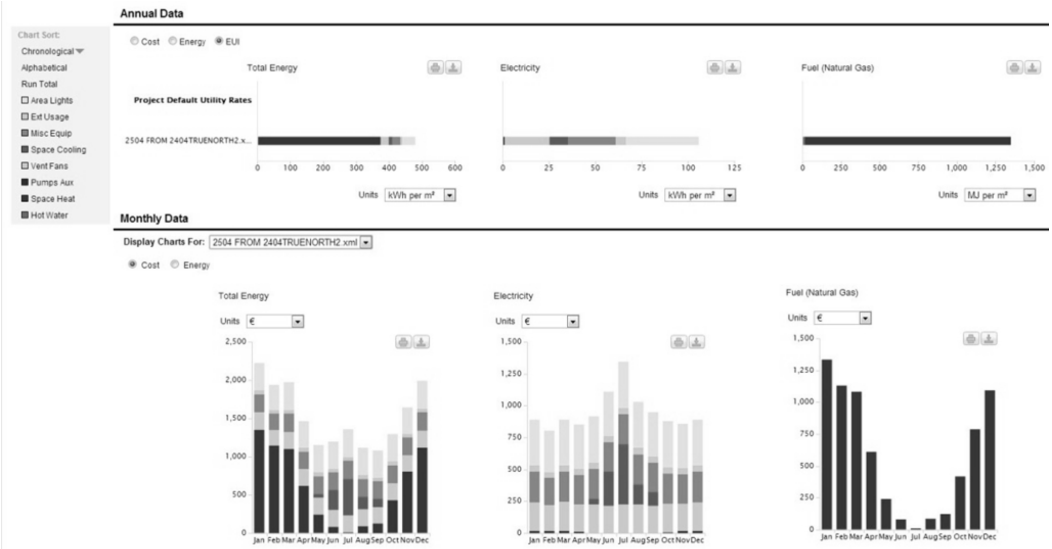


Figure 3.71: An example of charts provided by GBS- EUI annual and monthly data.

Getting to Carbon Neutral

As mentioned previously GBS provides information also for making a building energy efficient. One way to achieve that is to be designed as *carbon neutral*. Carbon neutral, or having a net zero carbon footprint, refers to achieving net zero carbon emissions by balancing a measured amount of carbon released with an equivalent amount sequestered or offset, or buying enough carbon credits to make up the difference (Wikipedia). The related information provided is:

Carbon Neutral Potential

This section summarizes the estimated CO_2 emissions for the building design and identifies the options to help reduce them. If the net CO_2 emissions are less than zero, there is a high potential for this building to be carbon neutral.

Carbon Footprint

Base Run Carbon Neutral Potential

Annual CO_2 Emissions	Mg
1 Base Run	33.0
Onsite Renewable Potential	-24.0
Natural Ventilation Potential	-0.3
Onsite Biofuel Use	-26.3
Net CO_2 Emissions	**-17.6**

Net Large SUV Equivalent: -1.8 SUVs / Year

Assumptions

Base Run Carbon Neutral Potential Assumptions

Carbon neutrality is defined here as eliminating or offsetting fossil based electricity and fuel use. For example, if the electricity grid is 60% fossil fuel and 40% hydroelectric, reducing grid electricity use by 60% and offsetting the onsite fuel use would make the project carbon neutral. Use any combination of efficiency, natural ventilation, onsite renewable energy, carbon credits and biofuels to reach this goal. Onsite renewable potential is the sum of the photovoltaic and wind potential shown below. Onsite biofuel use is assumed to replace onsite fossil-based fuel use for the project.

Figure 3.72: Carbon neutral potential and assumptions.

Electric Power Plant Sources

The U.S. Environmental Protection Agency has historical records for all the fuel and emissions of all power plants in the United States and the Carbon Monitoring for Action (CARMA) database has the carbon emissions data of more than 50,000 power plants world-wide. This section summarizes the fuel sources for electricity generated in this region. In order for a project to be carbon neutral, electricity consumption must be reduced.

Electric Power Plant Sources in Your Region	
Fossil	64 %
Nuclear	N/A
Hydroelectric	33 %
Renewable	3 %
Other	N/A

Figure 3.73: Electric power plant resources in the region of Scaria.

Photovoltaic Potential

The web service automatically analyzes every exterior surface of the building, including roofs, walls, and windows, for their estimated potential to generate electricity using photovoltaics. Exterior shades are not currently included in the photovoltaic analysis. The results of this analysis are summarized in this section. Note that this analysis assumes that PVs can be installed on vertical as well as horizontal surfaces as long as the surface generates significant amounts of PV power.

Wind Energy Potential

This section refers to the estimated annual amount of electricity that can be generated from one 15-foot-diameter wind turbine of conventional design.

Photovoltaic Potential (more details)	
Annual Energy Savings:	94,893 kWh
Total Installed Panel Cost:	€974,239
Nominal Rated Power:	122 kW
Total Panel Area:	882 m²
Maximum Payback Period:	28 years @ €0.28 / kWh

Wind Energy Potential	
Annual Electric Generation:	553 kWh

Figure 3.74: Photovoltaic and Wind energy potential data.

Natural Ventilation Potential

The tool approximates the annual operating hours and energy required to mechanically cool and ventilate the building. It also estimates the annual number of hours that outdoor air could be used to naturally ventilate the building. Potential energy savings associated with not running the mechanical cooling and ventilation system during this period are projected, and finally, the net hours that cooling is required, even with natural ventilation, are estimated.

Natural Ventilation Potential	
Total Hours Mechanical Cooling Required:	1,316 Hours
Possible Natural Ventilation Hours:	222 Hours
Possible Annual Electric Energy Savings:	1,350 kWh
Possible Annual Electric Cost Savings:	€373
Net Hours Mechanical Cooling Required:	1,094 Hours

Figre 3.75: Natural ventilation data.

Summarizing all the above, it becomes clear that GBS could be a valuable tool for estimating the energy behavior of a building as long as the financial aspect of it, but also provides some basic information of how to improve the facility's operation and minimizing the energy consumption and cost. If for example the parochial house starts to operate like a little museum (as the municipality of Scaria intends to do), it would be easy to estimate the differences and determine the sources needed for its operation by easily adjusting parameters like the occupancy, the working schedule and the building type.

4. FIRST SPECIFICATIONS AND CONCLUSIONS

BIM software is designed for modern architectural buildings, therefore it sets some limitations when applied to Cultural Heritage documentation and management. The complex geometry that characterizes such buildings can be handled parametrically, but requires a certain level of expertise in 3D perception and modeling, otherwise the design process could become more time consuming.

Hence, the creation of libraries with parametric architectural elements could be a viable solution in Cultural Heritage applications. This requires a deep research and elaboration on the data that define a monument (drawings, historic references) in order to define the elements in the best way possible. But after that this data need to be shared among the experts which means that the development of a ‘common language’ is essential. This ‘common language’ is not other but the IFC standard, with feature classes specially designed for architectural/heritage applications that could fully describe the complex objects of those cases.

In addition, the models that BIM software handles are simplified surfaces. Some geometric details may not be described completely, while also the rendering of them is limited –at least for the time being- to solid colors or images of the precast materials in a repeated pattern. Like in this case study, products like orthophotos or textured models cannot be directly inserted into the BIM model, making the visualization more complete but adding also important knowledge.

Complementary to the above, data like laser scanning point cloud could not be exploited as they could, taking for example the case of the vaults. For extracting a surface that could preserve the geometry but at the same time to be a surface that other information could be applied, e.g. materials or phase of construction, external tool had to be used (GreenSpider® add-in). Hence, further investigation of how point clouds could be managed inside BIM software for best representation of the surfaces is deemed to be necessary.

It should be also investigated how to design the elements from the point cloud directly inside Revit® in an easier way. Until now the procedure is really time consuming and does not provide to the user the design level that a Cultural Heritage application would need. For the case study of Santa Maria for example, all the geometric information was taken from the drawings produced with Cloudworx® in AutoCAD®. It is a fact that laser scanning techniques are most common tool in surveys of built heritage; therefore any development in that field could be really beneficial.

Nevertheless, it should be highlighted that in this diploma thesis only Revit® 2013 was tested. That raises questions about the choice of the suitable software and that further research should be done, in order to explore the capabilities of others. Contemporary BIM software provides a profusion of tools that can facilitate the design and management the n-D models that they generate. And for that the user should be aware of which to use and how, in order to leverage the most of the BIM technology and apply it in challenging cases like those of built heritage. In this diploma thesis Revit®’s familiarization was a “learning-by-doing” procedure, while searching solutions for the special needs of this project.

Selecting a BIM approach for documenting and managing built heritage means that the basic design component is the object itself as it is in reality (a wall or a column) and not the lines that define it and that comes along with all of its properties. These three-dimensional detailed virtual models are a useful tool for improving remote access to data that could support advanced programs for preventive conservation and guarantee sustainable interventions and maintenance during the building's life cycle (Oreni et al., 2013, submitted for publication- CIPA conference). In that, BIM models' and BPA integration can be added too for making a more accurate approach in energy efficiency issues.

Last but not least, the contribution of the Surveying Engineer in such projects should be commented. Undoubtedly, the collaboration with Architects is necessary while 'interpreting' and "understanding" the monument, learning its history and defining the needs of the documentation and 3D modeling. In addition an Architect is essential in pointing out characteristics like the materials or ways of construction of the various elements, information that an Engineer is not trained to 'extract' from the monument.

Also, a Surveying Engineer lacks experience in 3D design, but due to the good perception of space that he has, it is possible to improve the design skills with personal effort and correct guidance from someone more experienced. All in all this process is a fine example requiring interdisciplinary approach.

Moreover, the use of different data sources that are used in Cultural Heritage projects requires the critical eye of an Engineer, especially when a part of them are topographic-photogrammetric data. The knowledge of their accuracy and reliability but also what and how good products someone can obtain from them, gives the Surveying Engineer an important role in the decision-making process and not to just follow the Architects' opinions.

Summing up, this diploma thesis proves that the role of the Surveying and Geomatics Engineer is not limited to the data acquisition and processing, but it can reach a higher level with the appropriate help and personal effort. Therefore, a Surveyor can be deservedly a member of an interdisciplinary research group that has as goal the substantive 'interpretation' and management of a Cultural Heritage's building.

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APPENDIX

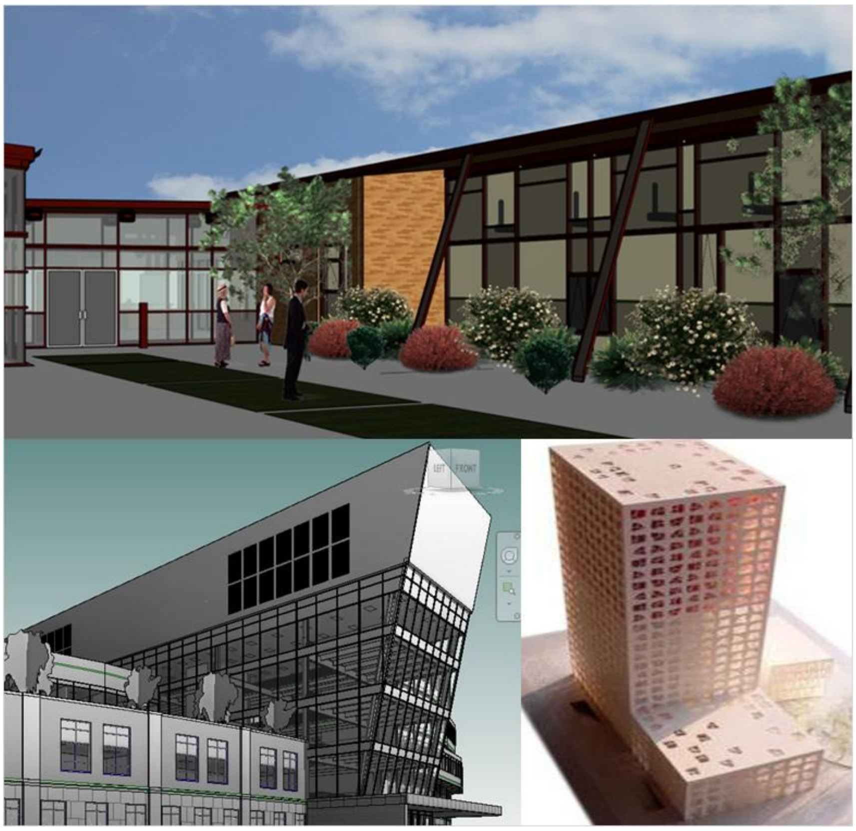


Figure 2.4.1: Architectural Design in Revit®.

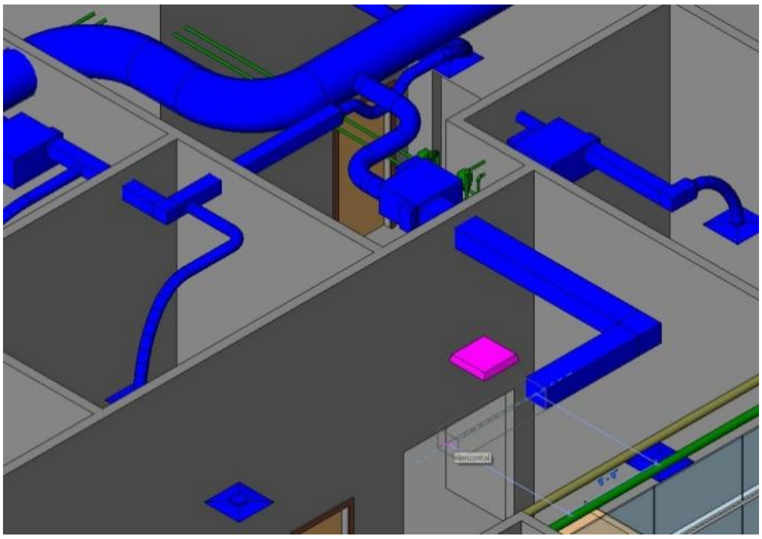


Figure 2.3: Part of a MEP system.

Figure 2.9: CityGML model showing semantic classes.

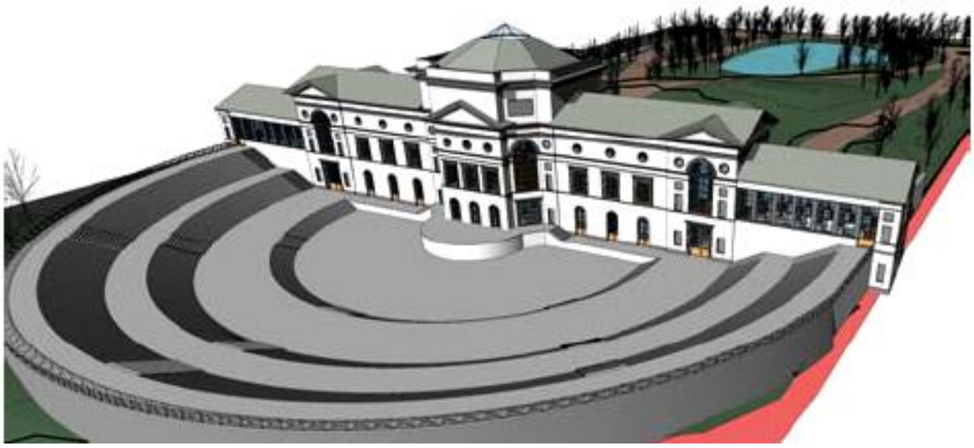


Figure 2.10: Exterior view of the BIM model of the Casino in Ghent.

Figure 2.13 : Geometric building components that are annotated to the 'central hall' of the Casino in Ghent.

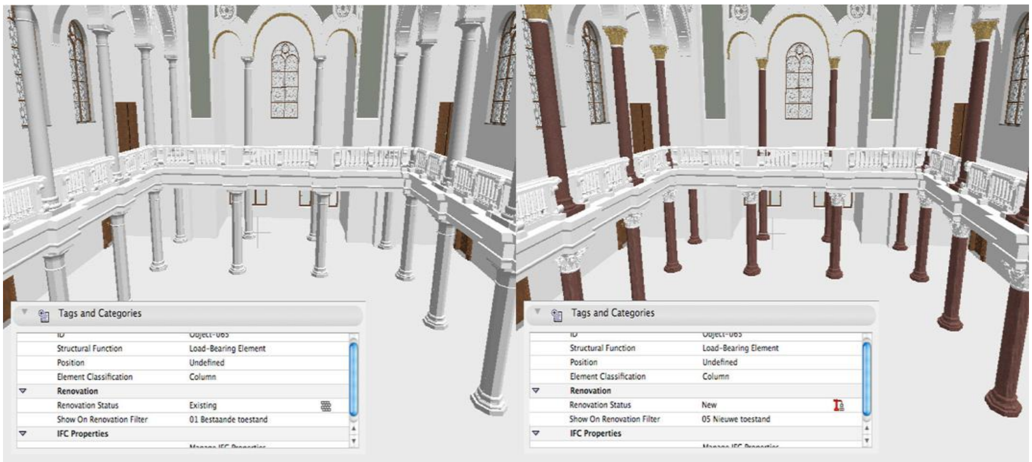


Figure 2.15 : Visualization of assumptions.

Figure 2.16: Comparison between historical photograph and interior rendering.

®.

Figure 3.14: The orthomosaic produced with ArcMap .

Figure 3.15: The example area to be refined.

Figure 3.17: The new orthomosaic of the example area.

Figure 3.18: Part of the arch on the orthomosaic from LPS (above) and Image Master (below).

Figure 3.19: The textured model of the example area.

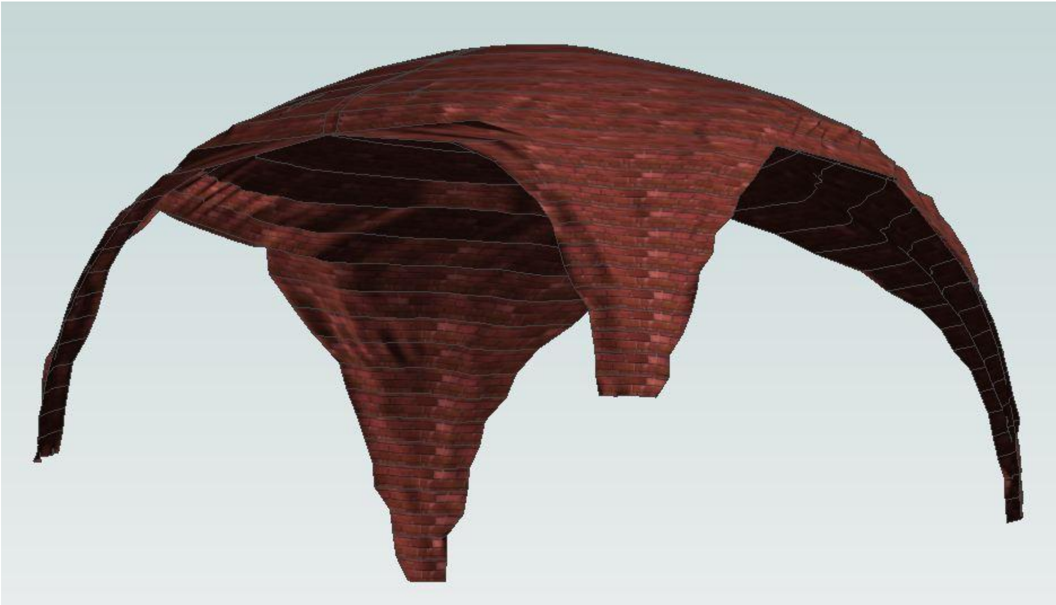


Figure 3.39: The first vault modeled with GreenSpider®.

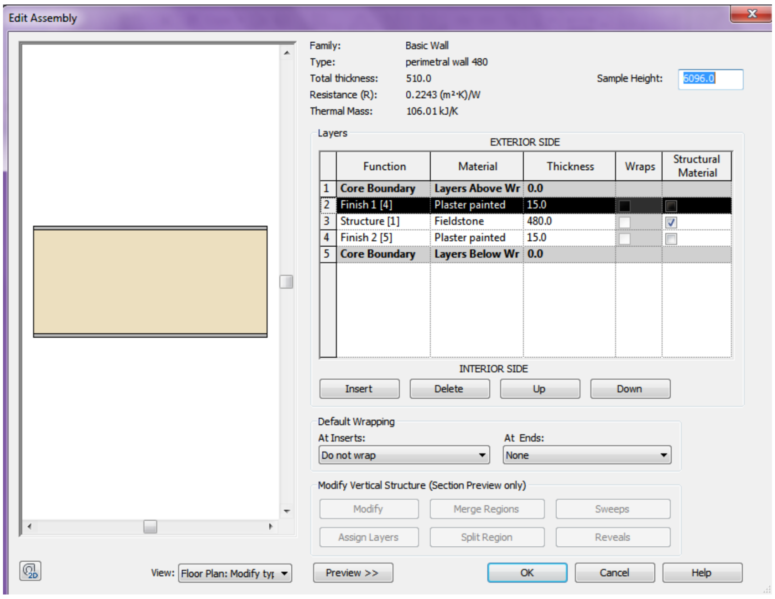


Figure 3.43: Modifying the material layers of the wall family “perimetral wall 480”.

Figure 3.44: Exterior view of the church's BIM in its final form.

Figure 3.45: The interior of the church in EW section in its final form.

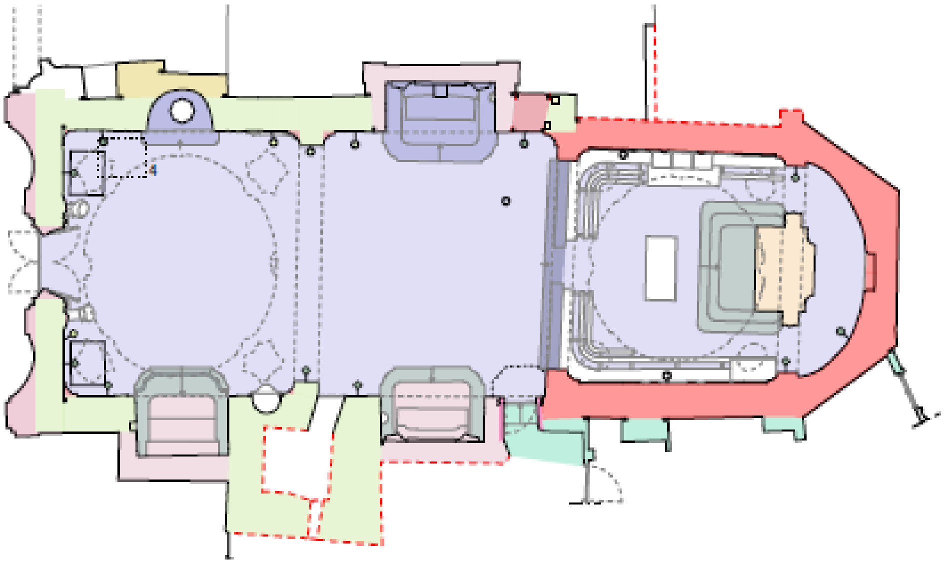
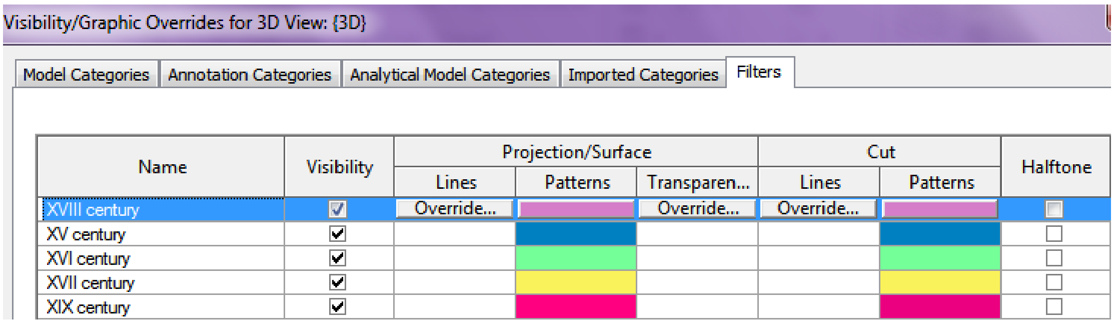


Figure 3.46: Part of the stratigraphy analysis were the different phases are visible in floor plan view– screenshot from A. Raimondi's thesis.



Visibility/Graphic Overrides for 3D View: {3D}

Model Categories | Annotation Categories | Analytical Model Categories | Imported Categories | Filters

Name	Visibility	Projection/Surface			Cut		Halftone
		Lines	Patterns	Transparen...	Lines	Patterns	
XVIII century	☑	Override...		Override...	Override...		☐
XV century	☑						☐
XVI century	☑						☐
XVII century	☑						☐
XIX century	☑						☐

Figure 3.47: The filters for the historic phases.

Figure 3.48: Different views of the model after phases were applied.

Figure 3.53: Screenshots from Rooms' (above) and Spaces' (below) tags.

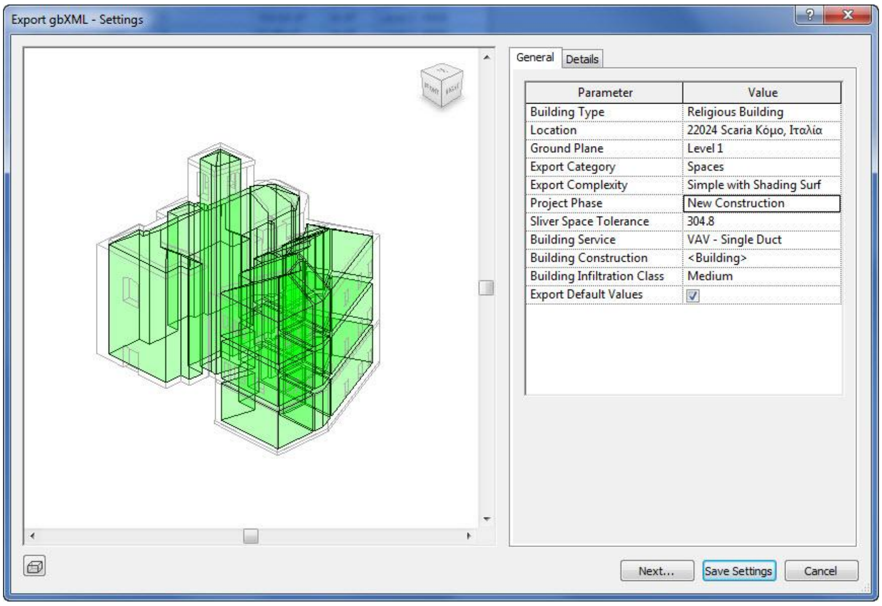


Figure 3.63: Screenshot from Revit®- Preview of the model's Spaces and some parameters of the BPA.

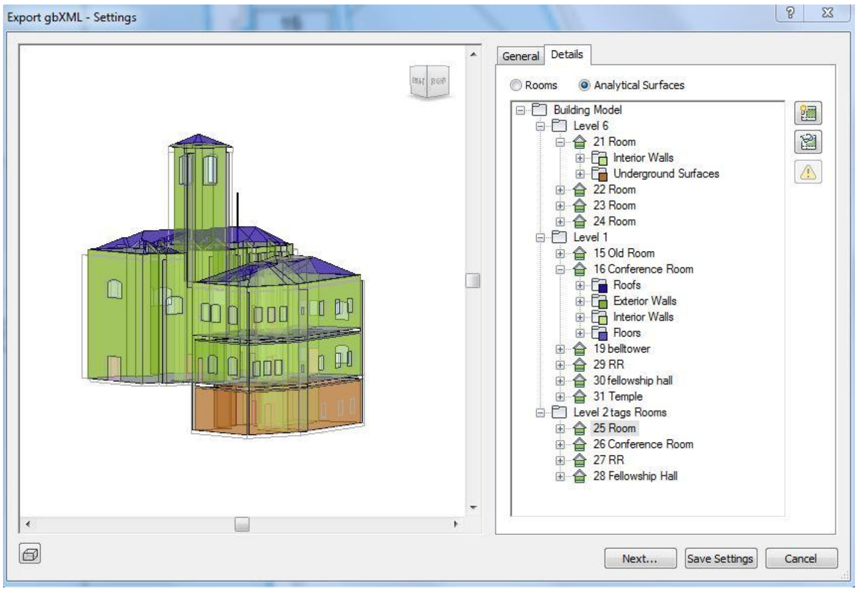


Figure 3.64: Screenshot from Revit®- Preview of the model's Analytical Surfaces.

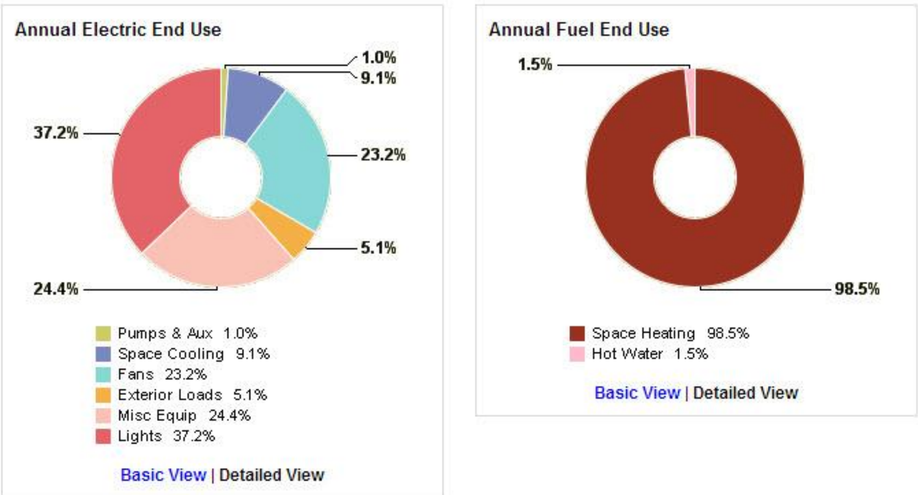


Figure 3.69: Charts of annual electric and fuel end-use.

Figure 3.71: An example of charts provided by GBS- EUI annual and monthly data.