

*AUTOMATIC RECOGNITION OF 3D
BUILDING MODELS FROM POINT
CLOUDS, FOR CONSTRUCTION
INSPECTION*



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ΜΟΝΤΕΛΩΝ CAD ΑΠΟ ΝΕΦΟΣ ΣΗΜΕΙΩΝ
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ABSTRACT

Building Information Models (BIMs) are becoming more popular in the construction industry for encoding, reusing, and exchanging information about structural assets. Automatically generating such representations for existing constructions is expected to play a significant role in building inspections. Image-based 3D reconstruction techniques or 3D scanners can be used to capture dense 3D measurements of a facility's as-built condition and the resulting point cloud can be manually processed to create an as-built BIM — a time-consuming, subjective, and error-prone process that could benefit significantly from automation. In this thesis we develop an automated method to assess the compliance of design specs in a building. Experimental results are presented with data obtained from simulated building scans and show the potential of the proposed approach for as-built dimension calculation and control. The method provides detailed information about the dimensional deviations of the as build model with respect to the as designed. These deviations are calculated at the level of individual building surfaces. Using this information the compliance to the building regulation is assessed. The evaluation of the system was based on experiments on a case study where different versions of a simulated scanned As-Built model were checked with the As-Designed BIM. The primary results presented in this thesis were successful in recognizing matching regions of building components between the examined models, calculating their dimensional deviations and assess the compliance of the As-Built model with the building regulation limits. The results provide evidence that this potential method can be successful in building inspections. More extensive field experiments will follow to characterize its performance in practice.

ΠΕΡΙΛΗΨΗ

Τα τελευταία χρόνια η μοντελοποίηση της κτηριακής πληροφορίας (Building Information Modeling) γίνεται όλο και πιο δημοφιλής στον κλάδο των μηχανικών. Η δυνατότητα ενοποίησης των διαδικασιών σχεδίασης, υλοποίησης και διαχείρισης ενός κτηρίου σε ένα τρισδιάστατο μοντέλο, είναι το βασικό πλεονέκτημα τους. Η αυτόματη δημιουργία τέτοιων μοντέλων για υφιστάμενες κατασκευές, προβλέπεται να παίζει σημαντικό ρόλο στον τομέα της επιθεώρησης και του ελέγχου των κτηρίων. Η αποτύπωση και ο έλεγχος ενός κτηρίου με τεχνικές τρισδιάστατης ανακατασκευής από φωτογραφίες ή με τη χρήση 3D Laser σαρωτών προϋποθέτει την χειροκίνητη επεξεργασία του νέφους σημείων που λαμβάνουμε από τις τεχνικές αυτές. Πρόκειται για μια διαδικασία χρονοβόρα και επιρρεπή σε σφάλματα, η οποία θα μπορούσε να επωφεληθεί σημαντικά από την αυτοματοποίησης της. Σε αυτή την εργασία, αναπτύξαμε μια μέθοδο ελέγχου συμμόρφωσης των κατασκευαστικών διαστάσεων ενός κτηρίου με τα όρια που θέτει ο οικοδομικός κανονισμός. Τα πειραματικά αποτελέσματα που παρουσιάζονται, βασισμένα σε δεδομένα που έχουν ληφθεί από προσομοιωμένες σαρώσεις κτηρίων, δείχνουν τη δυναμική της προτεινόμενης προσέγγισης για τον υπολογισμό των διαστάσεων και του ελέγχου της υφιστάμενης κατασκευής. Η μέθοδος υπολογίζει αναλυτικά διαστάσεις σε κατασκευαστικές περιοχές ενός κτηρίου, και τις αποκλίσεις τους από το θεωρητικό μοντέλο της οικοδομικής άδειας του κτηρίου. Οι αποκλίσεις αυτές υπολογίζονται σε επίπεδο επιφανειών των κατασκευαστικών στοιχείων που συνθέτουν το κτήριο. Με βάση αυτή την πληροφορία, εκτιμάται η συμμόρφωση της κατασκευής με τον οικοδομικό κανονισμό. Η αξιολόγηση του συστήματος βασίστηκε σε πειράματα, όπου διάφορες παραλλαγές ενός προσομοιωμένου κατασκευασμένου κτηρίου ελέγχθηκαν έχοντας ως αναφορά ένα θεωρητικό BIM μοντέλο. Τα αποτελέσματα που παρουσιάζονται στην εργασία εμφανίζουν την ικανότητα της μεθόδου να αντιστοιχίζει επιτυχώς τις περιοχές του κατασκευασμένου κτηρίου με το θεωρητικό, να υπολογίζει τις αποκλίσεις ανάμεσα στις περιοχές και να ελέγχει τη συμμόρφωση των διαστάσεων με βάση τον οικοδομικό κανονισμό. Τα αποτελέσματα δείχνουν ότι η μέθοδος μπορεί να έχει πιθανή επιτυχία στον έλεγχο των κτηρίων. Περαιτέρω πειράματα βασισμένα σε πραγματικές μετρήσεις θα ακολουθήσουν για την αξιολόγηση του συστήματος στην πράξη.

Σημείωση:

Η εργασία είναι γραμμένη στην Αγγλική γλώσσα. Για ευκολία προς τον Έλληνα αναγνώστη, έχουν προσαρτηθεί στο παράρτημα οι διαφάνειες από την ελληνική παρουσίαση της εργασίας στην εξεταστική επιτροπή του μεταπτυχιακού, που πραγματοποιήθηκε στις 24 Ιουνίου 2015.

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1 INTRODUCTION – MOTIVATION

Construction industry is crucially different from manufacturing: the latter usually relates to the mass production of similar items without the purchaser usually being known beforehand. Construction, on the other hand, is done for a specific client, and on-location [1]. In developed countries, construction as an industry amounts to a six to nine percent of their gross domestic product [2]. Construction initial phases include planning, design, and financing of a project; it then continues until said project is built and ready to be used.

Construction is in no way a single activity nowadays; even more so, large-scale construction can be considered an affair directly related to human multitasking. Under normal conditions a project manager manages the job, which a construction engineer or manager, an architect or a design engineer supervise. It is easily understood that effective planning is essential for the successful execution of a project. There are a lot of things that must be considered before and during the execution of the project in question by those involved: among them, zoning requirements, environmental impact, effective scheduling and budgeting, safety regulations within the construction site, the availability and transportation of the needed materials, their logistics, inconveniences caused to the public caused by possible delays in construction to name only a few.

Construction generally comprises of three sectors: infrastructure, industrial, and buildings[1]. Building construction can be further categorized as residential and non-residential (or commercial and institutional). Infrastructure is often registered as heavy/highway, heavy civil or heavy engineering: Those terms incorporate large public

works, bridges, motorways, water/sewage networks and utility distribution. Finally, Industrial construction refers to projects such as refineries, chemical processing plants, power generation or manufacturing plants and mills, to name only a few. Other divisions, into markets or sectors, break the industry further [2].

Construction has not adopted industrialization techniques of an equal level to other sectors of the industry. Automation is uncommon, or at least low-degree in construction processes. The main factors to this are: 1) This industry is intense in labor and site-based, 2) Weather conditions heavily affect it and 3) its projects are quite often unique and singular[3].

This industry is in constant need of project performance assessment with as much speed and precision as possible. Metrics that can track performance in an efficient and meaningful manner have to be utilized. As an example, progress during construction and tracking of productivity require quantity and building elements' progress assessment, or assessment of conducted tests, etc. The evaluation for 3D similarity between as-built and as-planned three-dimensional objects is, among other facets, required for construction quality assessment. The common methods to assess construction progress depend on intensive manual collection and processing of data. Such manual tasks usually are hard to undertake, costly, and in many cases only partially effective in producing correct information. This results in difficulty in making management decisions that are fast and correct [4].

The immobile property's legal framework must be fitting to the related construction project. Such legal framework contains all governmental regulations related to the use of property, and obligations during the construction process. The project in question must conform to possible zoning and building code laws. Such laws state that building inspections are performed on structures at different stages of construction [5]. Such inspections are needed to assess compliance with the relevant enforceable laws and regulations related to building, plumbing, electrical, mechanical or other construction issues.

Unlike the shift to more industrialized building methods and widespread use of prefabricated building elements which is observed in other countries [6], constructions in Greece present differences in the building techniques, the legal framework and the inspections carried out during the creation of a construction project [7]. For this reason,

this thesis focuses primarily on Greek reality, without however preventing it to find application in other countries.

1.1 Overview of Construction in Greece

Constructions are one of the basic pillars of Greek economy and one of the most dynamic sectors of the Global market. They consist of a multitude of products and services, which differentiate, depending on their position in the process of production and evaluation of construction works. The services of buildings' and infrastructure (i.e. roads or other constructions for the benefit of the public) constructions by technical and construction entrepreneurs, as well as other specialized construction undertakings (demolitions, electrical and hydraulic installations etc.) are within the core of this sector.

In Greece, according to a study by the Foundation of Economic and Industrial Research (IOBE) , this sector's contribution during previous year was estimated at 11% of Gross Domestic Product (GDP), while today, due to the financial recession, it is estimated at about 4% [7]. Despite the great decline of construction activity, the contribution of this branch to the Greek economy remains important, as it supports various other financial sectors and its influence is multipliable within the broader scope of the country's economy.

The narrow core of Construction represented, during 2013, 1.6% of the total added value and 4,7% of the total employment within the Greek economy. The close interconnection of construction activity not only with the industry of construction and other materials that are used in construction, but also with architectural / technical studies' services as well as commerce, with the addition of the substantial support it provides towards the realization of investment works in sectors such as tourism, industry and commerce, as well as the housing and urban planning development, make Constructions an especially important sector towards the evolution and development of Greek economy.

The construction sector is influenced by a plethora of financial, regulatory and structural factors, many of which have radically varied during the last years' crisis. Bureaucratic obstacles often set unnecessary barriers in real estate sales and licensing of construction works.

The absence of a full-fledged zoning and urban planning design makes transactions vulnerable to future modifications, thusly postponing important investments. The existing

system of zoning designs shows weaknesses in the fields of planning, application, tracking and updating.

The system is characterized by:

- Overregulation and complexity of the current legal and regulatory framework.
- The existence of multiple, often overlapping, levels of design and unnecessary restrictions which discourage entrepreneurship.
- Time consuming and ineffective procedures of designing, approval and revision of zoning and urban planning projects.

At the same time, important problems rise within public works, with a result, in most instances, of delays and budget exceeds, without necessarily better, more qualitative results. All the above, despite the fact that their influence isn't easily measurable, are important factors that define the evolution of the constructions branch.

The size and status of building reserve defines the needs of developing or renovating buildings and residence. For this reason, it presents a special interest for the constructions' branch, as it includes potential benefits, because of aging as well as attrition of a big portion of this building reserve. The total number of residences within the boundaries of the Greek state were 6.4 million in 2011, out of which a big portion (1,4 million buildings) was built during the '70s. During the decade of 200, a total of 986.000 buildings were constructed, about the same number as the previous decades of '80s and '90s. The big majority of buildings (about 55%) has an age of over 30 years (they have been built before 1981). In the other end, about 7% was built after 2006, which means that it had an age of 5 years or less in 2011.

The characteristics of the buildings' reserve, as well as the needs for interventions at older buildings, could prove beneficial for the branch of constructions, as the renovation or replacement of the aged building reserve is an important sector of potential market growth, under the prerequisite that the conditions of financing within the economy will have been stabilized.

According to the conclusions of this IOBE study and the proposals of the Association of Enterprises for the Quality and Development of Constructions (SEPAK), in paragraph 5.2 a series of measures for the recovery of constructions are proposed. Within these proposals, an emphasis is given to *the need of promotion and development of organized building, as well as the reform of the building reserve*. Also the need for modernizing the institutional framework is presented, in matters that pertain to the quality of materials,

studies and construction, not only at the public but also at the private sector, toward a direction of qualitative upgrading of the constructions' branch.

1.2 Construction Inspection

By State Law 4030/2011 «New method of Issuing of Building Permits, Construction Checks and other Clauses» [5], mandatory checks for every work that is executed with a building permit were instituted, which are made by responsible controllers *with a local check («autopsy»)* and *a check of the correct application of the studies, on the basis of which the building permit was issued*. Currently, any new building that is constructed, has to be checked so that the legitimacy of its construction and its accordance to the approved building permit are confirmed.

In Greece, even today, *there's a lack of knowledge of the true status of the built environment*. There is no database that contains, in an organized manner, information on the existing buildings within a given area, their constructional data etc. So, with the aim of recording of the real status of the real estate properties in the country, and of the acquisition of a complete overview of constructed areas, since January, 2014, the creation of a building identity has been put in piloted application [8]. The identity of the building will be registered with the electronic records of the Ministry of Environment by a private engineer and will consist of all the data of the building permit and all the property, static and energy data of every existing real estate property.

For all these data to be filled out, a check of the building under examination will have to take place, of an analogous kind of the check that building controllers make in new constructions. After they collect the data by making a local check («autopsy») and take necessary measuring, they will compare the data with the data included within the building permit of the existing building. This move is expected to contribute to a more correct developmental zoning planning of the country, as well as to countering illegal building.

1.3 Technical Framework

Building Information Modeling (BIM) is 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 [9].



Figure 1.1 The life cycle of a building. (source: Advance Solutions Design Software, <http://www.advancedolutions.com/images/2016/services/bluepoint-services.jpg>)

The rising use of BIM models by architects, engineers and constructors has led to a reducing of the cost and the time needed to build, as well as the improvement of communication between the parties involved in the design and construction of a building. This technology offers a series of possibilities and benefits, not only during the phase of conceiving and designing a building, but also during the process of its construction and use. A building, while being the product of an architectural study in the form of a CAD model, in reality contains more data and is more complex than the corresponding building described within the study. And it is common for the final building constructed to have differences to the theoretical model, important to a bigger or lesser degree. In some cases, a digital model might not be available at all. The tracking of construction works of a building is an important factor within the whole process. The compliance to the plans of the building permits and the design specs is a thing of concern not only to the responsible authorities, but also the engineers involved. The knowledge of the true condition of a building is essential to matters related to its use, as well as future renovations.

1.4 Purpose and aim of this thesis

On the basis of all the aforementioned, it is apparent that a large number of building inspections by autopsy is required. Therefore, the automation of the autopsy process of an existing building or part of it, as well as the legal check of the building presents special

interest. The benefits from such an approach are many: Capturing speed, accuracy and credibility of the measurements, transparency of checks etc.

The measuring of a building can be made faster by using Laser or Image Scanning systems [10]. The result of such measurements is more credible, as the total of a building is recorded, by dense point clouds, in contrast to the taking of point distances by conventional measuring with the use of a measuring band [11]. Additionally, by fully automating the process, the integrity of checks can be ensured [12].

It is also essential for methods of modeling of building information that pertains to the «as-built» condition of a building. This requires the capturing of the three-dimensional condition of a real building and its comparison to its three dimensional CAD design. Today the main method of capturing and evaluating of built spaces [13] is the manual measuring with conventional systems and the rebuilding, with the use of these capturings, of an updated As-Built CAD plan [11]. The technology of Laser Scanners offers the possibility of recording of complex surfaces and areas, which could be used in the building of BIM models that are suitable to track construction works and check compliance of said works in relation to the specs that have been set by its design.

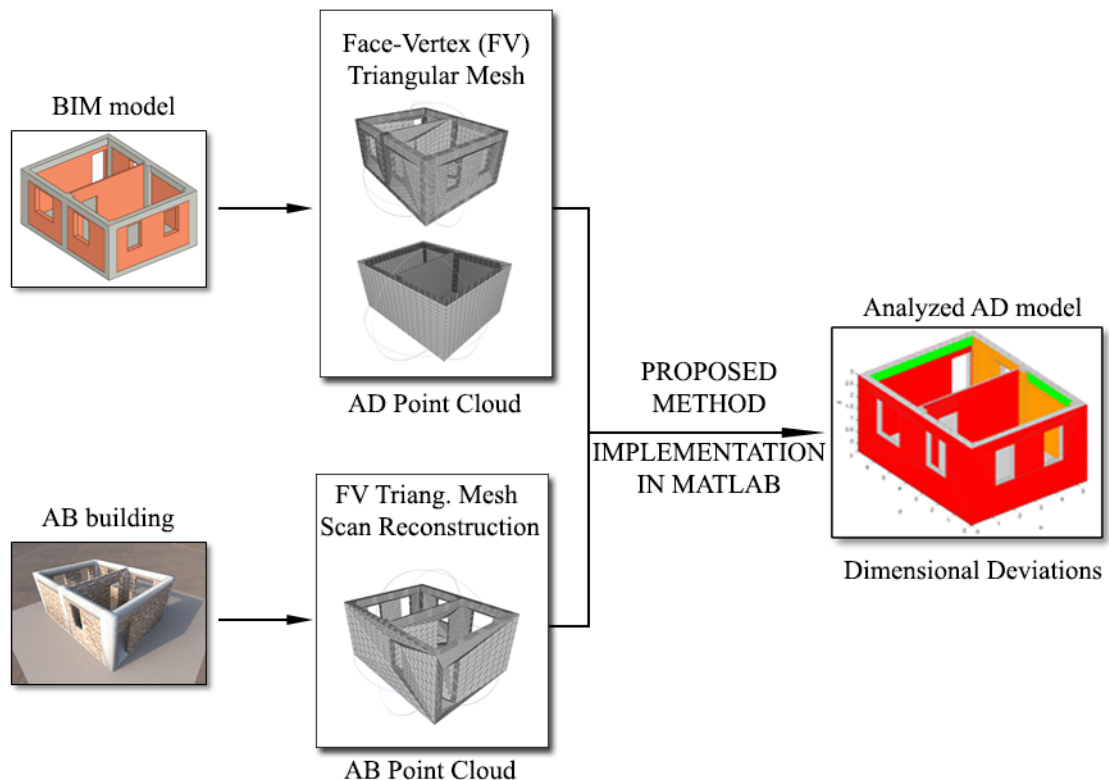


Figure 1.2 Overview of the Proposed Method’s main idea

Within this thesis, we develop an automated method to assess the compliance of design specs in a building. The method accepts two inputs: i) a 3D point cloud from the scanning of a constructed building, and ii) an existing BIM model of the building. The method provides detailed information about the dimensional deviations of the as build model with respect to the as designed. These deviations are calculated at the level of individual building surfaces. Using this information the compliance to the building regulation is assessed.

1.5 Existing Research

The AEC (Architecture-engineering-construction) community has, during the recent years, begun to widely accept techniques for three dimensional (3D) imaging and analysis of as-built conditions of buildings. The reason for this is that such techniques have been recognized as having the potential to advance the industry, especially considering that by their use, defects on construction sites can be detected earlier, reducing the danger of project budgets being consumed because of construction defects.

1.5.1 Automated Cad Model Recognition and Quality Assessment methods of As-Built models

The as-built modeling process with AD BIM focuses on two areas: (i) the area of checking that the as-built conditions actually match the as-designed conditions (geometry checker), and (ii) in case of mismatches, the *area of updating the existing BIM to reflect the actual as-built conditions*.

Image based Techniques

The progress of a construction can be tracked by use of vision-based systems, some of which are more suitable for this task [14–17]. The general methodology of such system is as follows: the first step is the registration of digital pictures of the site, and the registration of the project's 3D Computer-Aided Design (CAD) model in a common coordinate system by use of techniques that estimate camera. The following step compares the site's digital pictures to the project model's data. Various different alternative approaches can be used for this comparison. For examples, in some cases each of the 2D images is compared with a corresponding virtual image generated using the 3D model and the estimated camera pose [15,18].

In [14] a comparison between the CAD model and a 3D model that has been reconstructed from the site pictures takes place. Finally, in [16,17], an approach similar to [15] is proposed by Lukins et al., with an added step which compares each picture to pictures

that have been previously captured using the same camera pose. Regions of interest are identified as regions of the images that show significant changes since the previous shot, and a search for newly built elements is only conducted within these regions of interest.

The work of Lukins et al. [16,17] shows great potential: It employs a high automation level (human intervention is limited to camera installation and its initial registration with the project's CAD model), it is resilient and reliable to varying environmental conditions, and it can distinguish regions of interest to conduct examination and detect progress.

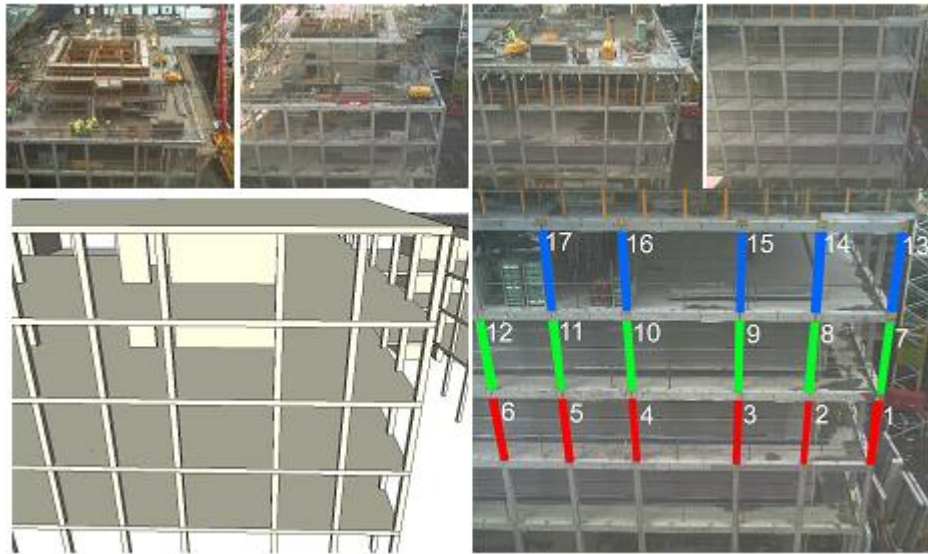


Figure 1.3 Building progress tracking. Example of column detection.
(reproduced from [16])

These methods still have limitations directly related to:

1. The size and type of changes that can be detected,
2. The object detectors, and the region-of-interest sensitivities to changing lighting conditions, especially when shadows are present,
3. The resilience to unexpected closings (occlusions) which are common in construction sites and may lead to false detection of regions of interest, and subsequently to false object detection; and
4. The difficulty to give solutions in the existence of depth ambiguities.

For the check of dimensional compliance, Ordóñez et al. [19] follows two differing image-based approaches aimed at controlling flat elements' dimensions. Yet, both of them need significant human input: the points to be measured have to be manually selected. Shih and Dunston [20] have also recently shown success on evaluating Augmented Reality (AR) for steel column inspection (anchor bolt positions and

plumbing). Such results show the possibility of accurate steel column inspection based on Augmented Reality. Again, this system needs significant human interaction, and users skilled in 3D visualization and 2D projection that are required for the registration of the images' model. All these sadly lead to expensive and time-consuming inspections, even though the results reported can be accurate.

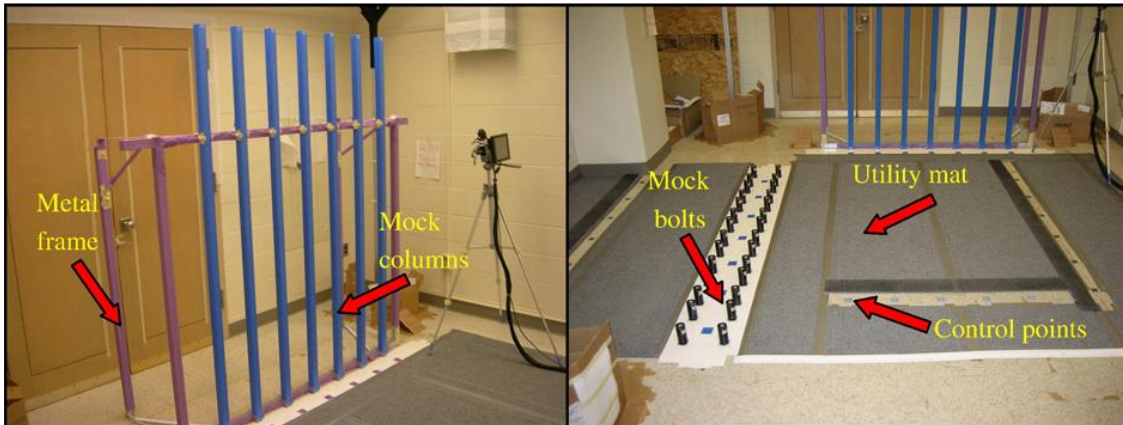


Figure 1.4 Evaluating Augmented Reality (AR) for steel column inspection. this system needs significant human interaction and skilled users. (reproduction from [21])

As a conclusion, as Rabbani and van den Heuvel [22] already note, even considering that major advances have taken place in image processing during recent time, image-based approaches -particularly when dense stereo-vision is not applied- are almost sure to remain limited. The reason is that their aim is to extract dense 3D data from 2D images, presenting a difficult-to-solve problem that is ill conditioned, particularly in complex scenes such as those of construction sites. Goldparvar- Fard et al. [15] present a method which enables the user to extract sparse 3D data from a series of images by utilizing the structure-from-motion principle. However, no results have yet been published demonstrating the possibility to automatically analyze such sparse 3D data in a reliable way and manage to procure accurate information related to progress or dimensional quality.

1.5.1.1 3D Scanning based Techniques

Compared to digital imaging, the advantage of laser scanning is that it actually acquires 3D data with good accuracy [23]. For this reason, even considering that they are expensive to acquire (between 40.000€ and 90.000€ for a standard scanner), laser scanners show attributes that can be effectively used to track 3D projects' status and subsequently, track progress tracking and control dimensional quality [17]–[20].



Figure 1.5 The FARO Focus^{3D} X 130 laser scanner, by Trimble. (*source: [23]*)

As an example, a system is presented by Gordon et al. [24] which employs a 3D free-form shape recognition algorithm to automatically recognize CAD objects in laser point clouds. This algorithm recognizes shapes by representing, and then matching, model and sensed data, utilizing local surface descriptors which are referred to as spin-images [25]. This system is very general and can prove very resilient to occlusions because of its basis on local features. However, its performance is reported to deteriorate significantly in complex cases, such as construction sites where search objects sometimes do not have very distinctive features. It has to be duly noted that in object recognition, it is crucial that data are represented without ambiguity: no two objects should have the same representation [26]. But the problem with 3D models of Buildings is that the objects that constitute them (e.g. columns, beams) show strong similarity, which can result in strong ambiguities.

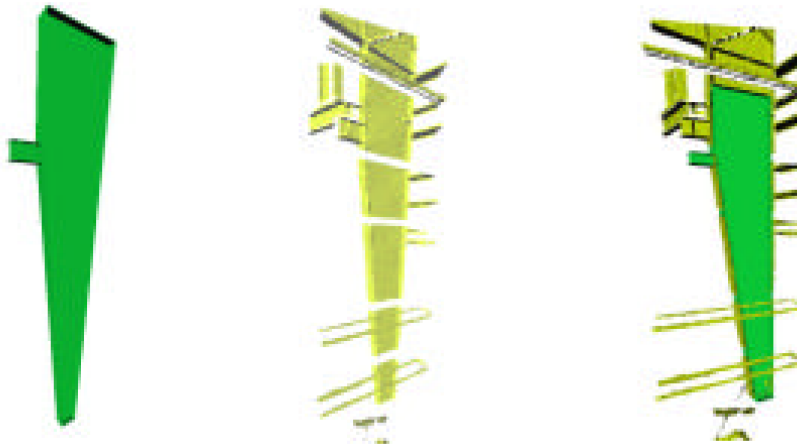


Figure 1.6 Recognition progress for a steel column. Left: Design Model (step 1). Middle: Range Data from Laser Scan (step 2), Right: Column Recognized Using Information from the previous two steps. (reproduced from [24])

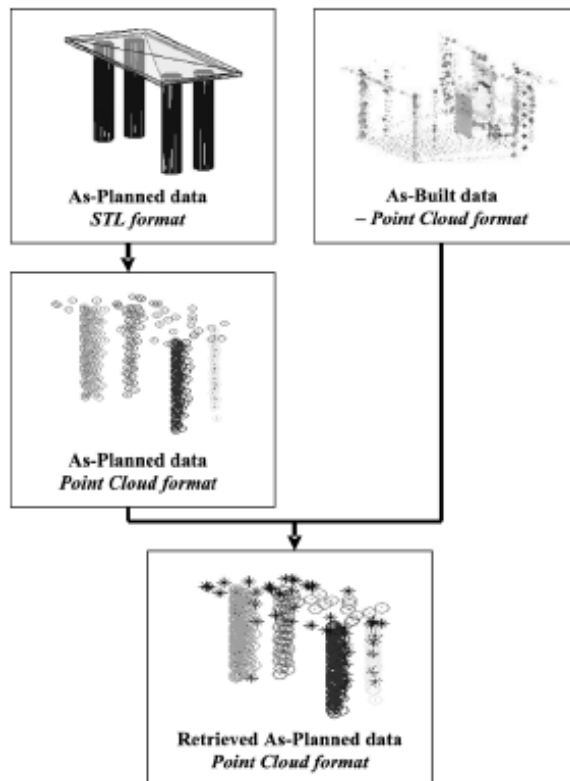


Figure 1.7 Automated retrieval of 3D CAD model objects in construction range images. As-built and as-planned data at different stages of the retrieval process. (reproduced from [4])

Shih and Wang [27] opt for a laser scanning- based system to control dimensional compliance of finished walls. Biddiscombe [28] reports successful utilization of laser scanning on an actual tunneling project to control as-built dimensions. Bosche et al. presented a method to track as-built 3D status of construction sites in an automated manner by use of laser scanning and project 3D CAD modeling [29]. In [4] Bosche also shows a method to efficiently assess construction progress, by automatic retrieval of 3D

CAD model objects in construction laser scanned data. Developing this method, Turkan et al. employs 4D CAD models, which include schedule to track progress in automated way [12,30].

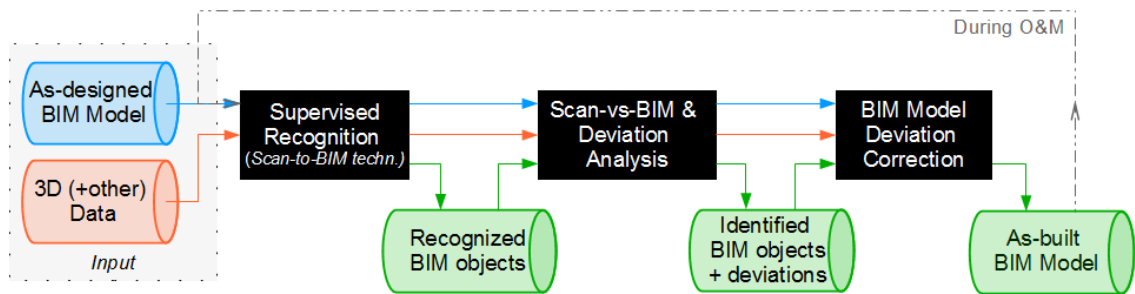


Figure 1.8 Data processing system for life-cycle BIM model dimensional information management, as proposed by Bosche et al. in [31].
(reproduction from [31])

Existing BIMs can be used to enhance the detection of components' and their recognition processes. The recognition of AD BIM contained objects can be employed to eventually identify possible missing elements or deviations from the model. The modeling accuracy of the modeling is directly dependent to registration accuracy. Bosché et al. [31] have already shown that it is possible to track the built status of MEP components by utilizing existing BIMs, generated for example with the method he proposes in his earlier work [4]. Recently an automatic method based on Hough transform integrated the abovementioned framework. The result is a significantly accurate reconstruction which makes assessment of the as-built status of MEP infrastructure easier [32]. Through this work, the authors actually challenge the dogma that neither the AD BIM nor the 3D scan is the ground truth, proposing that these data need to be combined to model MEP installations properly [12].

The use of laser scanning on construction sites still remains limited, despite all the aforementioned works and achievements and the undoubted acknowledgement of how accurate and versatile laser scanners can be. A highly possible reason is that currently proposed systems such as the above, still show poor automation and/or efficiency (for example, considering the number of elements that could be investigated within a tight time frame). The result still is poor benefit-cost ratios not yet comparable to traditional manual inspections results and speeds.

2 THEORETICAL FOUNDATION

2.1 3D Models

3D models represent a 3D object using a collection of points in 3D space, connected by various geometric entities such as triangles, lines, curved surfaces, etc [33]. Being a collection of data (points and other information), 3D models can be created by hand, algorithmically (procedural modeling), or scanned.

Almost all 3D models can be divided into two categories.

- **Solid** - These models define the volume of the object they represent (like a rock). These are more realistic, but more difficult to build. Solid models are mostly used for nonvisual simulations such as medical and engineering simulations, for CAD and specialized visual applications such as ray tracing and constructive solid geometry
- **Shell/boundary** - these models represent the surface, e.g. the boundary of the object, not its volume (like an infinitesimally thin eggshell). These are easier to work with than solid models. Almost all visual models used in games and film are shell models.

Because the appearance of an object depends largely on the exterior of the object, boundary representations are common in computer graphics. Two dimensional surfaces are a good analogy for the objects used in graphics, though quite often these objects are non-manifold [34]. Since surfaces are not finite, a discrete digital approximation is required: polygonal meshes (and to a lesser extent subdivision surfaces) are by far the most common representation, although point-based representations have been gaining some popularity in recent years.

2.1.1 Polygon Meshes

A polygon mesh is a collection of vertices, edges and faces that defines the shape of a polyhedral object in 3D computer graphics and solid modeling. The faces usually consist of triangles (triangle mesh), quadrilaterals, or other simple convex polygons, since this

simplifies rendering, but may also be composed of more general concave polygons, or polygons with holes.

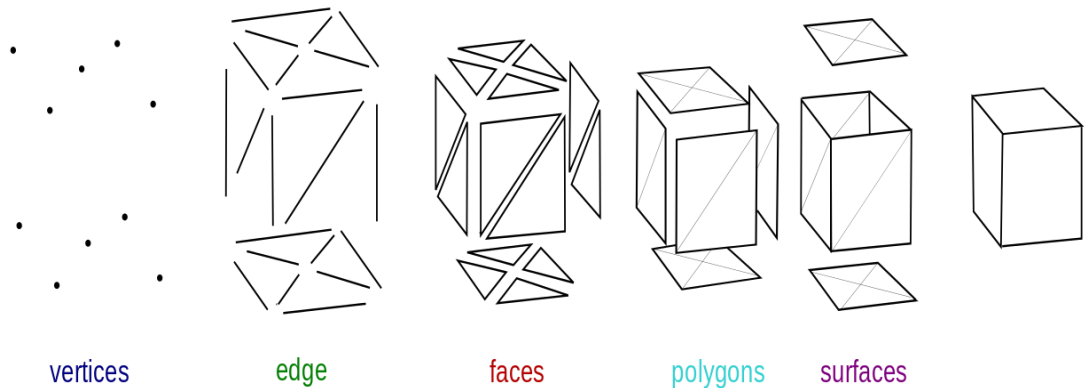


Figure 2.1 Elements of mesh modeling (*source: Mesh Overview, Elements of mesh modeling, Wikipedia, https://en.wikipedia.org/wiki/File:Mesh_overview.svg*)

The study of polygon meshes is a large sub-field of computer graphics and geometric modeling. Different representations of polygon meshes are used for different applications and goals. Volumetric meshes are distinct from polygon meshes in that they explicitly represent both the surface and volume of a structure, while polygon meshes only explicitly represent the surface (the volume is implicit). As polygonal meshes are extensively used in computer graphics, algorithms also exist for ray tracing, collision detection, and rigid-body dynamics of polygon meshes.

Objects created with polygon meshes must store different types of elements. These include *vertices*, *edges*, *faces*, *polygons* and *surfaces* (Figure 2.1). In many applications, only vertices, edges and either faces or polygons are stored.

A vertex is a position along with other information such as color, normal vector and texture coordinates. An edge is a connection between two vertices. A face is a closed set of edges, in which a triangle face has three edges, and a quad face has four edges. A polygon is a coplanar set of faces. In systems that support multi-sided faces, polygons and faces are equivalent. However, most rendering hardware supports only 3- or 4-sided faces, so polygons are represented as multiple faces.

2.1.2 Face-vertex meshes

Face-vertex meshes represent an object as a set of faces and a set of vertices. This is the most widely used mesh representation, being the input typically accepted by modern graphics hardware. Face-vertex meshes improve on VV-mesh for modeling in that they allow explicit lookup of the vertices of a face, and the faces surrounding a vertex. Figure

2.2 shows an FV mesh of a box. Vertex v5 is highlighted to show the faces that surround it. Notice that, in this example, every face is required to have exactly 3 vertices. However, this does not mean every vertex has the same number of surrounding faces.

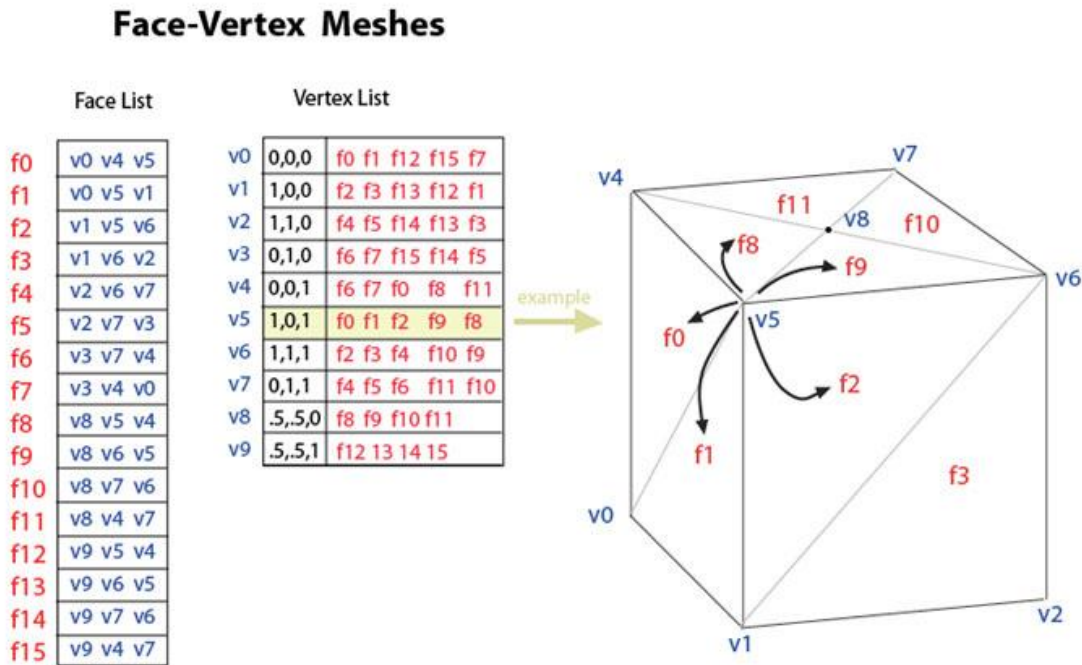


Figure 2.2 A face vertex (FV) mesh of a box. (Source: *Face-vertex meshes*, Wikipedia, https://en.wikipedia.org/wiki/File:Mesh_fv.jpg)

2.1.3 BIM Models of Buildings

BIM (Building Information Modeling) describes the technology of unification of the procedures of designing, effectuation and management of a building during its life course, in a three dimensional (3D) model. The 3D model which is created contains information that can prove extremely useful, allowing for the creation, storage, management and exchange of data in a flexible manner. The final objective is for the design, effectuation and management of a building to become more precise and economical.

BIM is a tool that allows the users to add and reuse the information related to a building during its whole life cycle. Despite the fact that it is a central system administering a multitude of information, its main characteristic is the three-dimensional modeling.

2.2 As-Built Modeling

An ideal automated as-built modeling process should generate a 3D model of the facility using data of a raw point cloud, with the aim of this 3D model to be rich semantically. Obviously, objects with certain geometry, attributes and relational characteristics

compose this model. An ideal As-Built BIM file that comes as a result of such a process should be in a standardized language used in buildings, such as the Industry Foundation Classes (IFC) data model, which is intended to describe building and construction industry data [35].

It is important to note at this point, that several factors of an objective nature can limit the as-built modeling process. As a result, it is unrealistic to expect, even from an optimal as-built method of modeling, to result in an AB BIM with the richness of an AD BIM. Some of the aspects that objectively limit the process of as-built modeling are the following:

- AD BIM models cannot be expected to include specific information -such as building costs or specifications- which relates to the designer's knowledge of building on a high level.
- Even if the data collection technology is optimized to effectively capture structural details such as, for instance, fasteners, or electrical or other outlets, the cost and time needed to capture and model such data in detail cannot be practically justified by the alleged added value to model such fine detail.
- There is the added obstacle of the inability to capture elements that are non-visible, or partially or fully hidden behind or within other element. As a result, such elements are not possible to appear in the finalized AB BIM; i.e., concrete reinforcements. Despite the fact that devices that can capture such elements exist (i.e ground penetrating radar hardware), the automatic interpretation of data these devices capture is still practically ineffective, and thusly unsuccessful at this point.

If the abovementioned limitations are taken into account, a desired result of an as-built modeling process can be defined as a reduced version of the complete BIM model. This reduced model contains the main visible building and spatial elements, as well as the connectivity –and nesting- relationships between them. [12]. As a result, the main challenges of a Scan to BIM process are (a) to *produce a correct fitting, yet simplified representation of a client specific BIM structure*, (b) to *successfully evaluate the quality of the product* and (c) to *detect (eventual) deviations between the BIM model and the actual structure*.

The following steps constitute the general as-built modeling process, from the initial data collection to the working BIM generation:

1. Point Cloud Generation
2. Point Cloud Pre-Processing (outlier removal, noise filtering, registration)

3. As-Built Modeling

The goal of such a process, as stated before, is the creation of BIMs that are rich in semantics. The elements detected by the process have to be information-rich and should successfully link, for example, back to the original point cloud, or to online databases, or other BIM models.

2.3 Data Capturing - Point Cloud Generation

A point cloud is defined as a set of data points in some coordinate system. Within a three-dimensional coordinate system, these points are usually defined by X, Y, and Z coordinates and often aim to represent the external surface of an object. 3D image reconstructions or 3D scanners can create Point clouds, by measuring large numbers of points on a object's surface, producing point clouds as resulting data files. Such point clouds represent sets of points that have been measured by the device.

Photographs (Imagery) are obviously a possible point cloud input source. Common ground imagery can be easily acquired, stored and exchanged. Billions of photographs are taken each year worldwide, with the resulting data estimated within the petabytes' region in size. A great number of these photographs are uploaded and exchanged through the Internet, with a great number of these images depicting urban sites. Such data is a proven valuable source of information to facilitate urban reconstruction on a large scale, in various projects. Aerial and satellite imagery has proven to be another important point cloud input source recently, after having been restricted to the professional photogrammetry and remote sensing for many years. Yet, especially during the last decade, such sources of input data have become more available. This has to attribute especially to the radical evolution of Web-mapping services such as Google or Bing Maps, and has already been successfully utilized for reconstruction [15,36–38]

LiDAR data is another type of input that could prove perfectly suitable in urban reconstruction. Such data utilize laser light projected on surfaces, capturing its reflected backscattering. The structure is determined utilize the principle of time-of-flight. These techniques produce very precise semi-dense 3d point-clouds, especially in long distance acquisition. LiDAR scanning devices are still expensive and not readily available to mass markets, yet land-surveying offices or civil engineering bureaus already frequently utilize scanning technology for documentation purposes. As a result, LiDAR data are already available, especially for urban reconstruction tasks. It should be noted that both terrestrial and aerial LiDAR input is used on many modern algorithms [18,39].

Both of the abovementioned techniques have been the object of extensive discussion – and subsequent comparison- in the Civil Engineering cycles, with the advantages of the low cost and time saving of the imaging systems contrasting to the higher accuracy –but expense of use- of the laser-scanning systems. With the coming of RGBD cameras into this area, the abovementioned depth and appearance sources become two established ways that are complementarily used towards the acquisition of accurate 3D point clouds [40–42].

What is concrete and independent to the source of data, is that the heart of the 3D reconstruction process is the registration procedure, which has the goal of bringing different data sets into the same system of coordinates. The differences focus on the data degradation each system leads to, and the possibilities available to recover from such degradation –and deformation.

For example, both laser scanning devices, and cameras of any kind, will have to be moved around the scene so that a good coverage is ensured. As a result, data degradation due to rigid deformations (i.e. translation, rotation) must be taken into consideration. Additionally, the loss of the third dimension during the process of imaging, leads to the image-based systems need to triangulate points of correspondence that belong to images taken from different viewpoints so as to infer depth, utilizing certain assumptions for the internal camera model-induced transformations; the most common method is the use of perspective transformation, in association with the pinhole camera model. Appearance cues (e.g. local interest points) lead this process. The registration of laser scans is less involved and less subject to errors in comparison to image scanning. However, within laser scanning techniques, appearance cues might not be available. In such cases registration will mostly have to rely on geometric information.

Figure 2.3 shows non-contact techniques divided further into image-based, range-based, combined or other techniques; contact methods consist of manual or other techniques.

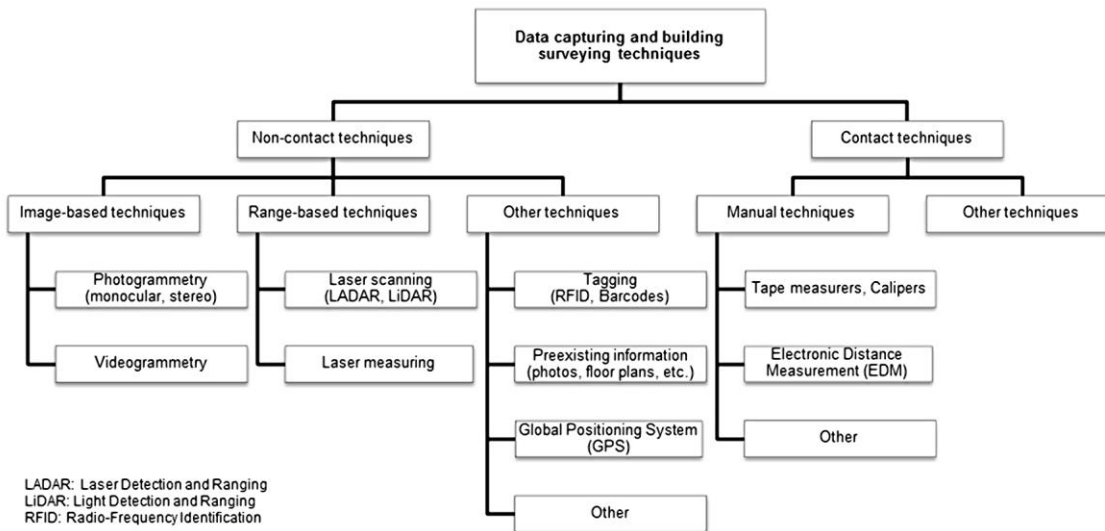


Figure 2.3 Systematic overview of data capturing and surveying techniques to gather existing buildings' information (reproduced from [43])

Point clouds resulting from a 3D scanning process are used in many instances, for example towards the creation of 3D CAD models for manufactured parts, metrology/quality inspection, and towards many other aspects of applications in animation, rendering, visualization or mass customization.

Despite the fact that users can render and inspect point clouds directly, for them to be used in the majority of 3D applications, they have to be converted to polygon mesh or triangle mesh models, NURBS surface models, or CAD models. This conversion process is known as *surface reconstruction*. Many techniques of conversion of a point cloud to a 3D surface exist; some of them such as the Delaunay triangulation, alpha shapes, and ball pivoting, build a network of triangles over the existing vertices of the point cloud. Others convert the point cloud into a volumetric distance field and then utilize a marching cubes algorithm to reconstruct the implicit surface so defined.

Industrial metrology or inspection by use of industrial computed tomography is one application within which point clouds are used directly. *The point cloud of a manufactured part is aligned to a CAD model (or even another point cloud), and then compared to check for differences.* Possible differences usually are displayed as color maps which give a visual indication of the deviations between the manufactured part and the CAD model. Users can also extract geometric dimensions and tolerances directly from the point cloud, use point clouds can to represent volumetric data (i.e. in medical imaging). The use of point clouds achieves multi-sampling and data compression. Point clouds are one source used in geographic information systems to create digital elevation

models of terrains. Finally, point clouds are also utilized in the generation of 3D urban environment models.

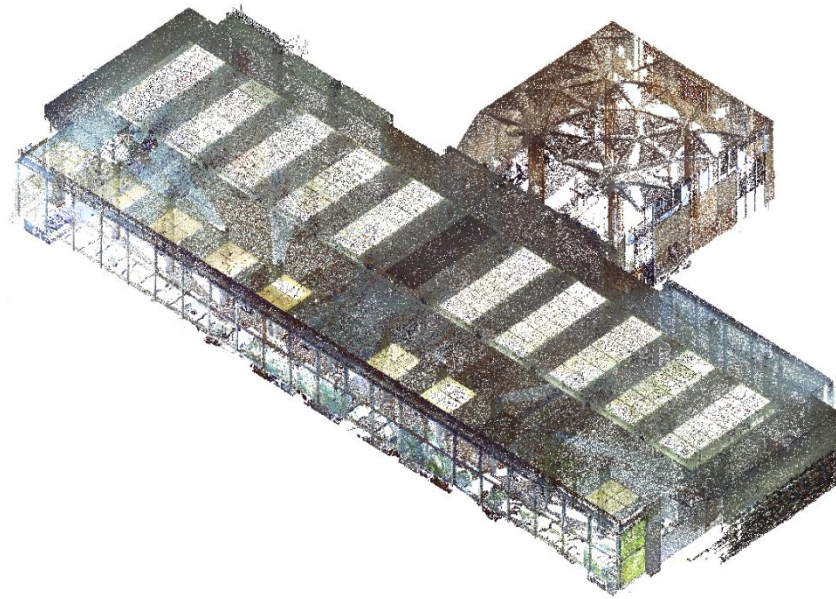


Figure 2.4 Point Cloud of a scanned library building (*reproduced from [44]*)

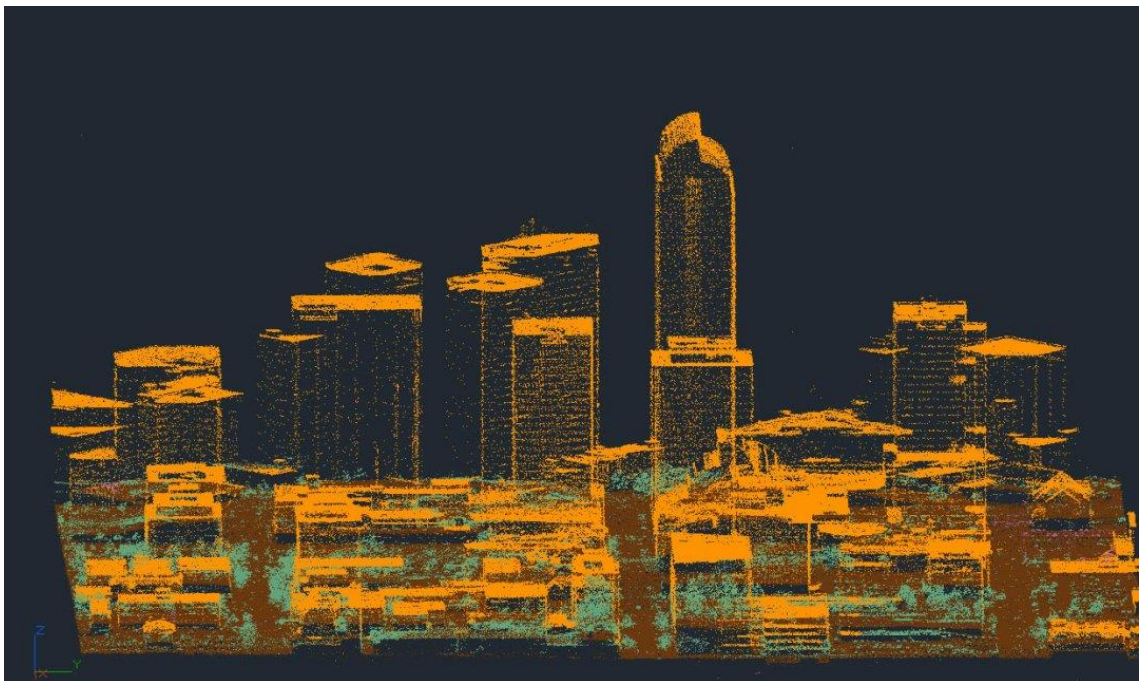


Figure 2.5 Point cloud data representing buildings, vegetation, and ground (*source, Manage Point Clouds in AutoCAD Map 3D, Catalyst Magazine Online, <http://www.cadalyst.com/gis/manage-point-clouds-autocad-map-3d-13390>*)

2.4 Pre-processing

The accuracy of the as-built modeling process directly relies on how accurate the point cloud data measurements are. For that reason, the preprocessing of the input data towards

the removal of outliers, noise reduction and missing data compensation noise is a required initial step in as-built modeling. If the point clouds are very large in size, the user can apply an initial segmentation of these clouds into smaller parts and these smaller parts are processed in parallel. The downsampling of the point cloud, is a valid alternative to segmentation e.g. through voxelisation, which is the partitioning of the point cloud according to a 3D grid, and the replacement of all points within a cell with the centroid of the cell. Users can also utilize voxelisation to gain adjacency information between the points, which can help estimate density, or prove otherwise useful later during modeling. Users can also utilize tree structures to store the voxelised point cloud for memory efficiency.

2.4.1 Outlier removal

Local statistics are the basis of a local outlier factor defined in the majority of approaches, e.g. local density, distance to nearest neighbors, or eigenvalues of the local covariance matrix. The identification of outliers is effectuated either by the direct application of a hard threshold, or by the definition of a global distribution – usually assuming a normal distribution– and by the identification of points that diverge from said distribution. Some methods identify outliers in a setup without parameters, through the comparison of the local sampling density of a point to the average local sampling density of its neighbors, distinguishing sparse outliers from temporal artifact outliers such as scene-motion induced artifacts, pruning the latter through identification of the apparently coherent clusters that pass the local statistics test, but that appear in only one or few scans, and other scans that cover them see through them. [12]

2.4.2 Noise filtering

Noise filtering techniques, similarly to outlier removal techniques, are applied through the study the local neighborhood of each point and the subsequent performance of smoothing operations, with over-smoothing of the sharp local features being the main trap to avoid. The key towards the prevention of this behavior is the application of anisotropic filtering with the utilization of mean curvature flows to perform anisotropic filtering of point clouds; however, high complexity makes this technique ineffective in cases of large point clouds. A more efficient technique is to apply anisotropic filtering on the normals of the points computed, eventually updating the positions of the points are accordingly. Other techniques concentrate on the design of noise-robust algorithms to bypass the filtering step and avoid the potential loss of information.[12]

Point cloud preprocessing is currently an active research field, with many tools being available through open-source libraries and software channels like PCL or Meshlab.

2.4.3 Registration

Registration is the correct and consistent *alignment of various 3D point cloud data views into a complete model*. The aim of registration is the discovery of the relative positions and orientations of the separately acquired views in a global coordinate framework, with the goal of perfectly overlapping the intersecting areas between them. For every set of point cloud datasets acquired from different views a system is needed that can align these datasets together into a single point cloud model. This is a prerequisite for the application of the following processing steps (such as segmentation or object reconstruction).

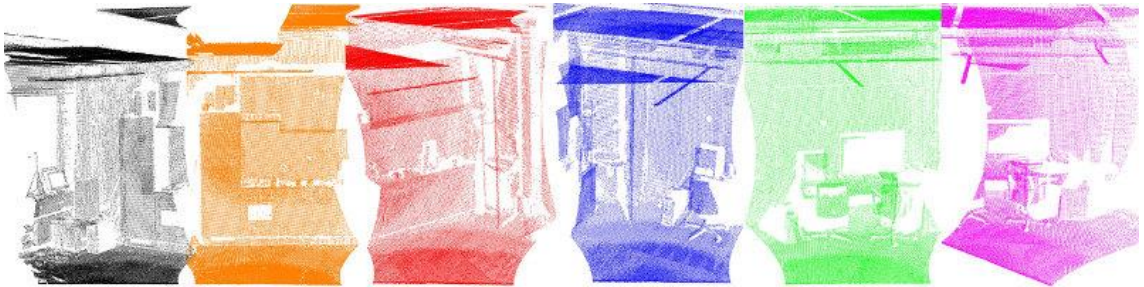


Figure 2.6 Six individual datasets has been acquired using a tilting 2D laser unit.
(source: *The PCL Registration API, Point Cloud Library*,
http://pointclouds.org/documentation/tutorials/registration_api.php)

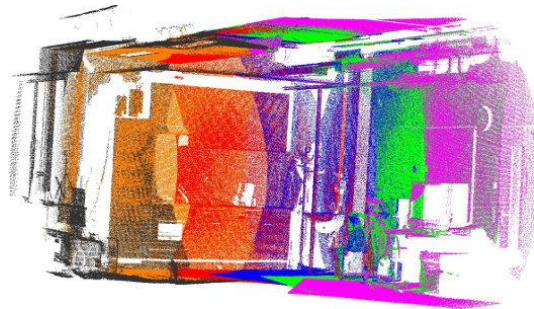


Figure 2.7 The complete point cloud model after registration.
(source: *The PCL Registration API, Point Cloud Library*,
http://pointclouds.org/documentation/tutorials/registration_api.php)

In Figure 2.6, a tilting 2D laser unit has been used to acquire a set of six individual datasets. Since each of these scans only represents a small part of the surroundings, it is important to find a valid method to register all these six scans together and create the complete point cloud model shown in Figure 2.7

The correct point correspondences in the given input datasets must be found, and then rigid transformations that can rotate and translate each individual dataset into a consistent global coordinate framework must be estimated. This registration problem can be easily solved if the point correspondences are perfectly known in the input datasets. Viewed through a representation point, this means that a selected list of points in one dataset have to “coincide” with a list of points from another dataset. And when the estimated correspondences estimated are “perfect”, then the registration problem has been solved in a way of closed form.

Algorithms allowing the user to estimate multiple sets of correspondences can be used, or bad correspondences’ rejection methods that estimate transformations in a robust manner from them. The most common algorithm is that of Iterative Closest Point.

2.4.4 Iterative Closest Point Algorithm (ICP)

One of the methods used for registrations most often, is that of the Iterative Closest Point (ICP) [45] and its variants. ICP is an algorithm applied with the aim of minimizing the difference between two clouds of points. It is commonly used for the reconstruction of 2D or 3D surfaces from different scans, or for the localization of robots and the planning of optimal paths (for example, when wheel odometry proves unreliable due to slippery terrain or other factors), for the co-registration of bone models, etc.

In this algorithm, one point cloud (the “reference” or “target”) is kept fixed, while the other one (the “source”) is transformed to best match the “reference”. ICP then searches for the best rigid transformation (rotation, translation) which minimizes the distance and aligns the source point cloud data with the reference model, by repeated alternation between

- i. a stage that computes point correspondences between model points and data points given a transformation, and
- ii. a stage that updates the current transformation given the correspondences computed under (i).

The registered models in this method are not limited to point sets; they also include polylines, parametric curves, implicit curves, triangles, parametric surfaces, and implicit surfaces.

The convergence to (at least) a local minimum is ensured; accurate alignment is obtained providing that the initialization is good enough. With poor initialization, however, this method gets stuck at a local minimum far from the global minimum.

The speed and robustness of this method have been the focus of extensive study.

To avoid local minima, registration is commonly performed in two steps:

- i. Coarse registration, to obtain a rough initial alignment, then
- ii. Fine registration, based on ICP optimization, so that the solution is refined.

The coarse registration is generally the result of the detection and matching of local features within geometric hashing schemes or RANSAC-based approaches. Such local features can be any combination of points, lines, curves, and, of course, surfaces. Johnson and Hebert's proposed approach computes Spin Image local features in a dense manner, thusly avoiding the error-prone feature detection step. Other approaches bypass the feature matching completely, directly relying on points instead; I.e. a randomized approach has been proposed by Aiger et al., on the basis of geometric invariants of sets of points. The performance of the methods mentioned above depends highly on the noise level, percentage of outliers, and overlap between the two point clouds. That is the reason that the choice of the coarse registration method is primarily data driven.

ICP variants are often used to complete the fine registration procedure [46]. Among other methods, the more notable ones are free form surface registration using angular invariant features, or modified ICP methods such as the dual interpolating point-to-surface method. Fitzgibbon's ICP version [47] does not follow the abovementioned two traditional steps (i,ii). It rather proposes a formulation that incorporates the search for correspondences into the optimization problem, and the Levenberg–Marquardt algorithm (application of general-purpose non-linear optimization) is used to directly minimize the registration error. This formulation was recently utilized by Zollhöfer et al.[48], having been initialized using the PatchMatch algorithm [49], with the results obtained being state-of-the-art in regard to real-time registration of depth images [12].

The last step is the actual computing of the transformation from the remaining set of good correspondences, which takes place through:

- The evaluation of some error metric based on correspondence
- The estimation of a (rigid) transformation between camera poses (motion estimate) and minimization of error metric

- The optimizing of the structure of the points
- Examples: SVD for motion estimate; Levenberg-Marquardt with different kernels for motion estimate;
- The use of rigid transformation towards the rotation/translation of the source onto the target, and the potential execution of an internal ICP loop with either all points, or a subset of points, or the keypoints.
- The iteration of the above steps until some convergence criterion is met.

Essentially, the algorithm steps are:

- For each point in the source point cloud, it finds the closest point in the reference point cloud using neighbor search. For better speed a k-D tree structure can be used [50,51].
- Using It estimates the best transformation (the combination of rotation R and translation t) that minimizes the error:

$$R, t = \underset{R, t}{\operatorname{argmin}} E(R, t)$$

In the method proposed, the point to plane error function has been chosen. For each transformation found in the previous step the error is given by:

$$E(R, t) = \sum_i 1^N \|Rp_i + t - m_i'\|^2,$$

where m_i' is the projection of p_i on the closest surface. The surfaces are calculated by a Least squares normal estimation from point clouds using Principal Component Analysis (PCA) [52].

For a k number of iterations, the transformations R_k, t_k are calculated by:

$$R_k, t_k = \underset{R, t}{\operatorname{argmin}} \sum_i = 1^N \|Rp_i^k + t - m_i^{k'}\|^2,$$

Where

$$p_i^k = R_{k-1}p_i^{k-1} + t_{k-1}$$

- Using the best transformation obtained by the iterations, the source point cloud is transformed.
- It iterates (re-associates the points, and so on) until it converges to a minimum.

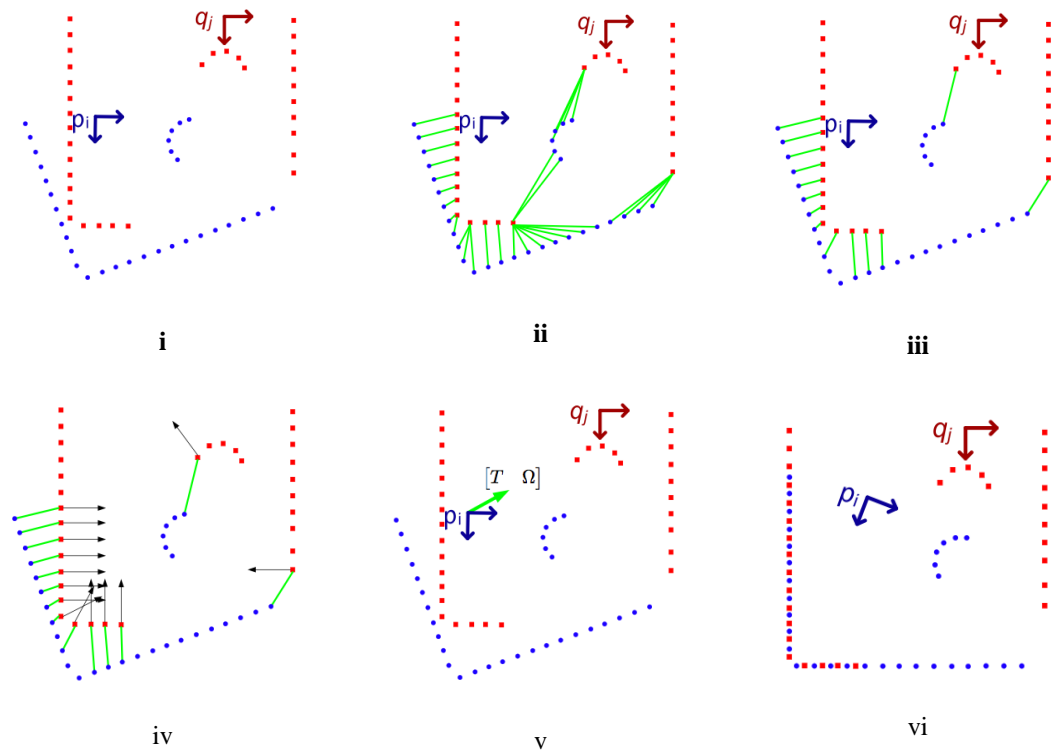


Figure 2.8 ICP Steps. (i) Blue is the target point cloud that we wish to align with the reference (red), (ii) Matching, (iii) Weighting/ Match Rejection, (iv) Error, (v) Compute transformation minimizing error, (vi) the result of the alignment after the completion of the iterative method. (source: Dr. Francis Colas, *Iterative Closest Point Algorithm, Information Processing for Robotics, ETH Zurich*)

2.4.5 Creating a model from the point cloud

The modeling of a BIM from a point cloud of a facility includes three tasks: (i) The modeling of the geometry of the components (“What is the shape of this wall?”), (ii) the assignment of an object category and material properties to a component (“This object is a brick wall.”), and (iii) the establishment of relationships between components (“Wall1 is connected to Wall2 at this location.”). These tasks do not have to be executed sequentially; they even may be interleaved. This depends on the workflow.

Converted polygons –usually triangles- may be used to form surfaces for the initial modeling of the data. This depends on the algorithm each method implements. This process can take place either during the initial scan stage [30], or after the completion of all data transfer to the general coordinate system and the estimation of surfaces from the total point cloud [31]. The aim of the geometric modeling task is the creation of simplified representations of building components by method of fitting geometric primitives to the point cloud data. Geometric primitives can be individual surfaces or volumetric shapes.

For example, a simple wall could be modeled as a rectangular box (cuboid) or as a planar patch.

Simple geometric primitives, however, may not model surfaces like moldings or decorative carvings so well. In such cases, different techniques might have to be used for the modeling process. For linear structures (i.e., moldings), splines can be fitted to the data and then the cross-section can be swept along a trajectory to form the a cross-section of the model and, subsequently, the object model [53]. More complex structures (e.g., decorative carvings) might require non-parametrical modeling, for example by use of triangle meshes, or a known object models database can be used to facilitate their modeling [54].

Considering that BIMs are usually defined via the use of solid shapes, representations of surfaces have to be converted into solid models. The modeled components should be labeled as object categories. Standard BIM categories, for instance, include wall, roof, slab, beam, and column. Additionally, modelers can create custom object categories based on individual project needs. After that, objects might be further improved with the use of other meta-data, such as material properties or links to specifications for custom components. Models also have to set topological relationships between components, and between components and spaces, since these are important in a BIM. Additionally, connectivity relationships have to be set, indicating which objects are connected to one another and where they are connected. For example, adjacent walls will have to be connected at their boundaries, and walls will have to be connected to slabs at the bottom. Furthermore, modelers have to use containment relationships for the encoding of locations of components that are embedded within one another, such as windows and doors embedded within walls [55].

The expected output of as-built modeling for AD BIM-equipped facilities is an AB BIM that reflects the as-built conditions in a precise manner: of course, such conditions are not uncommon diverge from the original design, to a lesser or greater degree. However, the means to obtain the AB BIM in this case are different to those of the previous section, because in this case, the modeler can actively use the AD BIM to guide the modeling process.

When the modeling process is thusly guided by use of the AD BIM, the object recognition is less prone to errors, in comparison to the previous section methods. The main difficulty in this case, is how to execute an accurate registration between the AD BIM and the scan

that can be computationally efficient at the same time. And it has to be noted that, in the case of existence of large deviations between the as-built conditions and the original design, the difficulties of as-built modeling with AD BIM are similar difficulties to those of as-built modeling without AD BIM.

2.4.6 Quality Assessment of As-Built models

Various applications, such as renovation design or facility management can utilize As-Built BIMs as central project knowledge bases [55]. However, to support such applications, timely, detailed, and comprehensive quality assessments (QA) of the laser-scanned data and As-Built BIMs have to be executed and their results taken into consideration. Project delays can be reduced, and the proactivity of the decision-making can be improved, by use of effective quality assessment. Better use of the models and corresponding data relies on detailed and comprehensive quality information about the data and the As-Built models.

A high level of understanding of as-built models is necessary to ensure fully automatic quality assurance inspections of construction sites and correct automated detection of defects. The most obvious method is to use *3D object recognition* algorithms to successfully identify building components. And object recognition is challenging in a construction environment for more than one reasons: First of all, the majority of 3D object recognition algorithms can only handle rigid 3D objects, for which a precise 3D model is already known. Yet, objects on construction sites are highly varied, both in shape and size. Plus, for many components, 3D models are unknown or are only approximate to those components' true shape. Additionally, a factor that complicates matters further is the high amount of clutter that is usually present in active construction sites, such as scaffolding, material storage, formwork, or other temporary installations.

3 PROPOSED METHOD

3.1 System Overview

The implemented method analyzes a three-dimensional As-Built model of a building acquired by a scanning method and with the help of its theoretical As-Designed BIM model, calculates dimensional differences in building component parts. At the same time the systems examines whether these deviations are within the limits set by the building regulations.

The general process comprises of the following steps:

- i. As-Built alignment to BIM Model
- ii. Coplanar Region Extraction
- iii. Region Matching
- iv. Deviation Estimation
- v. Assessment of Building Regulation Compliance

The first part of the proposed system is an algorithm, which enables automated registration of a point cloud from a scanned construction, to the As-Designed 3D Model. A variation of the ICP method is used for alignment purposes.

The second part of the proposed system is an algorithm, which analyzes the as-built data. This algorithm's methodology involves segmenting the as-built and as-designed models into coplanar regions.

In the third part, the extracted coplanar regions of the As-Built model are associated to the As-Designed, with the use of a matching metric.

The fourth part –and step- of the proposed system is the identification of deviations between the associated as-built and as-designed model regions.

In the final part of the proposed system, the identified deviations are compared against the construction specifications to determine whether they are, in fact, out of bounds.

Each of these tasks presents significant research challenges individually.

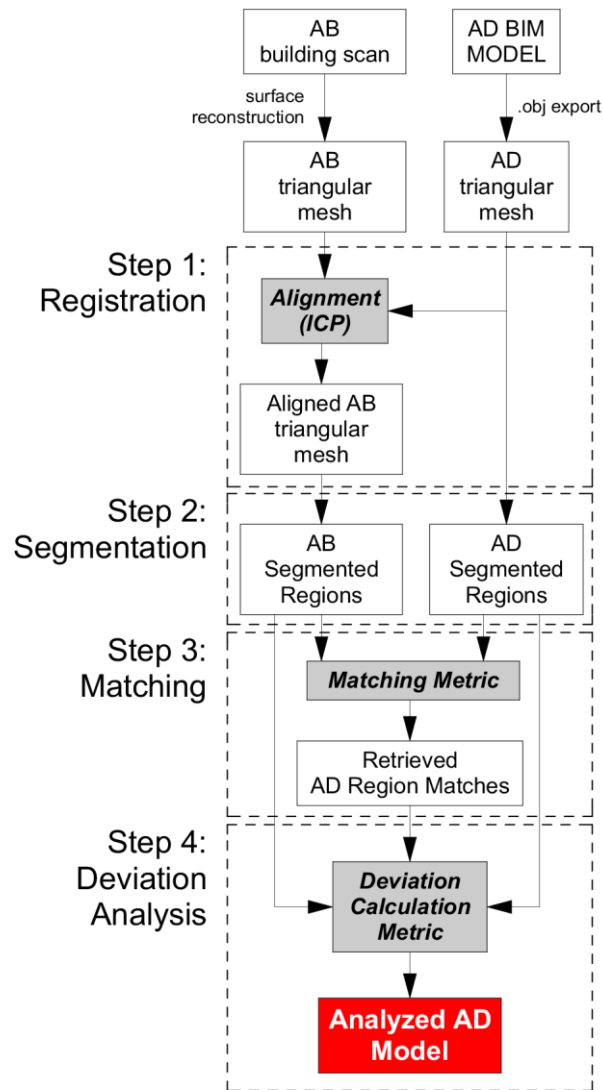


Figure 3.1 Deviation Analysis Method, Overview Diagram

3.2 Input Data

The basic models used in the method are two: the As-Designed and the As-Built models.

3.2.1 As-Designed model

The As-Designed model, is the model that has been designed and checked to be in accordance to building regulations, has acquired a building permission and is the model in accordance to which the building will actually be constructed. For this method, we consider that this is a BIM model, which contains all necessary information in relation to the elements that compose the building. In this manner, we have information on the size and type of the building's structural elements (slabs, columns, beams, walls etc) as well as information related to the organizing and structure of the building spaces (realized construction, room limits, building volume etc)

3.2.2 As-Built Data

The As-Built data result from the scan of the actual building. In our method, we consider that the point cloud we get from the building scan has been converted to a three dimensional triangular surface mesh model, by use of one of the existing techniques [55].

3.2.3 3D Mesh Model Format

The input data of this method, are the three dimensional models of the buildings that are checked. In order for us to receive the information contained in the theoretical three dimensional model, it is necessary to have full access to its data. However, CAD models are stored in data formats protected by intellectual property laws, such as DXF, DWG, PLN etc. For this reason, it is necessary to convert 3d CAD models to an open source code data format. This format must be suitable, so as the least possible loss of three-dimensional information takes place.

OBJ (or .OBJ) is a geometry definition file format that Wavefront Technologies initially developed for its Advanced Visualizer animation package. This file format is open and has been adopted by other 3D graphics application vendors as well; it is a universally accepted format.

This OBJ file format is a simple data-format that represents 3D geometry alone — namely, the position of each vertex, and the faces that make each polygon defined as a list of vertices, and texture vertices. Vertices are stored in a counter-clockwise order by default, making explicit declaration of face normals unnecessary. OBJ coordinates have no units, but OBJ files can contain scale information in a human readable comment line. Faces are defined using lists of vertex, while Polygons such as quadrilaterals can be defined by using more than three vertex indices. OBJ files also support free-form geometry, which uses curves and surfaces to define objects such as NURBS surfaces.

3.3 Alignment

Inspecting and analyzing a measured part is only possible if the As-Built captured data is properly positioned and oriented in 3D with the As-Designed reference Model.

In the proposed method, the AB point cloud is aligned to the AD model's virtual point cloud by using a variation of Iterative Closest Point (ICP) [45] algorithm, as proposed by Zhang [56]. Zhang proposes a modified K-D tree algorithm for efficient closest point computation. In this work a statistical method based on distance distribution is used to

deal with outliers, occlusion, appearance, and disappearance. This method enables subset-to-subset matching.

Input Data are:

- reference and source point clouds,
- number of iterations.

Output data is:

- The As-Built point cloud data after the refined transformation has been applied.

3.4 Planar Segmentation

In this step both the AD and AB models are segmented into individual coplanar regions.

This process is achieved in two basic steps, or stages:

- i. Finding the parallel planes that the model include
- ii. Segmenting those parallel planes into continuous coplanar regions

3.4.1 Parallel Plane Extraction

The method's segmentation algorithm, is implemented in Matlab. The system assumes that the model has been previously converted into a triangulated mesh. Such representation is very common in computer science applications, because:

- it is simple to handle, while
- it is able to preserve shape information.

During the first stage, a check takes place on the model's faces, so as to determine which are parallel. This can be implemented by iterating through all the faces of the objects that the 3D model contains.

- i. For all the triangular faces, the normal vectors are computed.
- ii. Next, starting from the first face, the inner product of its normal vector by the normal vectors of all other faces is calculated, and a check is made to determine if this product is within the limits of the angular tolerance defined. In the implementation of the system an angular tolerance of 15 degrees is taken as a threshold.

- iii. Following this, the faces that have been found to be parallel, are registered in the same Plane Group. The faces that have been registered are marked as processed, so that they are not included to the calculations of the next search.
- iv. In the next iteration, again a triangle from the remaining unmarked Face Search Pool is chosen and the cross products are recalculated.
- v. Finally, when the process completes, the model's triangles have been grouped in groups of parallel levels.

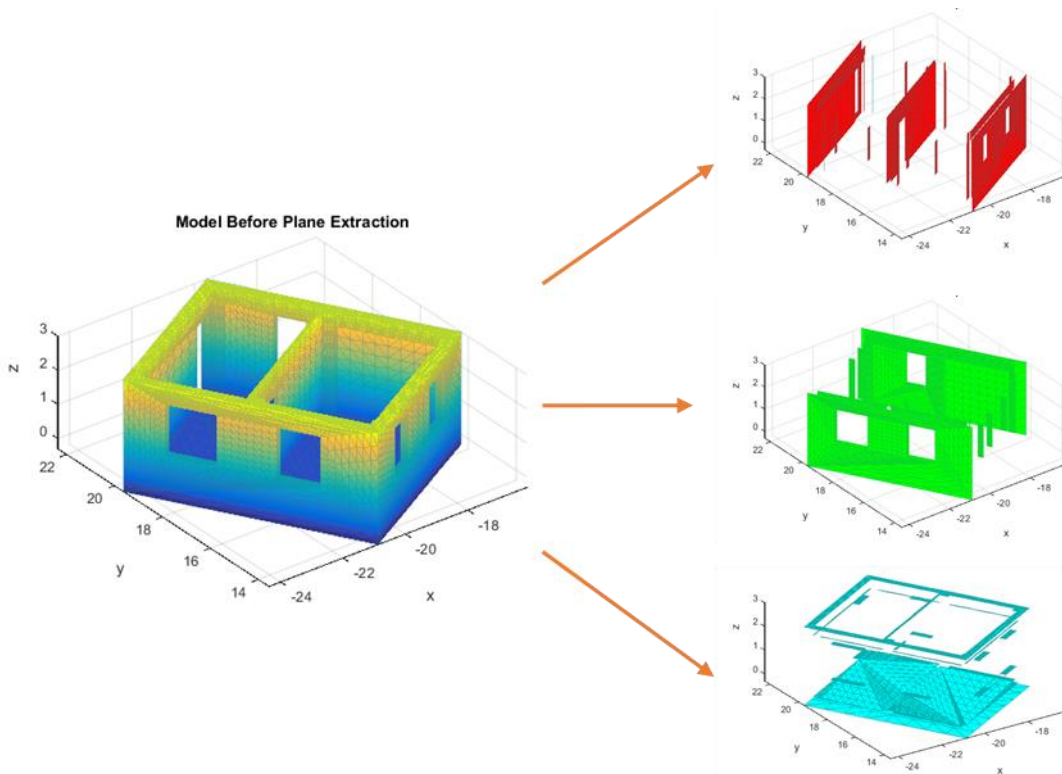


Figure 3.2 Parallel Plane Groups, extracted from the model with the use of face normal vector cross products

3.4.2 Coplanar Region Extraction

During the next stage of the process, each group of parallel faces is checked so that a splitting of the surfaces to coplanar regions takes place. This is achieved through the application of a region growing algorithm.

Initially the first parallelism group is selected.

- i. The first coplanar region is defined. An initial triangle and its vertexes are registered to it.

- ii. A check takes place on the remaining sum of triangles, so as to determine whether regional triangles that include a common vertex exist. If neighbouring triangle is found, it is added to the sum of triangles of the coplanar region and its vertexes are respectively added to the sum of that region's vertexes. The triangles found are removed from the search pool. The search of the expanded group of vertexes is repeated on the reduced group of triangles, the new triangles recognized are added to the region and so on.
- iii. When no neighbouring triangles result from the search anymore, a new coplanar region is defined, a triangle from the pool with the remaining points is registered and the search process detailed above is repeated.
- iv. In the end, all the triangles of the initial parallel group have been registered into coplanar regions. When the triangles of the first parallelism group are complete, the second is checked and so on, until all triangles have been registered into parallel coplanar regions.

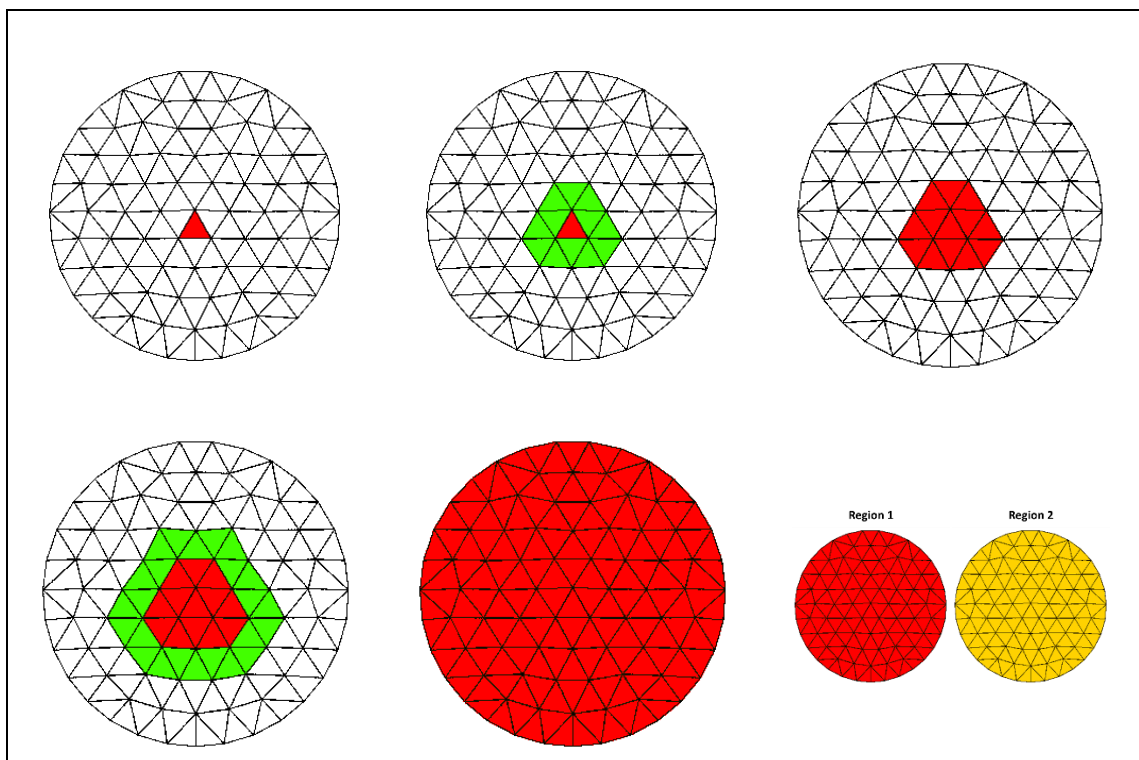


Figure 3.3 Illustration of the Region Growing Algorithm implemented in Matlab. Starting from a mesh face seed, a search for neighbour faces based on the triangles' vertexes takes place. After every iteration, the face population is grown. Eventually all neighbouring faces are grouped into a single region.

Proposed Method

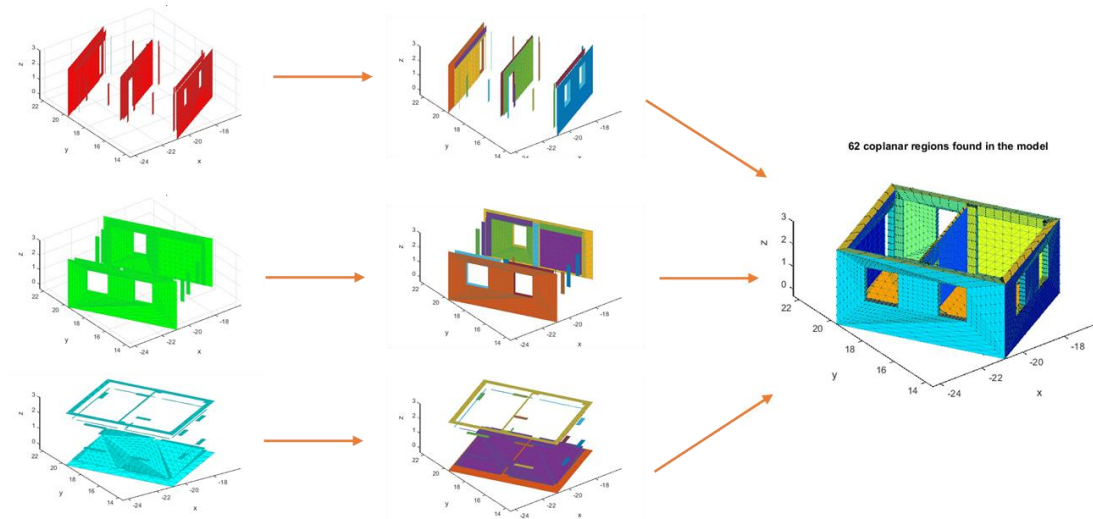


Figure 3.4 Coplanar Region Extraction with the use of the Region Growing Algorithm

3.5 Matching Metric

In this next step of the method, the assignment (mapping) of the coplanar regions that have been calculated, between the theoretical (As-Designed) and the real model (As-Built) is carried out.

Inputs:

- the reference model's R_r regions

$$R_r = \{i \mid i: \text{reference model region}\}$$

- the target model's R_t regions, which we want to assign (map) to the first one

$$R_t = \{j \mid j: \text{target model region}\}, \text{ and}$$

- a threshold d_{max} value is defined.

Output:

- The coplanar regions pairs that were matched from the target model as assigned (mapped), and
- The matching distance for each pair.

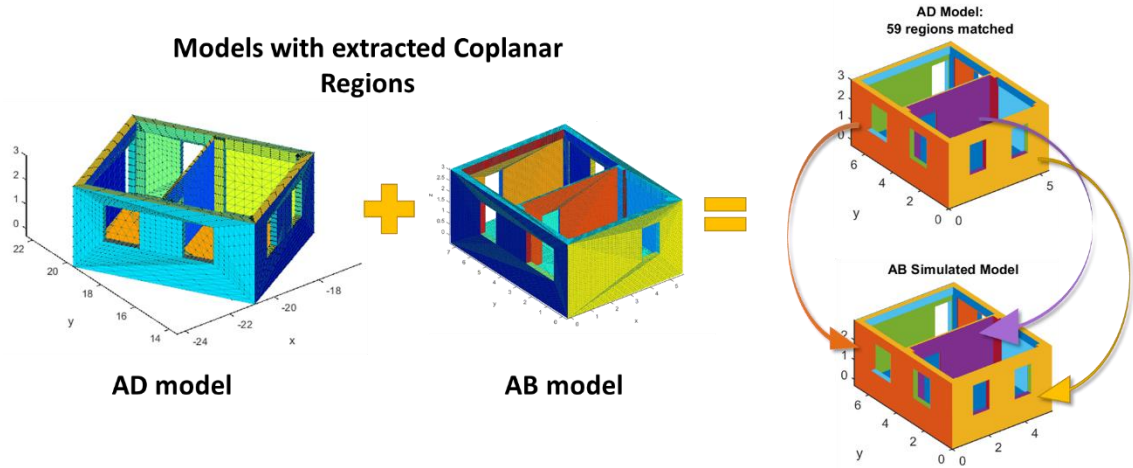


Figure 3.5 Overview of the region matching procedure goal

Algorithm outline:

- i. Initially, the normal vectors of all regions are calculated.
- ii. Every region Rr_i of the reference model is compared with all target model's Rt_j regions:
- iii. It is checked whether the regions compared are parallel, by calculating their normal vectors cross product. If the angle between the vectors is below the angular tolerance ($AngTolerance=5$ degrees), the regions are considered parallel. By taking into account a tolerance, we counter the possibility of a bad alignment by the ICP.

iv. If a parallelism is derived by the examination of Normal Vectors, then,

- v. for the two examined regions Rr_i , Rt_j their points clouds Pr , Pt are taken:

$$Pr_i = \{m \mid m: \text{point in region } Rr_i \},$$

$$Pt_j = \{n \mid n: \text{point in region } Rt_j \}$$

- vi. For every point Pr_{im} in Rr_i , the Euclidean distances $D_{imj} = \{d(Pr_{im}, Pt_{jn})\}$ from every point Pt_{jn} of Rt_j are calculated. These values are truncated to d_{max} . In the implementation of this method, the value $d_{max} = 2$ was manually selected.
- vii. Every point Pr_{im} is assigned the minimum distance from the points of Rt_j .

$$d_{imj} = \min\{D_{imj}\}$$

- viii. The average distance d_{ij} of these minimum distances is calculated.

$$d_{ij} = \frac{1}{N} \sum_{N=1}^m d_{imj}$$

- ix. For every point Pt_{jn} in Rt_j , the Euclidean distances $D_{jni} = \{d(Pt_{jn}, Pr_{im})\}$ from every point Pr_{im} in Rr_i are calculated. These values are also truncated to d_{max} .
- x. Every point in Rt_i , is assigned the minimum distance from the points of Rr_j .

$$d_{jni} = \min\{D_{jni}\}$$

- xi. The average of these minimum distances d_{ji} , is calculated.

$$d_{ji} = \frac{1}{N} \sum_{N=1}^n d_{jni}$$

- xii. Finally, the maximum of the average distances d_{ij}, d_{ji} is selected and registered as the distance Di, j between the source region Rr_i and target region Rt_j under examination.

$$D_{ij} = \max\{d_{ij}, d_{ji}\}$$

- xiii. If no parallelism is derived, then the value inf is registered as the distance D_{ij} between the source region and the target region that is examined.
- xiv. Every region Rr_i of the reference model, is matched to the region Rt_j with the smallest D_{ij} distance.

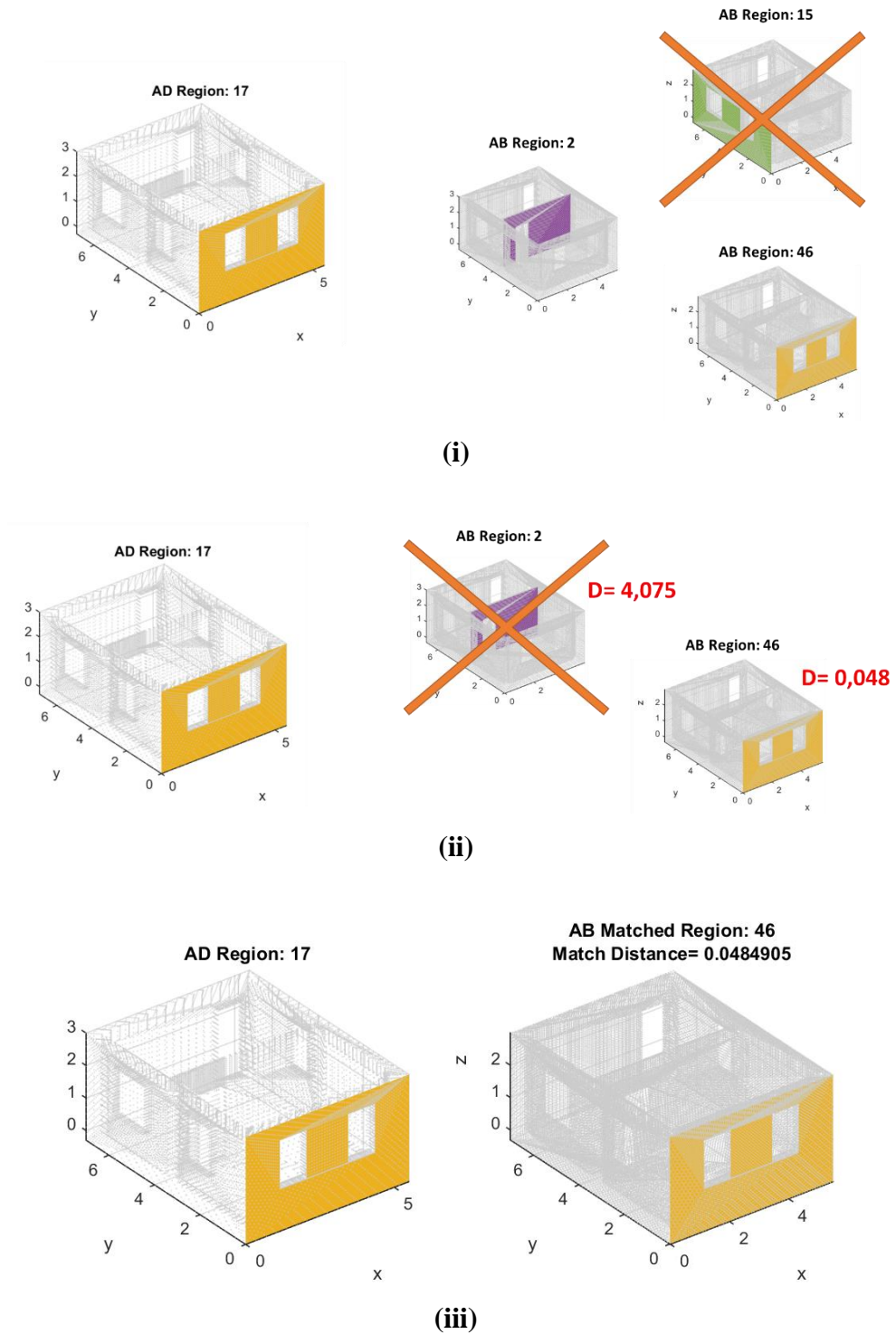


Figure 3.6 Overview of the region matching implementation in Matlab. (i) Rejection of non-parallel regions based on normal vectors, (ii) calculation of the distances between the regions, (v) region match with the minimum distance acquired by the distance calculation metric.

3.6 Deviation Analysis

In this thesis, the calculation of deviations focuses on the calculation of the differences of both the exterior and interior dimensions of the actual model from the theoretical one. The deviations from the external dimensions however are crucial for the legality of the construction. It is important for the inspector to have this information available: If there are deviations of the actual construction, at which point, and what the deviation value is.

Deviations in building interiors are difficult to visualize; that is the reason it is hard to compare the entire AD BIM Model with the As-Built model within a single operation, which would be ideal. To be able to have more detailed information of these deviations, we segmented the building into smaller surfaces belonging to slabs, columns, beams, walls of individual rooms; then deviation analysis was performed on each surface separately. Then, the calculations of deviations between the segmented two models' (As-Designed and As-Built) data, take place.

We consider that the surfaces of the AD model that are the limits of the realized construction and cover, are known from the BIM model. The calculation of deviations takes place after the completion of the coplanar region has completed, and knowing which of them belong to the exterior sides of the building.

Input:

- The AD and AB models, split into matched coplanar regions.

Output:

- The AD model, with the computed deviations of the surfaces of the AB model that belong to the limits of the exterior dimensions of the building.

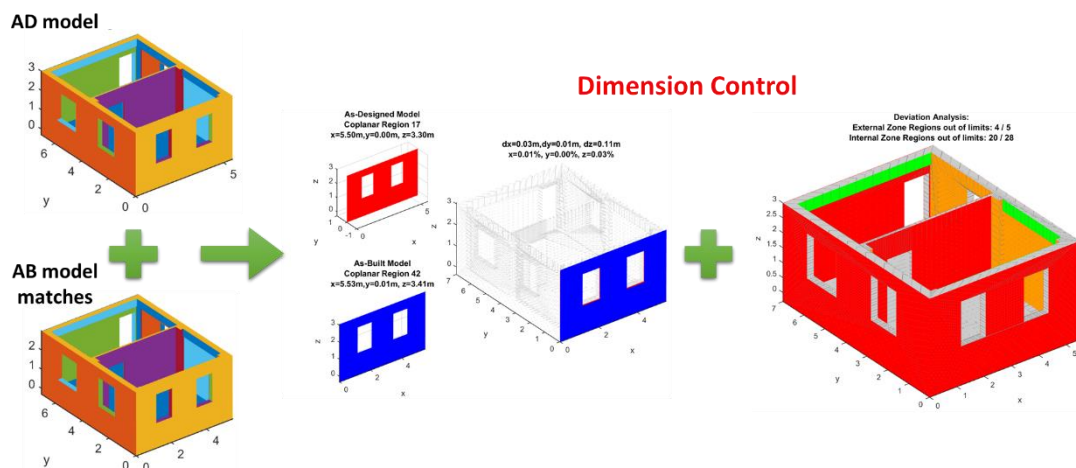


Figure 3.7 General overview of the deviation analysis procedure

Every region of AD is compared with all the regions of AB.

- i. Initially, it is checked whether the surface of AD belongs to an exterior or interior building zone boundary. If it does not belong, it is omitted.
- ii. If it belongs to a zone boundary, a reading of the region of the AB model that has been mapped to it, is carried out.
- iii. Finally the differences in the lengths of the matched AD and AB region sides are calculated, as well as the deviation percentage between them.

This information is coded as the variable *foul*. Thusly, if from the calculation it emerges that the deviations are within the regulation's limits, meaning, under 10 cm of length and less than 2% per side, the value assigned to foul is set to 0. If it is over one of the two conditions, the value assigned to foul is 1, and if it is over both limits, foul takes a value of 2. The results of these calculations are registered to the AD region checked.

After the completion of all the regions' checks, the information becomes available to the user. This way, the user can view, for every mapped region:

- i. At which part of the building it corresponds,
- ii. what are the dimensions of the theoretical one,
- iii. to which surface of the AB model that region has been mapped,
- iv. the actual dimensions,
- v. the difference in length and the percentage per axis.

Finally, the user can view the theoretical model in a summarized chart, with a marking of the surfaces that is related to whether they are with the maximum limits of deviation or not.

4 EXPERIMENTS

For the evaluation of the method, we used simulated scans of buildings. We consider that the As-Built building has been scanned, either by using a laser scanner or by application of a technique of point clouds creation using photographs, and this scanning has been converted to a mesh of triangles, applying one of the existing surface reconstruction techniques.

The evaluation of the building recognition, and the dimensional deviation analysis method was based under certain assumptions.

- i. The inspection of the building is taking place during the masonry building stage.
It is considered that if someone wishes to check if the building dimensions of a building conform to the approved ones, he can begin doing that during this phase of construction.
- ii. The building does not contain any objects that could become obstacles to a correct scanning and would lead to noise.
- iii. The actual buildings components should not exceed a deviation greater than 50cm than the As-Designed. For dimensional differences below 50cm, the method is asked to be capable of successfully detecting them. Taking under consideration that the Building Regulations in Greece do not allow deviations greater than 10 centimeters, the capability of detecting a variation up to five times that limit is considered satisfactory. Structural deviations of a component, greater than 50cm in length, are considered to be out of specifications for the method.
- iv. We assume that the layout of rooms does not change (for instance, a building that has been designed with two rooms on the designed plans, it is not allowed to have been built with three rooms. In this case the building will be out of specs).
- v. It is acceptable to have differentiation in openings (for instance, doors changing place, have less or more windows etc.). In this case the method should be able to successfully match regions with such differences.

4.1 Implementation Details

4.1.1 As Designed model setup

A BIM model of a theoretical building was designed. The design of this model was carried out in the architectural design program Archicad by Graphisoft [57]. In Figure 4.2, the floor plan of the designed building is shown. The external dimensions of the building are 5,50 x 7,00 m and its total surface is 38,50 m². Internally, it comprises of two rooms with a net surface of 14,97 m² and 16,77 m² respectively.

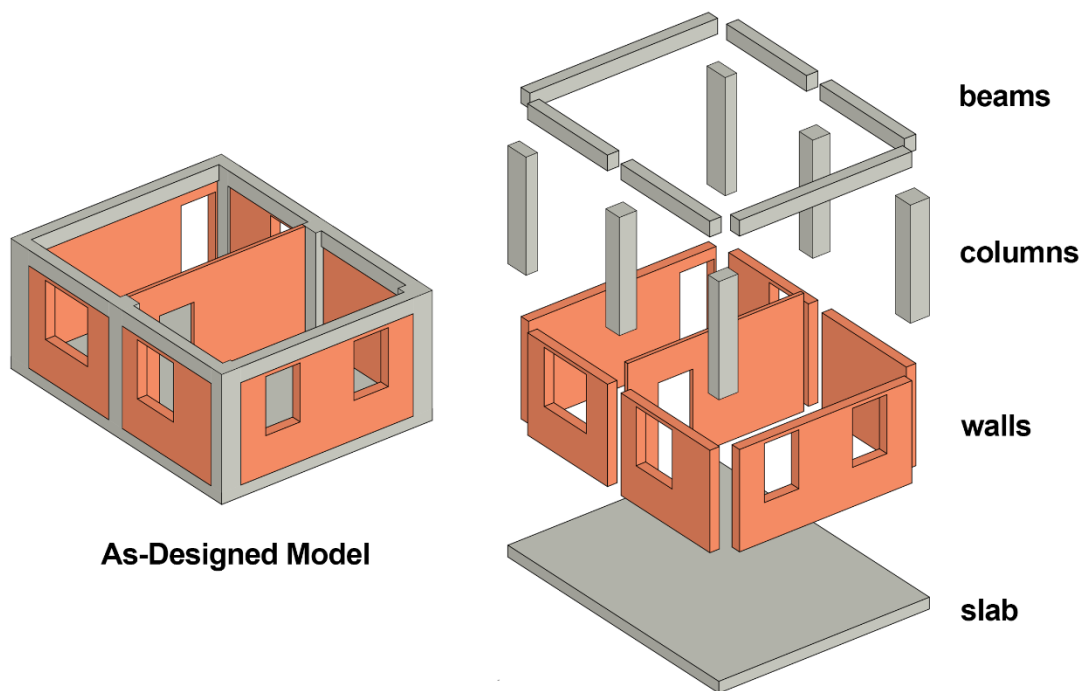


Figure 4.1 The structural components of the AD model

In Figure 4.1, the 3D As-Designed model of the building is shown, as well as the structural elements that compose the model. For depiction reasons, it was decided that there should be no slab on the building's roof.

The model comprises of 4 groups of structural elements. More particularly, it contains:

- Six *column* objects, called c1, c2, c3, c4, c5 and c6.
- Six *beam* objects, called b1, b2...b5.
- Seven *wall* objects, called w1, w2,...w7, and
- One *slab*, called s1.

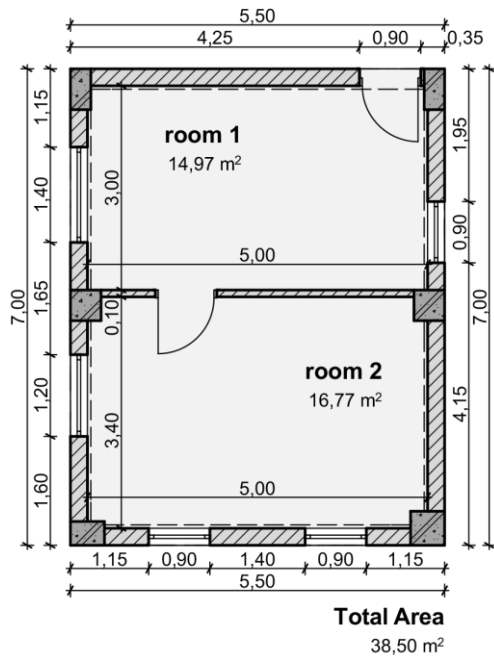


Figure 4.2 The As-Designed model which was used in the case studies.

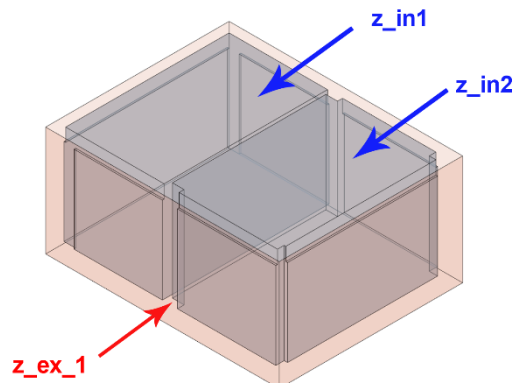


Figure 4.3 The structural zones of the AD model

Except the structural elements, the model is also described by three spaces (zones) that are related with the building's construction taking place. That was, as shown in Figure 4.3, the following are included:

- The external zone, which describes the realized volume and the building's construction, and is called z_{ext_1}
- Two internal areas that refer to the net surface of each room. These areas are called z_{in1} και z_{in2}

The three dimensional model of the model is converted to a triangular mesh and stored in an obj format. For the information of the BIM building to be utilized it was decided that three 3D meshes would be created.

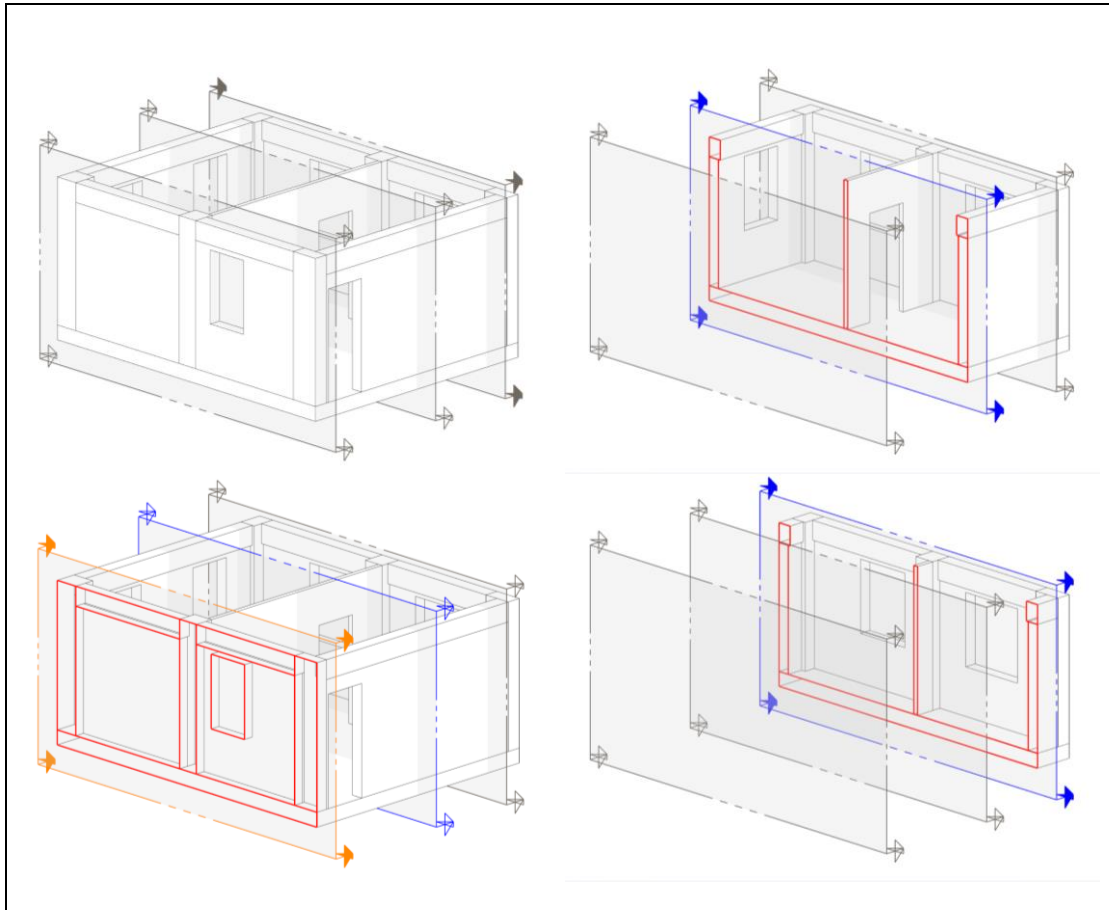


Figure 4.4 The As-Designed BIM model. The existence of internal hidden faces can be noticed, since the model includes each building component defined as an independent object.

- i. The first mesh is the *AD BIM Model*. It contains all the structural elements of a building. Each element constitutes a solid body and contains all its surfaces. This mesh also contains hidden internal surfaces (Figure 4.4).
- iii. The *Structural Zone Model* is constituted by the surfaces that are on the boundaries of structural space zones (including the building envelop and the room spaces). This mesh doesn't contain openings on the walls (Figure 4.5).
- iv. The *Building Skin Model* is a simplified version of the building, which describes the model's skin. The structural elements are not contained in their entirety: only the visible parts of their surfaces are contained, as shown in Figure 4.6.

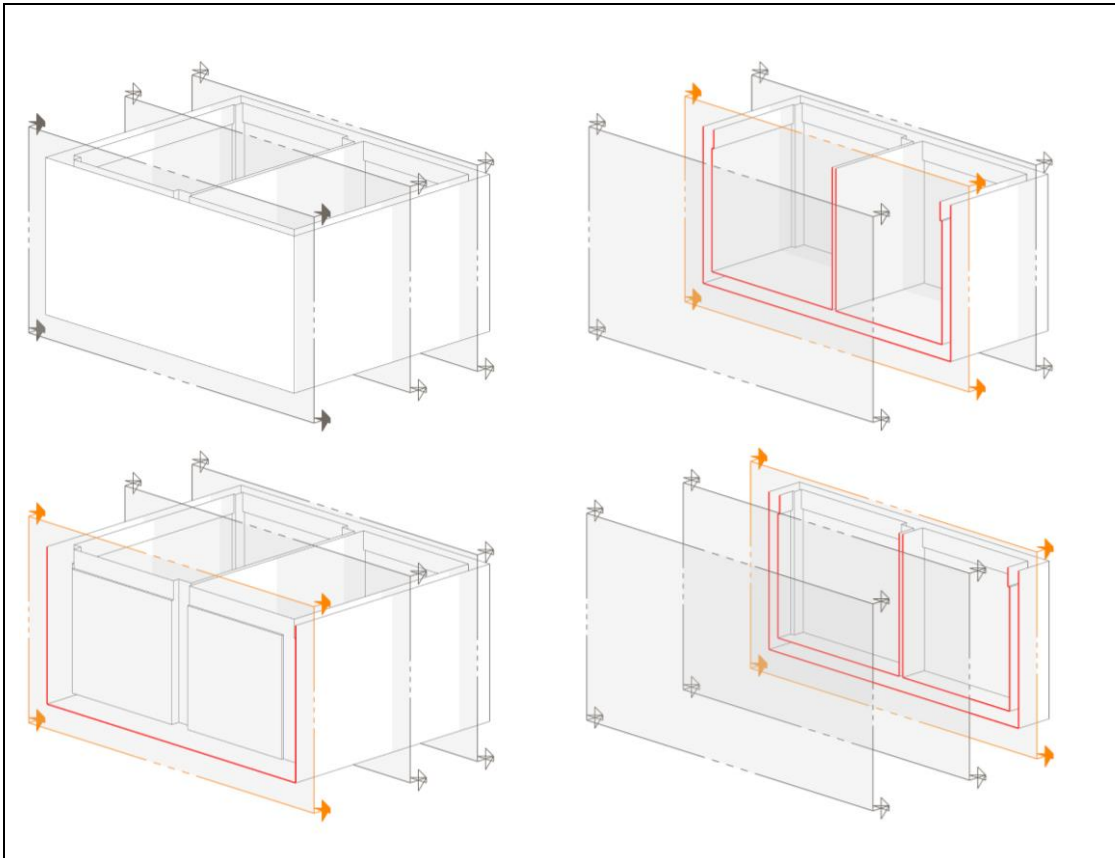


Figure 4.5 The structural zone model

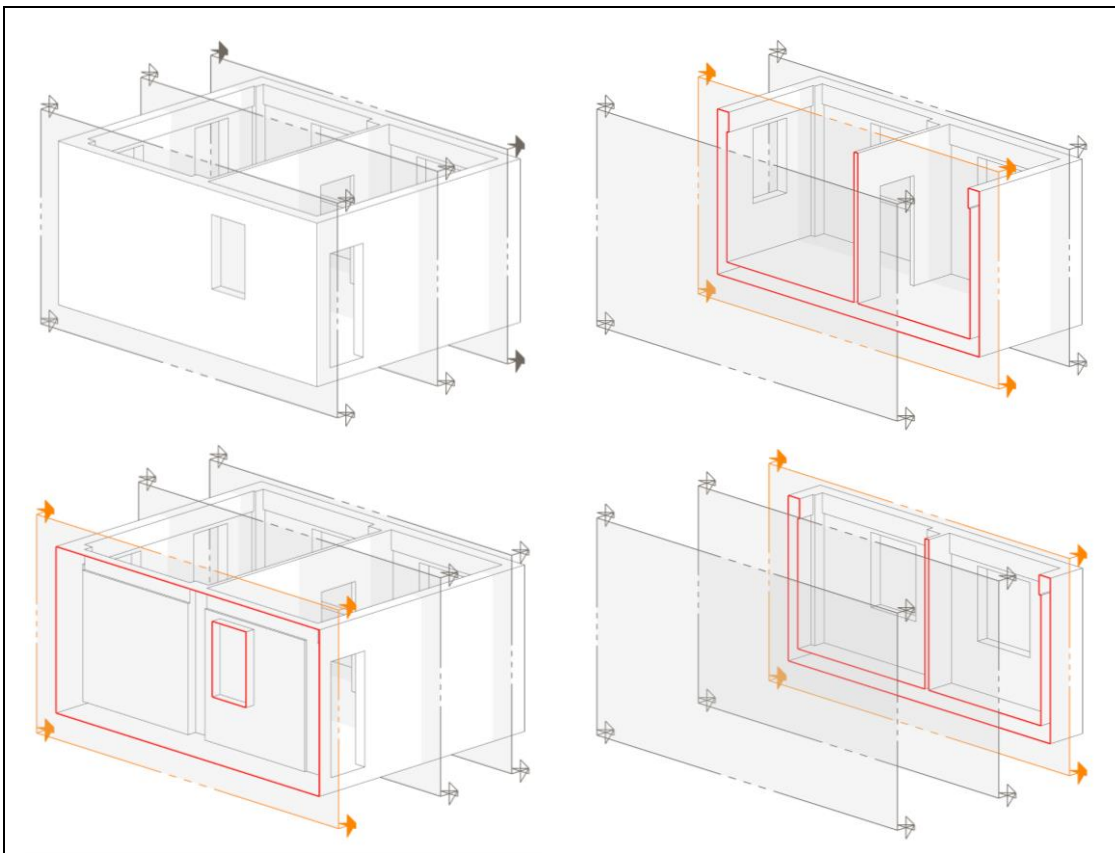


Figure 4.6 The simplified As-Designed skin model. As it's seen on the sections, there are not internal or double faces.

The reason that the models were organized in this manner, is that when the actual building is scanned, what is essentially created, is a model such as the second one, meaning that only the building's skin is scanned. But it is preferable, in regard to this method of recognition and comparison between the two models, for a 3D AD model of a corresponding type to exist. The existence of redundant surfaces, hidden, or double ones (such as in the case of the full model of the first version) creates errors in recognition.

The problem, in the case of the AD skinned model, is that the information that describes the kind of structural elements, the areas' limits etc, is lost. However, this kind of information is required in the process of recognition and matching of the actual to the theoretical model. This is why we were led to the creation of the two other types of 3D models, so that we could enter these required characteristics, having converted the initial BIM model to an obj 3D format.

Ideally, access to the BIM model data could be possible if the format used would be compatible with BIM information. In the current phase, no such thing was available, but we consider that this is something that will be taken care of in the future, and will be automatized, making the use of three different types of 3D meshes needless.

4.1.2 As Built model setups

For the evaluation of the method, a series of three-dimensional AB models were created, which are variations of the AD model. More specifically, four versions of simulated As-Built models were created.

Case 1: One-Axis Expansion

In this first case, we considered that the actual building presents differences in position and in orientation. It also presents a difference in dimensions on one axis. The dimensions of the AB building, despite being differentiated, do not exceed the limits imposed by regulation. (Figure 4.7). Aim of the particular experiment is for the method to be able to observe and record the differences in dimensions, however continuing to consider that the building is inside specifications. Differentiation

Case 2: Two-Axes Expansion

This model is differentiated as to the position, orientation and dimensions along two axes, without exceeding the limits imposed by regulation (Figure 4.8). Just like the previous experiment, the aim is to track changes without the building being considered out of limits.

Case 3: Three-Axes Expansion

Similar to the previous cases, the building in this case is differentiated as to the position and orientation, and its dimensions are different in regard to length, width and height, without the building being out of limits (Figure 4.9). The interest here is to observe how the method can track more extensive changes.

Case 4: Excess Expansion

In the fourth Case, the method's response in cases of extensive changes that exceed the limits imposed by regulation, was put into question (Figure 4.10). The deviations are quite severe, exceeding even 50 cm. The openings are also in different positions than those stated.

All the AB models were converted to obj triangular mesh. The saved model is similar to Skin Model type of the theoretical model, which was described in the previous paragraph. It is composed only by the surfaces that comprise of the building's skin, thusly simulating a model that would result from a three dimensional scanning of a building.

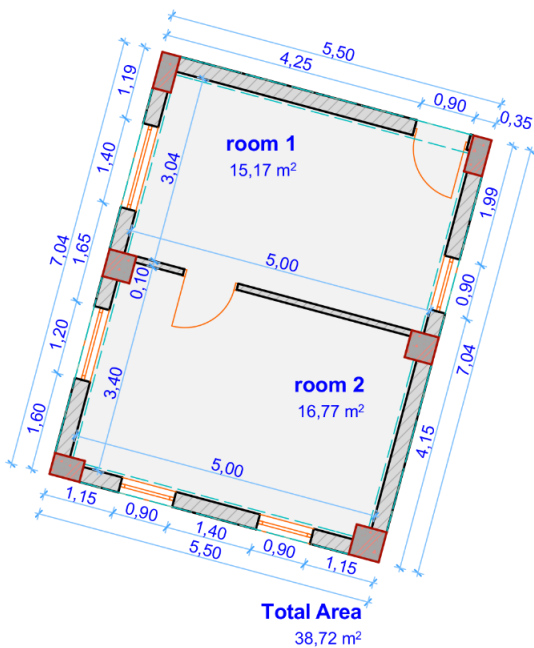


Figure 4.7 AB Model Case 1.

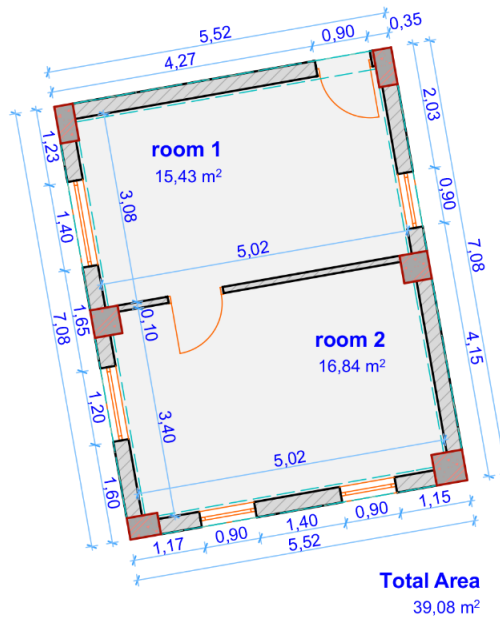


Figure 4.8 AB Model Case 2

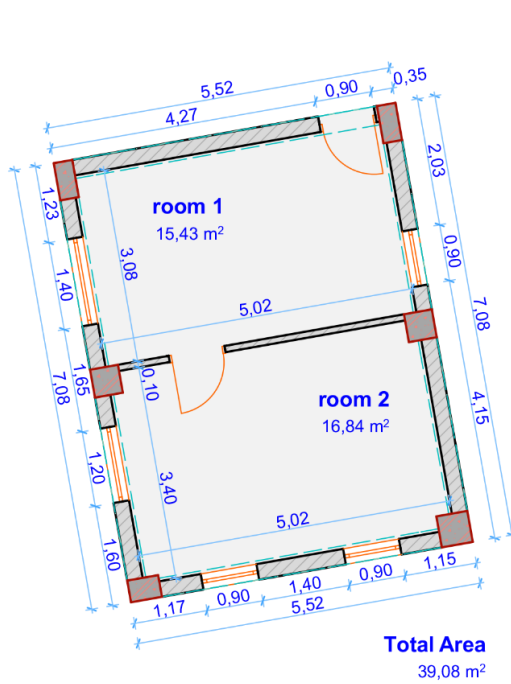


Figure 4.9 AB Model Case 3

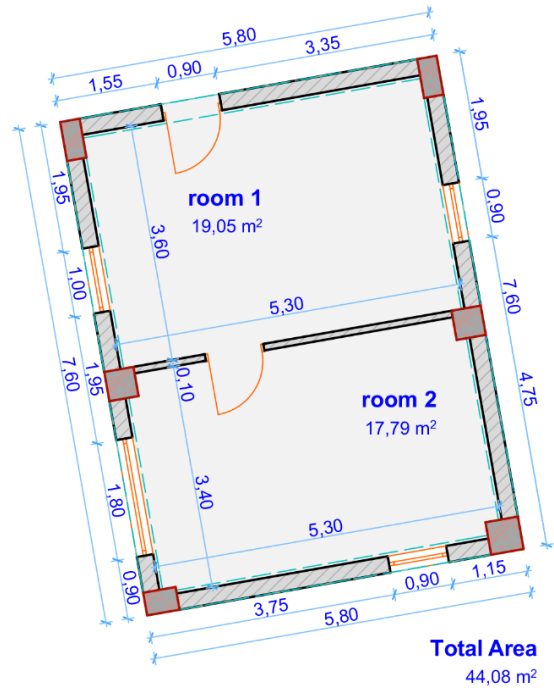
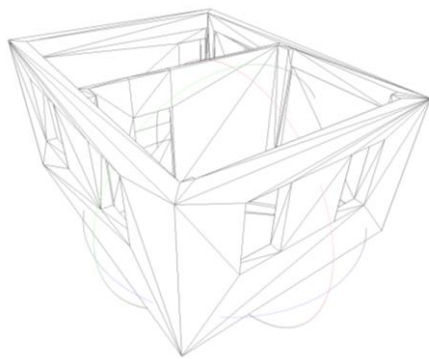
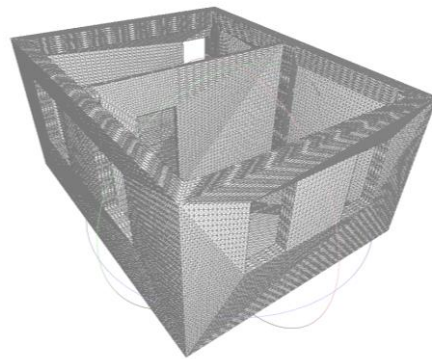


Figure 4.10 AB Model Case 4



(i)



(ii)

Figure 4.11 The triangular mesh, (i) before and (ii) after the surface subdivision process.

Following that, the model is subjected to a surface subdivision procedure (Figure 4.11) with the use of MeshLab software. By this technique, the mesh polygons are multiplied, so that the points and faces simulate the relative density that a point cloud resulting from an actual scanning would have.

In Table 1 the characteristics of the models that were used during the process of experimental evaluation of the method are shown in summary.

Table 1 Characteristics of the models used in the experiments

Model Characteristics	AD Model	Case 1:	Case 2:	Case 3:	Case 4:
Vertices	25.102	96.914	102.490	106.425	98.060
Faces	50.228	193.852	205.004	212.874	196.140
No. of Surfaces	63	63	63	63	59
External Zone Surfaces	5	5	5	5	5
Internal Zone Surfaces	30	30	30	30	30

4.1.3 Alignment

For the Alignment an implementation of the ICP algorithm for Matlab was used, using a k-d structure matching with extrapolation for optimal performance. The algorithm was set to a maximum of 60 iterations.

The inputs were the AD Models Point Cloud, which was the reference and the AB Model's Point Cloud respectively, which we want to align to the reference. The point clouds were acquired from the vertices list of the input model meshes.

4.1.4 Segmentation

For the coplanar region segmentation, a script was developed in Matlab including an original region grow algorithm, based on face vertices indexing. The input for the algorithm is a mesh model, and the output is segmented coplanar regions in the form of face groups, extracted from the input triangular mesh. As a parallelism threshold of angular tolerance, the value of 15 degrees was set (Normal Vectors with an angle of less than 15 degrees are considered parallel).

4.1.5 Matching

The matching metric algorithm was also developed in Matlab. The inputs of the algorithm are the points belonging to the segmented region groups of both the AD and AB mesh models. The system returns the AB regions that were matched to the AD model. In the implementation, a value of $d_{max} = 2$ and a parallelism angular tolerance of 5° degrees were set.

4.1.6 Deviation Calculation

For the final step, another algorithm was developed in Matlab, taking as inputs the coplanar region matches between the AD and AB models, and calculating dimensions for each region of the pair, as long as the difference in length between them. Finally the AD model is exported with its regions encoded according to the deviation analysis and whether they are found to be within the limits of the building regulation or not.

4.2 Results

The buildings' data for each Case were loaded in Matlab. Their processing returned the following data:

4.2.1 Case 1: One-Axis Expansion

In the first case, the method succeeded in aligning the initial As-Built model to the As-Designed model, by use of ICP, with an RMS Error of 0,0699 (Figure 4.12).

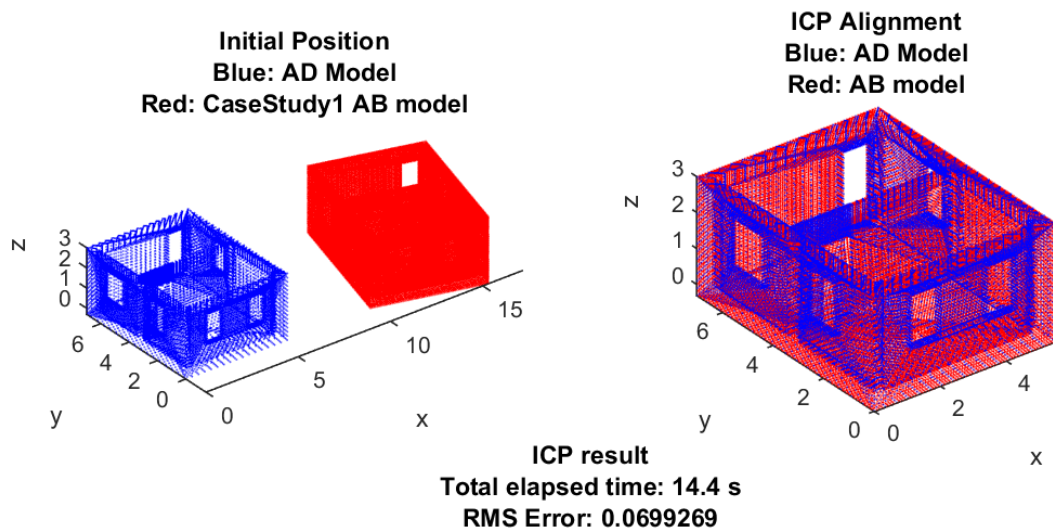


Figure 4.12 Alignment of the Case 1 AB model with the AD

Following that, and by applying the region growing algorithm, 62 out of 63 planar surfaces contained in the AB model, were recognized (Figure 4.13).

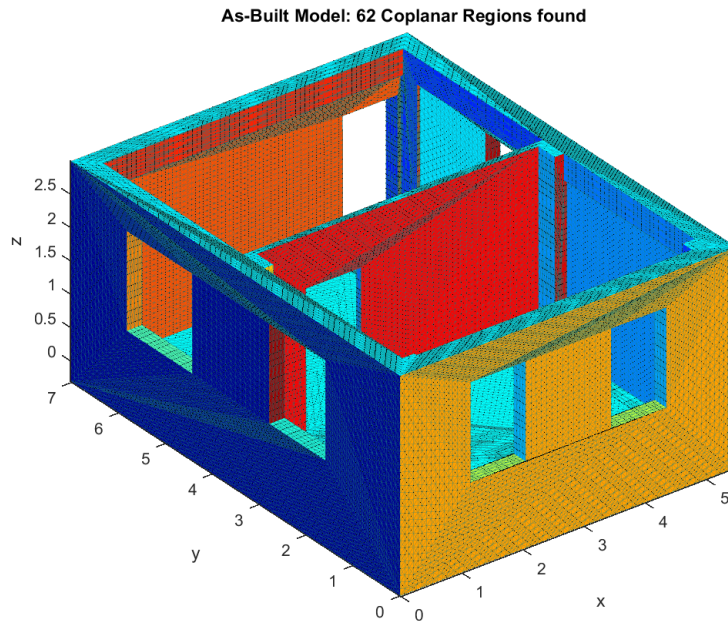


Figure 4.13 Case 1, As-Built Coplanar Regions as detected by the region growing implementation

The reason this happened is accountable to a modeling error. In Figure 4.14, two surfaces that are at the bottom side of two beams can be discerned. The two surfaces have been recognized as one coplanar region, when they should have been two. On closer inspection of the region, it was observed that the two surfaces are connected via one false, almost zero area face. At these point, the region growing algorithm sees that neighboring polygons exist, and thusly erroneously connects these two discernable regions via those polygons.

This occurrence is because of a modeling error originating during the process of density increase of the initial model that had been created for the needs of simulation. Similar kinds of problems were encountered in the rest of the Case Studies as well, leading to false segmentation of the coplanar regions.

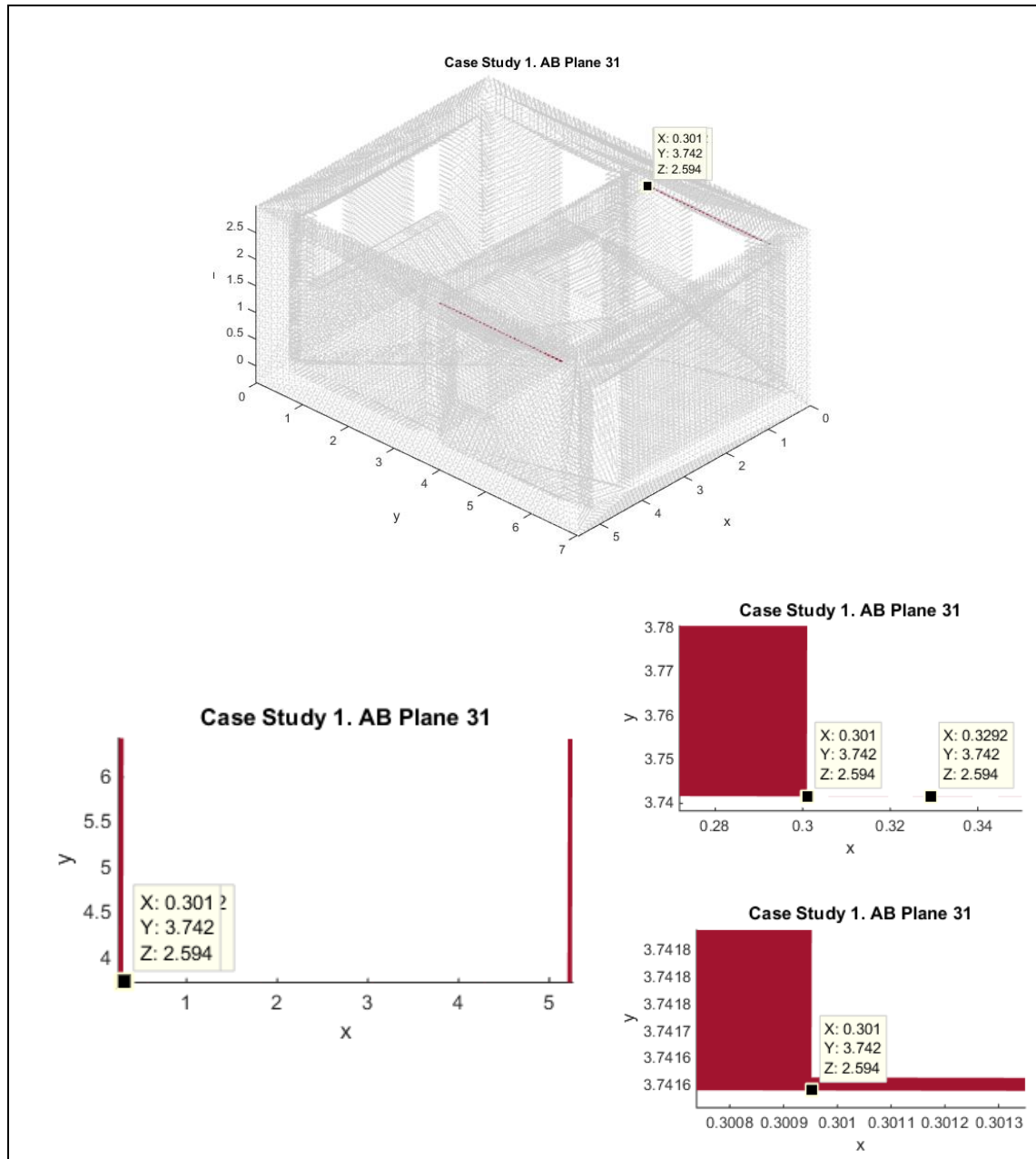


Figure 4.14 False faces produced during the surface reconstruction in MeshLab, in order to get a denser point cloud model for the simulation. In this case the two discrete surfaces on left and right are connected by an almost zero area triangular surface.

A second problem that was observed, is the false splitting of a coplanar surface into more regions. In Figure 4.15, two coplanar regions that have been output by the region growing algorithm are shown. These two regions belong to a coplanar surface and normally should have been one region. By inspecting the model, an inconsistency in the vertexes of the polygons comprising it was observed. It so shows in that figure, that at the regions' splitting limit, the triangles of level 55 have different vertexes from the triangles of level 50. This fact leads to a false splitting of these two regions, because the algorithm does not perceive that the planes' faces are neighboring. The existence of this problem, just like

the previous one, is to be accounted to a problematic modeling during the densification of the model in MeshLab. A similar error was observed in the rest of the Case Models as well.

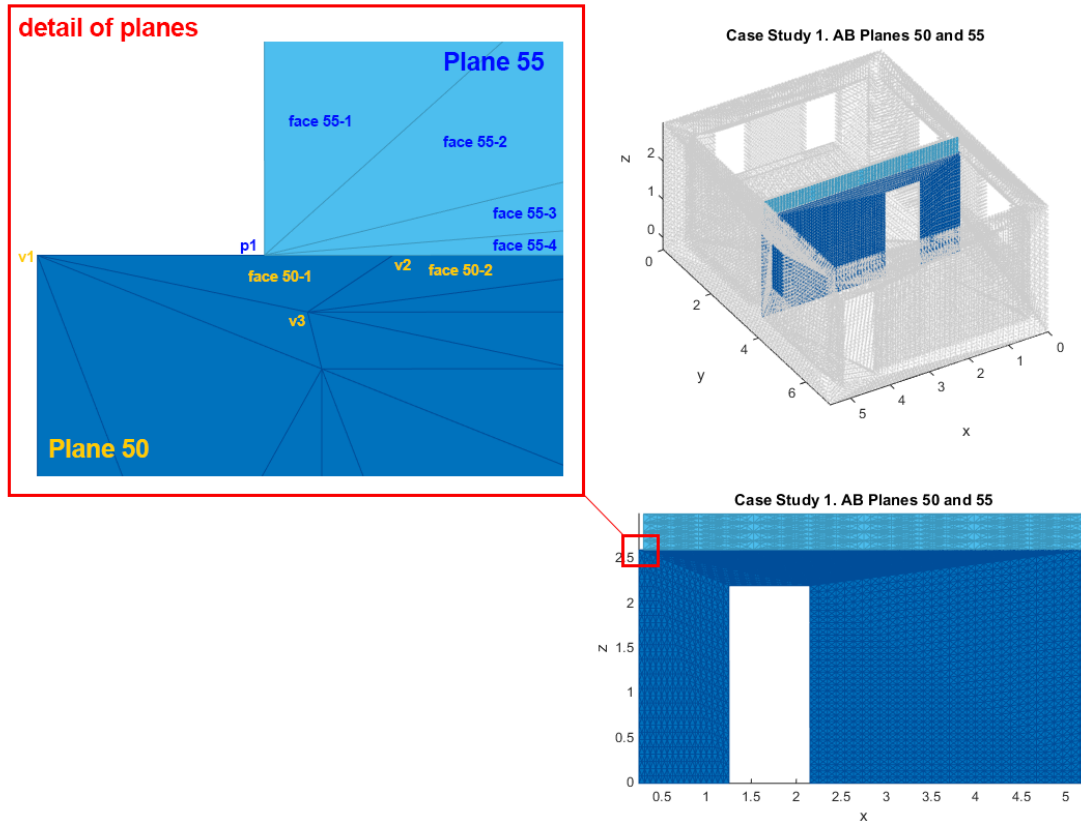


Figure 4.15 Disjointed faces produced during the surface reconstruction in MeshLab, in order to get a denser point cloud model for the simulation, leading to erroneous separation of a coplanar surface to individual regions.

With the use of matching metric, a total of 59 out of the 62 coplanar regions of the AB model, were successfully matched to the AD model. The surfaces belonging to the exterior sides of the building were all detected successfully. Out of a total of 30 surfaces contained in the AD model at the interior side of the construction zone, the method managed to match 28 to the As-Built model. In Figure 4.17, the results of matching the Regions between the AD and AB models. As can be seen in the same figure, the 4 internal surfaces of the AD model that couldn't be matched are the surfaces that are found at the points of the problematic output of the coplanar regions from the AB model that were reported above.

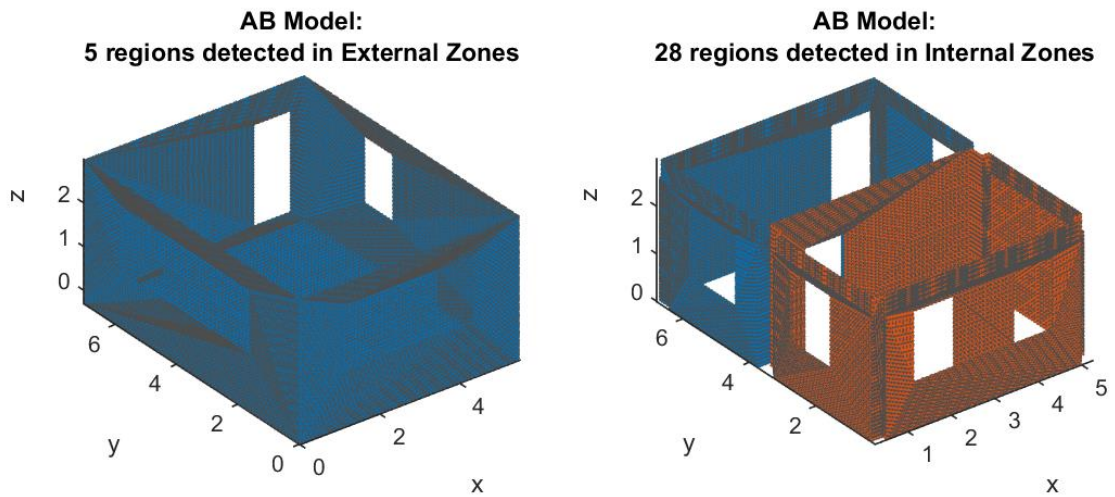


Figure 4.16 Zone Matching Results. The figure presents the regions of the Case 1 AB model that were matched to the external and internal zones respectively.

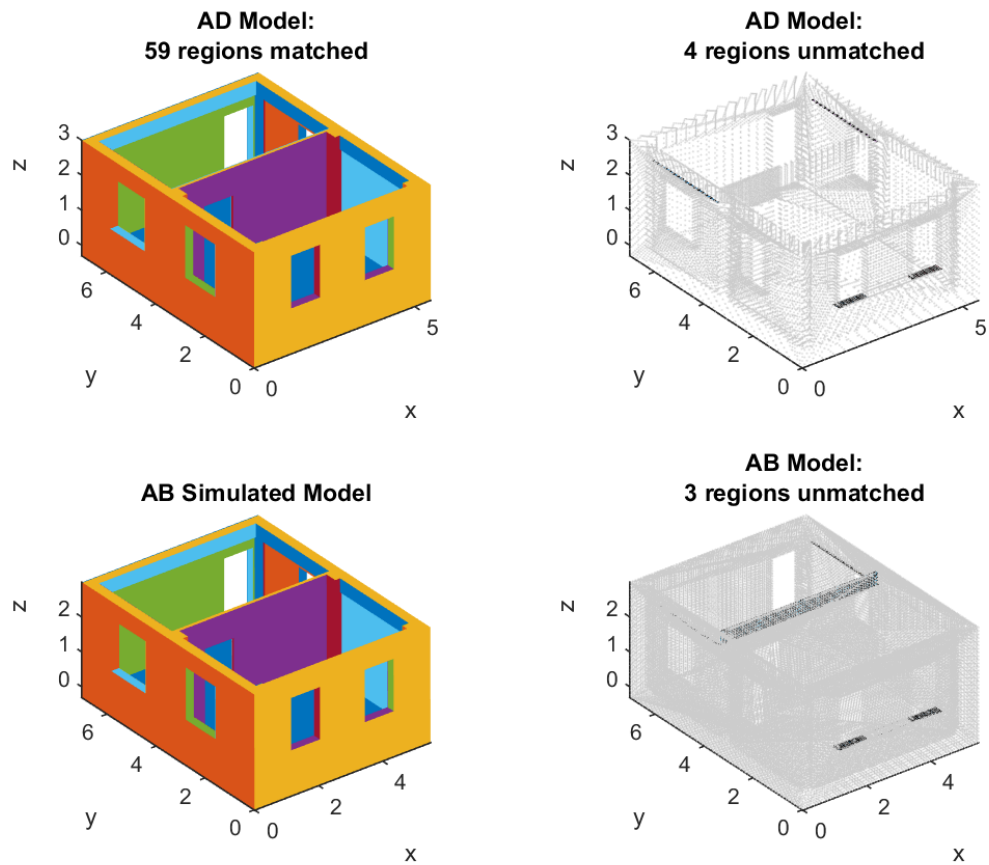


Figure 4.17 Coplanar Region Matching Results, Case 1

As to the checking of compliance of the AB model to the theoretical model, the data processing, as shown in Figure 4.18, leads to the conclusion that the exterior dimensions are within the limits imposed by regulation, a fact that corresponds to the truth.

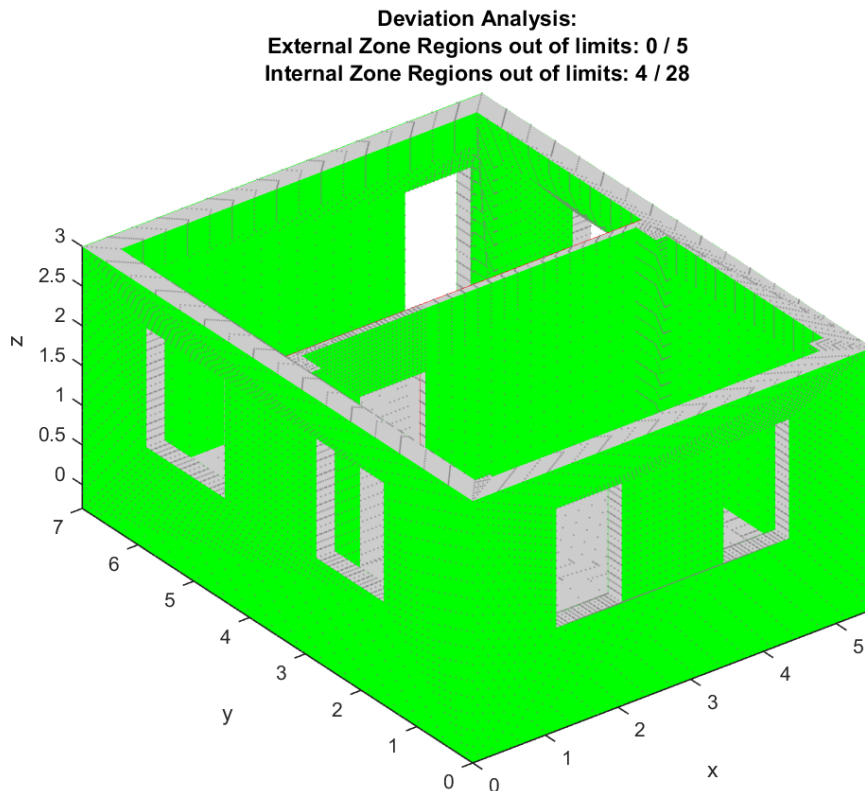


Figure 4.18 Deviation Analysis Results, for the Case 1 AB model.

In the interior dimensions, the method computed that four surfaces are out of regulation, which is false, because in reality the AB model does not exceed the imposed limits. In Figure 4.19, a case of false calculation of deviation is shown, which is accountable to bad segmentation of the coplanar regions of the AB model.

A different case of erroneous detection of deviations is shown in Figure 4.20. In this case, we observe two matched surfaces which refer to the bottom side of a beam that clearly protrudes from the wall. The method computed that, on the y axis, the dimensions of the AB model for this surface are larger than those provisioned in the theoretical model. The calculation of dimensions, as analyzed in paragraph 3.6, is carried out based on the projections of coordinates on the corresponding axis. As a result, the calculation precision directly depends on the correct alignment of the model by the ICP algorithm. When the models are absolutely aligned, no deviation errors because of alignment will occur. Otherwise, there is an error on the calculation precision, directly dependent on the RMS Error of the alignment. In the case shown in Figure 4.20, because of the small dimension on y, the error introduced because of the bad ICP alignment, leads to a false calculation of the deviation.

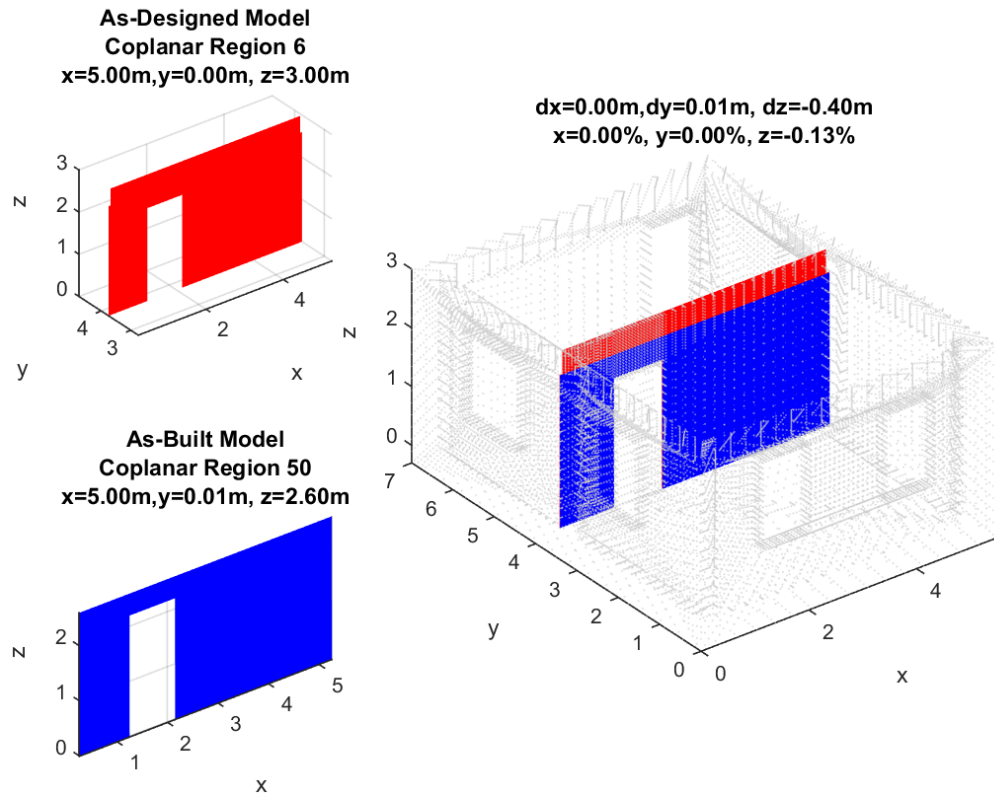


Figure 4.19 Erroneous calculation of deviation between two matched regions, due to bad region segmentation.

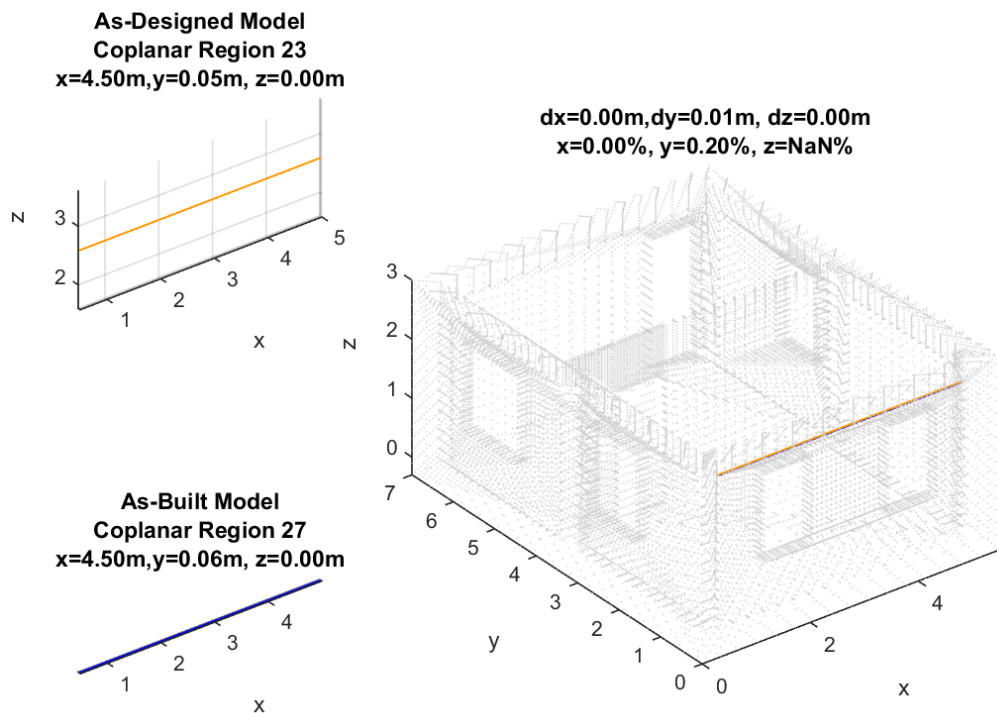


Figure 4.20 Erroneous calculation of deviation between two matched regions, due to bad alignment of the AB model by the ICP algorithm.

4.2.2 Case 2: Two-Axes Expansion

In the second Case, the method managed to align the initial As-Built model to the As-Designed model, by utilization of ICP with an RMS Error of 0,07.

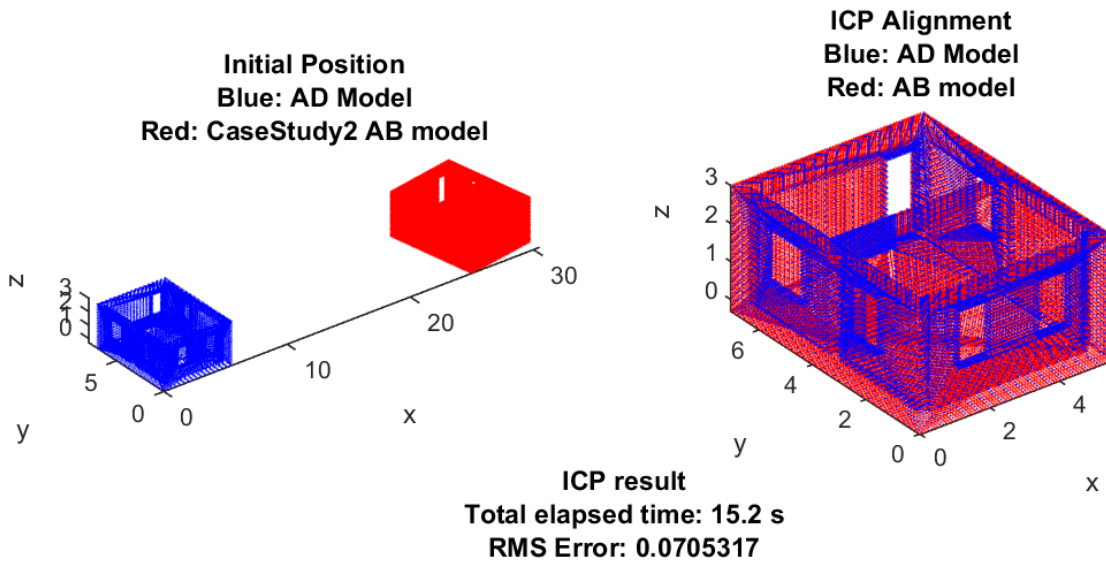


Figure 4.21 Alignment of the Case 2 AB model with the AD

Following that, and by applying the region growing algorithm, 62 out of 63 planar surfaces contained in the AB model were recognized (Figure 4.22, Figure 4.13).

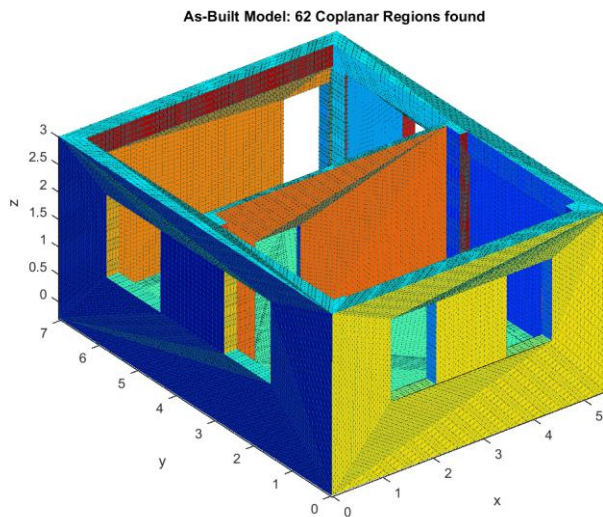


Figure 4.22 Case 2, As-Built Coplanar Regions as detected by the region growing implementation

By use of matching metric, a total of 59 out of the 62 coplanar regions of the AB model, were successfully matched to the AD model. The surfaces belonging to the exterior sides of the building were all successfully detected. Out of the total of 30 surfaces contained in the interior side of the construction zone of the AD model, the method successfully

matched 28 with the As-Built model (Figure 4.16). In Figure 4.23, the results of matching the Regions between the AD and AB models are shown.

As shown in Figure 4.24, the 4 internal surfaces of the AD model that weren't matched are surfaces that are situated at the points of problematic output of the coplanar regions from the AB model.

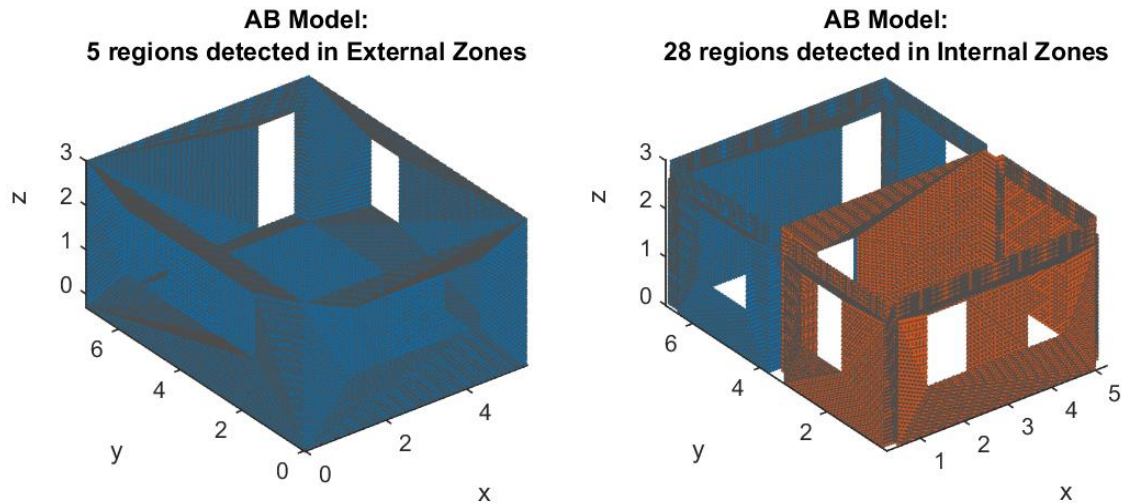


Figure 4.23 Zone Matching Results. The figure presents the regions of the Case 2 AB model that were matched to the external and internal zones respectively.

As to the checking of compliance of the AB model to the theoretical model, the data processing, as shown in Figure 4.25, leads to the conclusion that the exterior dimensions are within the limits imposed by regulation, a fact that corresponds to the truth.

Regarding interior dimensions, the method calculated that 12 surfaces are out of regulation. All of these 12 surfaces are wrongly characterized out of limits, as all internal dimensions are within limits despite their deviations. Out of these errors, 3 are accountable to modeling error, and 9 to bad alignment that introduces an error in the calculation precision.

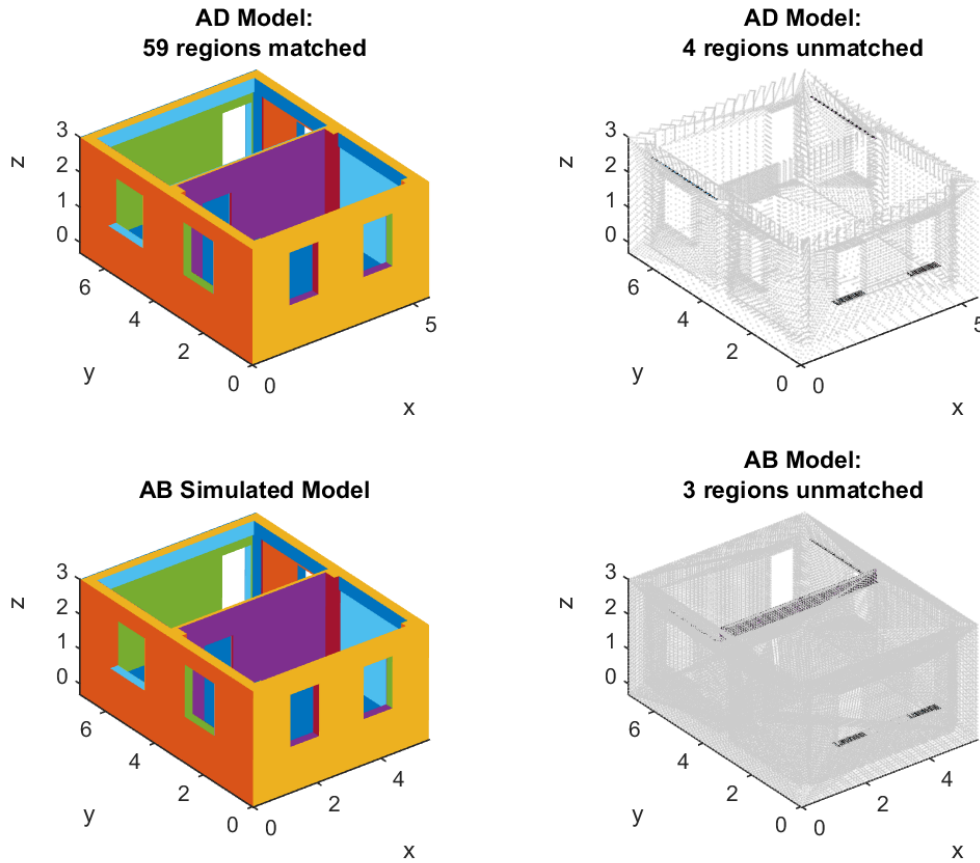


Figure 4.24 Coplanar Region Matching Results, Case 2

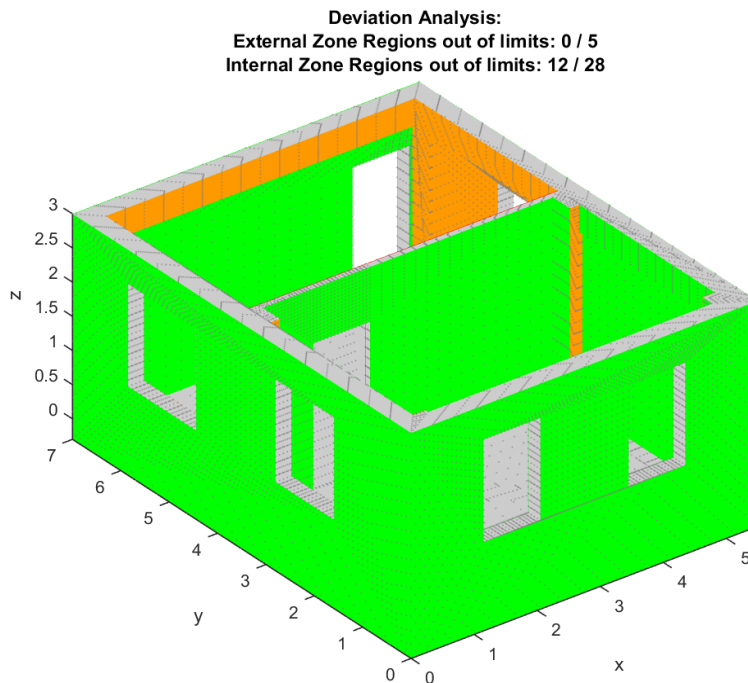


Figure 4.25 Deviation Analysis Results, for the Case 2 AB model.

In Figure 4.26, a case is observed, in which two different structural elements have been merged into a coplanar region, during the segmentation phase. Taking the Case into

account, in this particular case, the prop of the building is not actually out of the limits imposed by regulation, as it has the dimensions provisioned in the AD model. What actually is out of provisioned dimensions, is the beam. The impotence of differentiation of the regions as to the structural elements, in cases like this, is possible to lead to false results. This was a problem encountered in all case studies, and especially in the internal sides of the building, where greater differentiation in the surfaces exists.

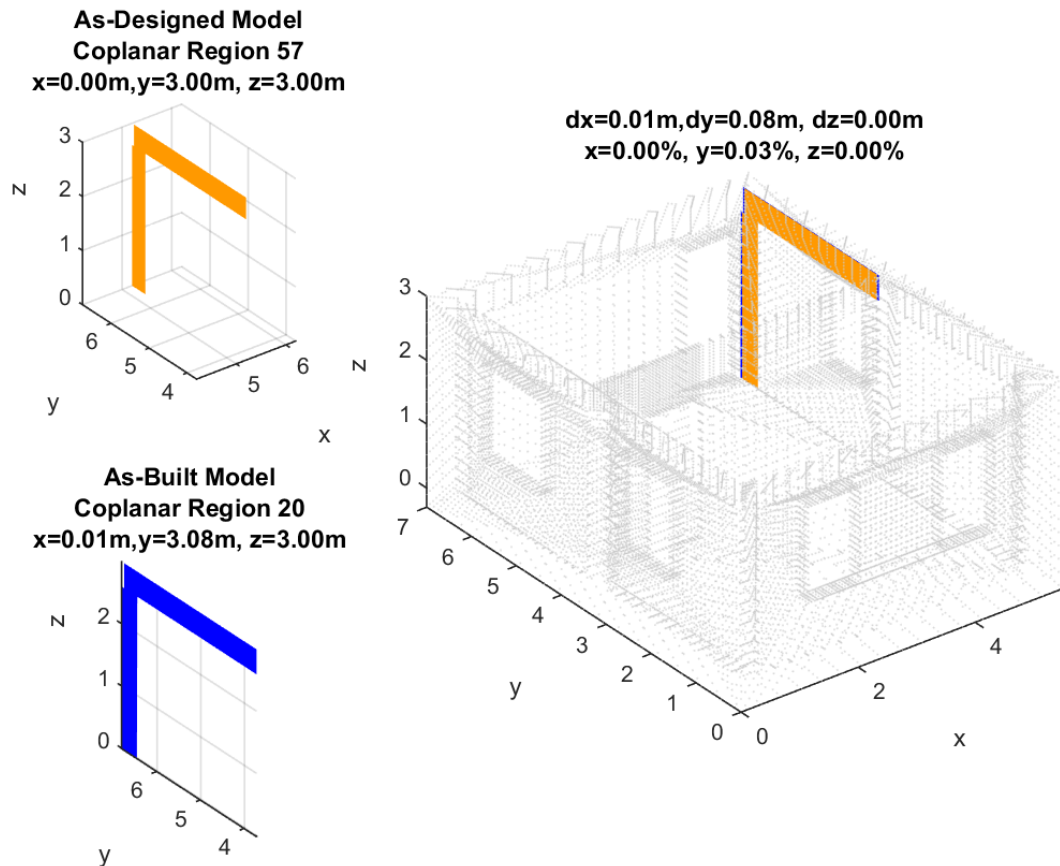


Figure 4.26 Merging of different building components during the region segmentation. In this case a column and a beam are extracted as a single region. This is an issue that can lead to erroneous deviation analysis in some cases.

4.2.3 Case 3: Three-Axes Expansion

In the third case, the method managed to align the initial As-Built model to the As-Designed one, by use of ICP with an RMS Error of 0,0753. (Figure 4.27).

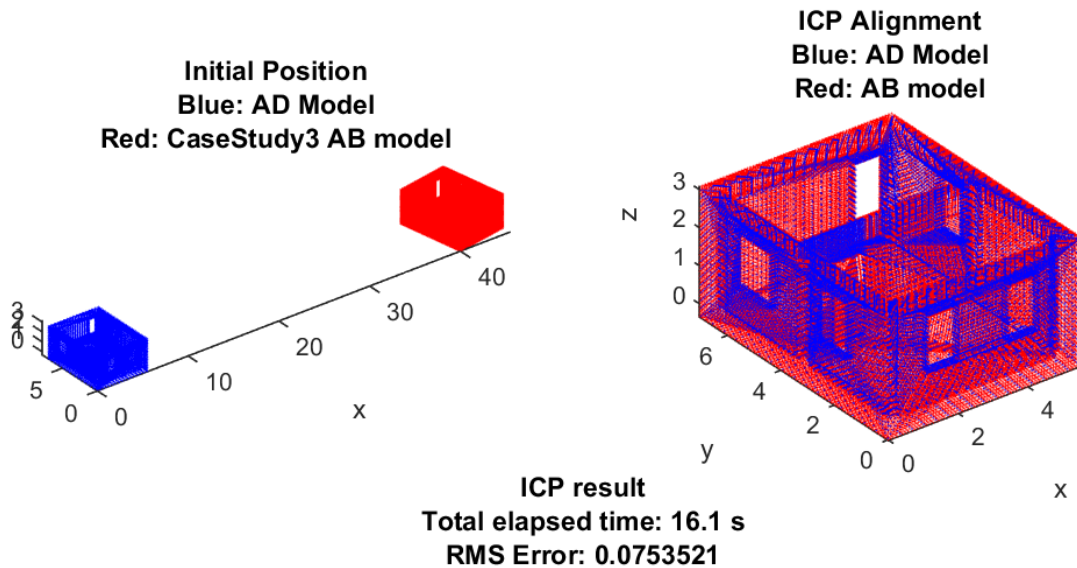


Figure 4.27 Alignment of the Case 3 AB model with the AD

Following that, by applying the region growing algorithm, out of 63 planar surfaces contained in the AB model, the method recognized 137 (Figure 4.28). Those extra regions recognized by the method, consist of almost zero area faces that are accountable to errors in modeling.

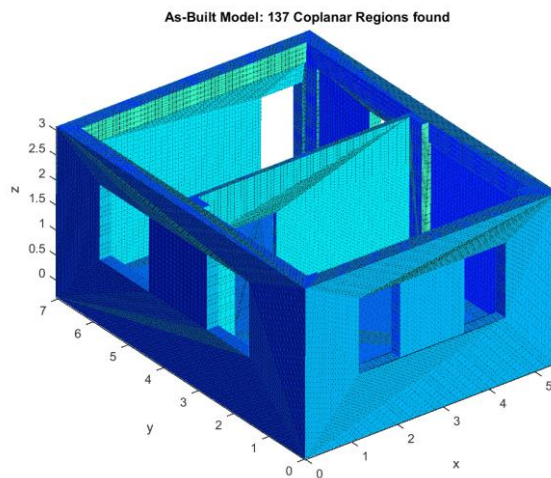


Figure 4.28 Case 3, As-Built Coplanar Regions as detected by the region growing implementation

By use of matching metric, a total of 59 out of the 137 coplanar regions of the AB model, were successfully matched to the AD model. The surfaces belonging to the exterior sides of the building were all detected successfully. Out of a total 30 surfaces contained in the AD model, in the interior side of the construction zone, the method managed to match 28 to the As-Built model. In Figure 4.29, the results of matching the Regions between the AD and the AB models are shown.

As shown in Figure 4.30, 4 internal surfaces of the AD model could not be matched. These surfaces are located at points of problematic output of the coplanar regions because of errors in modeling. Their existence didn't create particular issues during matching.

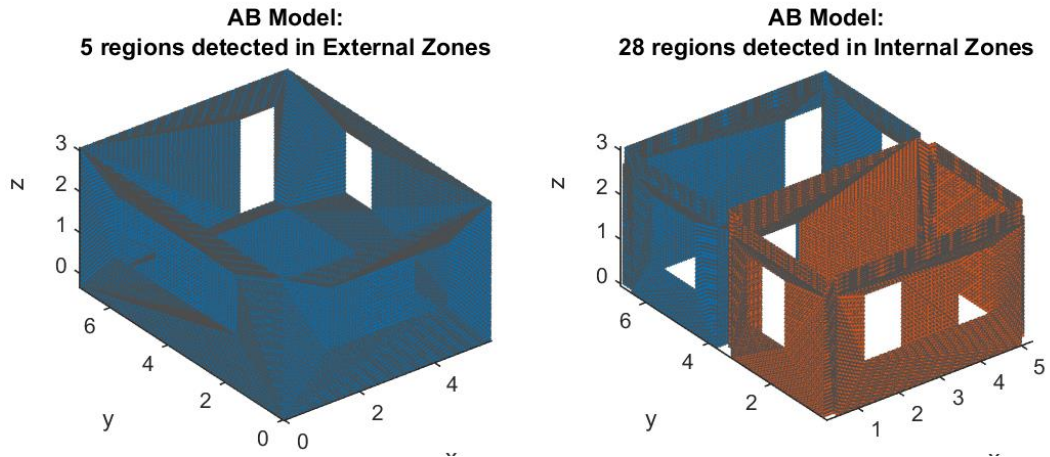


Figure 4.29 Zone Matching Results. The figure presents the regions of the Case 3 AB model that were matched to the external and internal zones respectively.

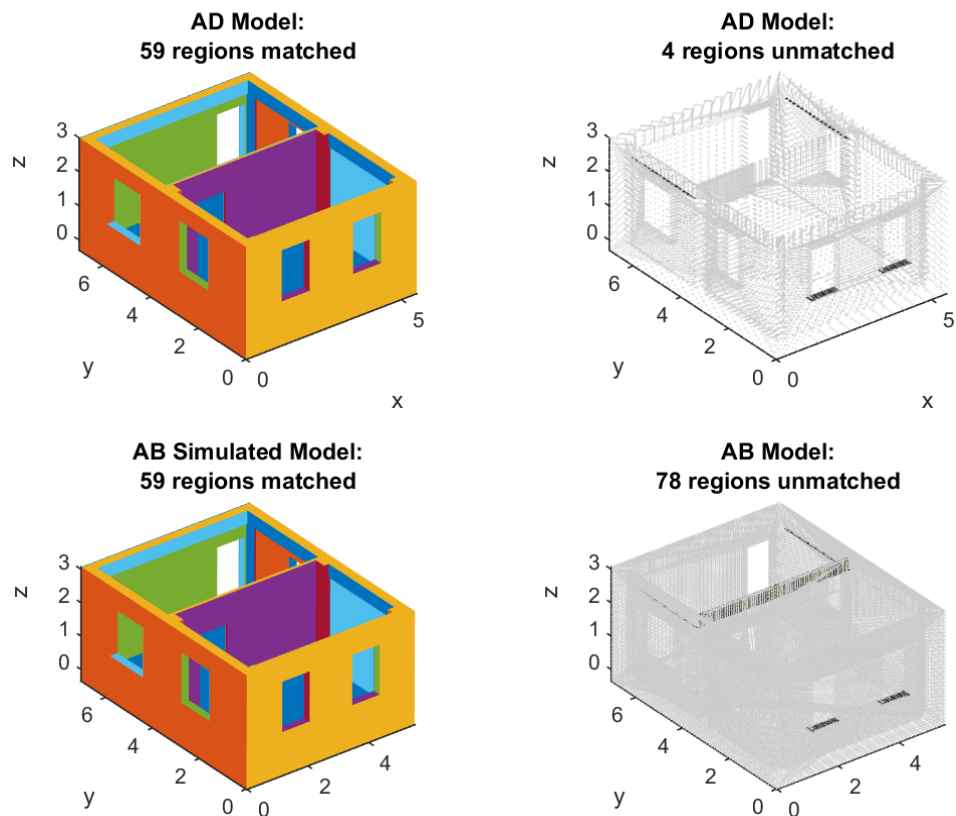


Figure 4.30 Coplanar Region Matching Results, Case 3

Regarding the compliance check of the AB model to the theoretical model, the data processing, as shown in Figure 4.31, led to the conclusion that 4 out of 5 exterior dimensions are outside the limits imposed by regulation, a fact which corresponds to the

truth. The fifth surface is the building floor, which, despite being different in dimensions between the AB building and the AD one, actually is inside the limits imposed by regulation. The 4 external surfaces, as analyzed by the method, exceed the limits in regard to height, and are thusly correctly defined as ‘out of limits’.

In regard to interior dimensions, the method calculated all 20 surfaces that actually are out of regulation bounds.

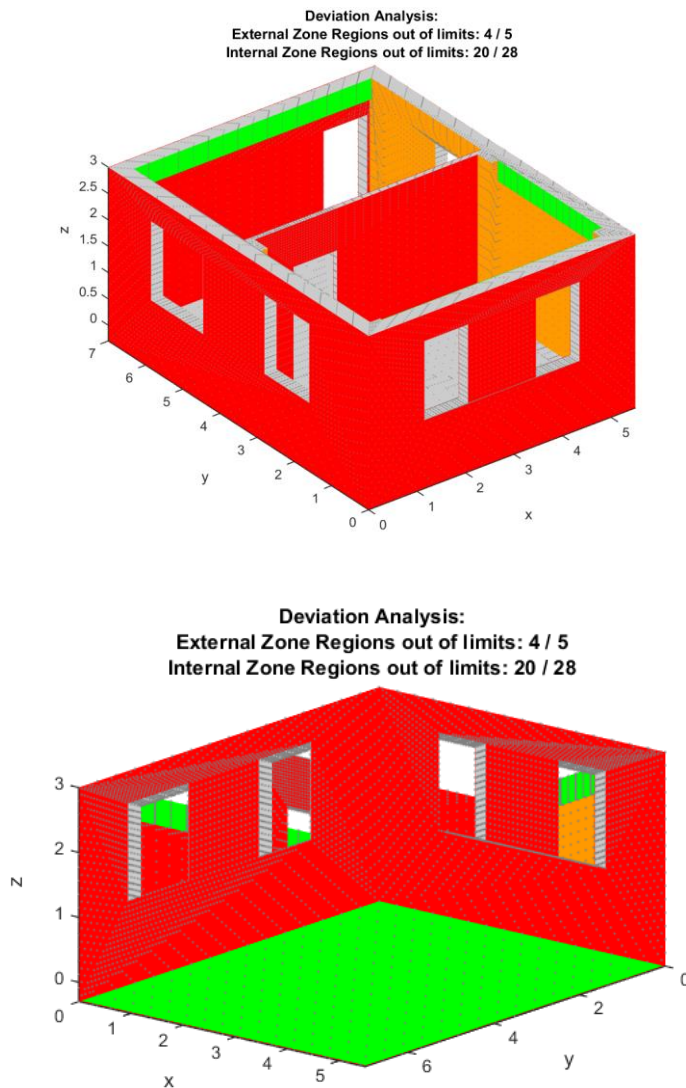


Figure 4.31 Deviation Analysis Results, for the Case 3 AB model.

4.2.4 Case 4: Excess Expansion

In the fourth Case, the method managed to align the initial As-Built model to the As-Designed, by use of ICP with an RMS Error of 0,1775. (Figure 4.32). We observe that, the bigger the differentiations are in the actual model, the bigger the error is, which is logical, since the model cannot be matched to the theoretical one. However, the increased

value of error is expected to produce extra errors in the measuring of dimensions of the elements and the computing of differences the actual model has, compared to the AD model.

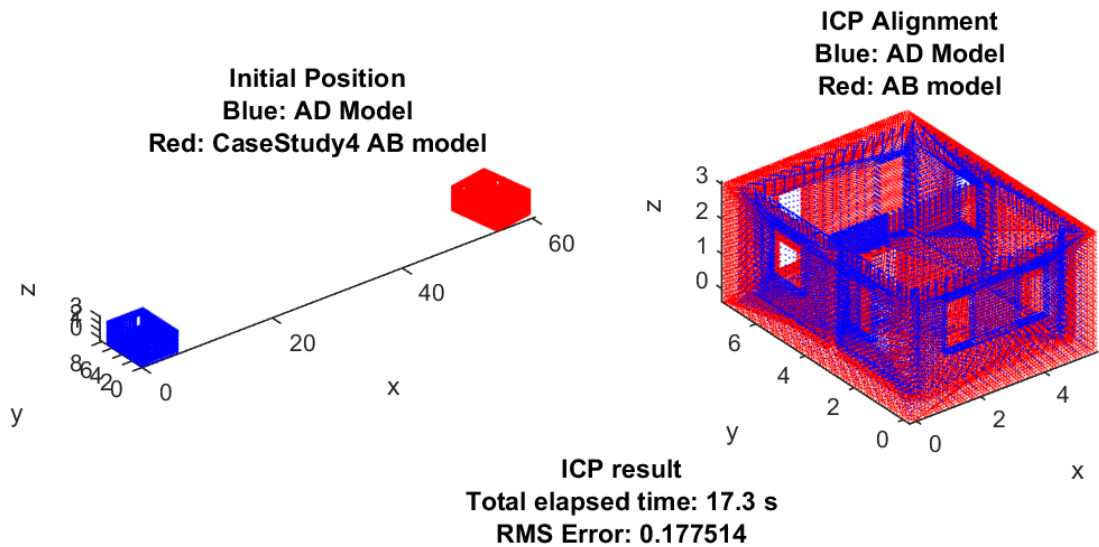


Figure 4.32 Alignment of the Case 4 AB model with the AD

Following that, by applying the region growing algorithm 59 out of 59 planar surfaces contained in the AB model, were recognized (Figure 4.33).

In Figure 4.34, the results of matching the Regions between the AD the AB models by applying matching metric: 52 out of 59 coplanar regions of the AB model, were successfully matched on the AD model.

Because of increased differences in the model dimensions, in comparison to the previous studies, an inefficiency in matching some regions was observed. As shown in Figure 4.34, the regions of the AD model that could not be matched –with the exception of those located at the points of problematic output of the coplanar regions from the AB model that were reported above- are also areas that haven't been built in the building (loss of window) or show significant modifications (door or window relocation, etc).

Experiments

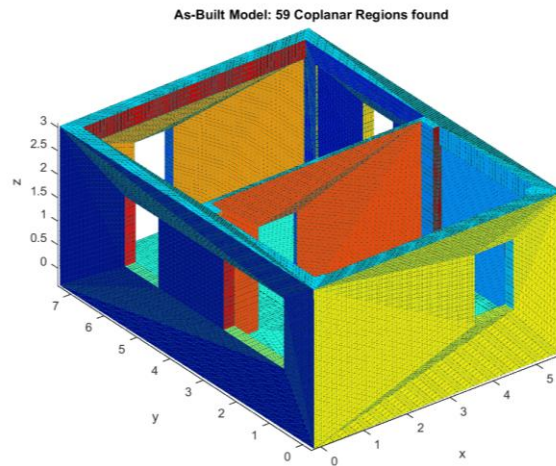


Figure 4.33 Case 4, As-Built Coplanar Regions as detected by the region growing implementation

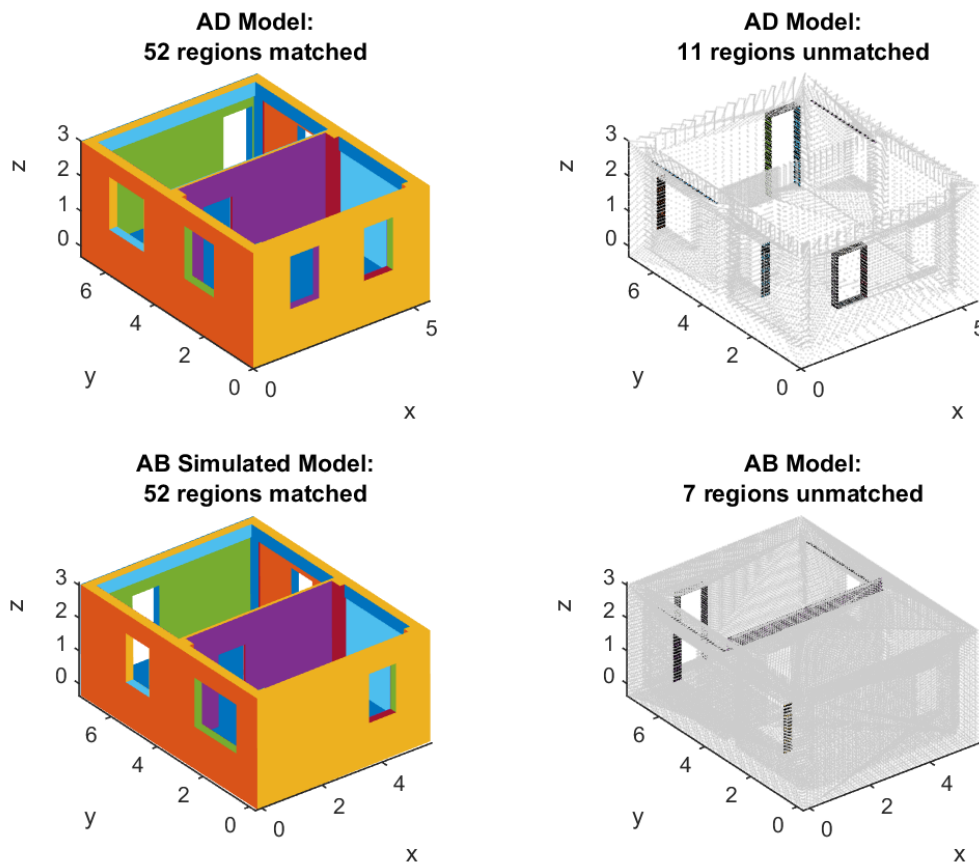


Figure 4.34 Coplanar Region Matching Results, Case 4. The great difference in the dimensions of the AB model, has led to region mismatching and failure of matching certain regions of the AB model to the AD. This failure is observed in objects that have higher discrepancy.

In the end, regarding the construction zones, the surfaces belonging to the exterior sides of the building were all successfully detected. Out of a total of 30 surfaces contained in the AD model in the interior side of the construction zone, the method managed to match 28 to the As-Built model (Figure 4.35).

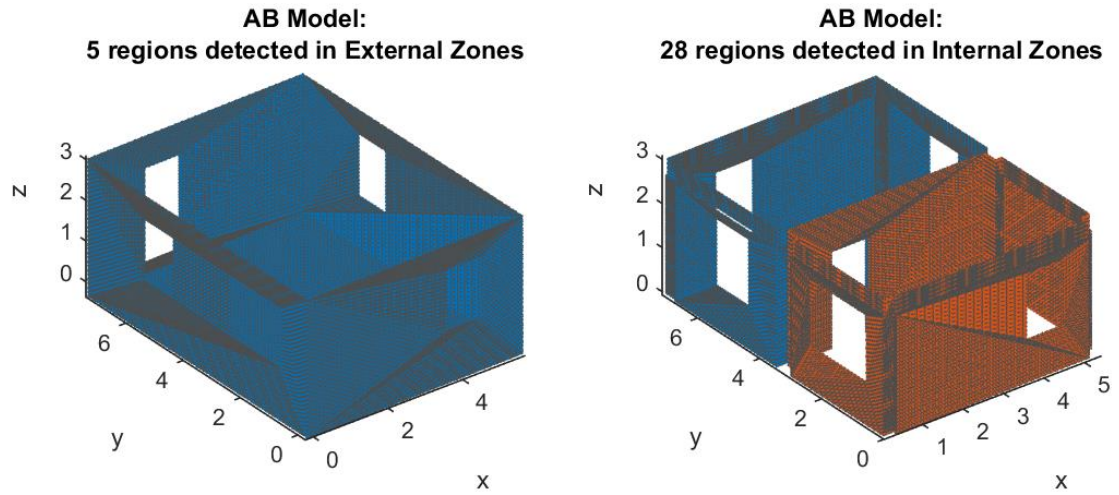


Figure 4.35 Zone Matching Results. The figure presents the regions of the Case 4 AB model that were matched to the external and internal zones respectively.

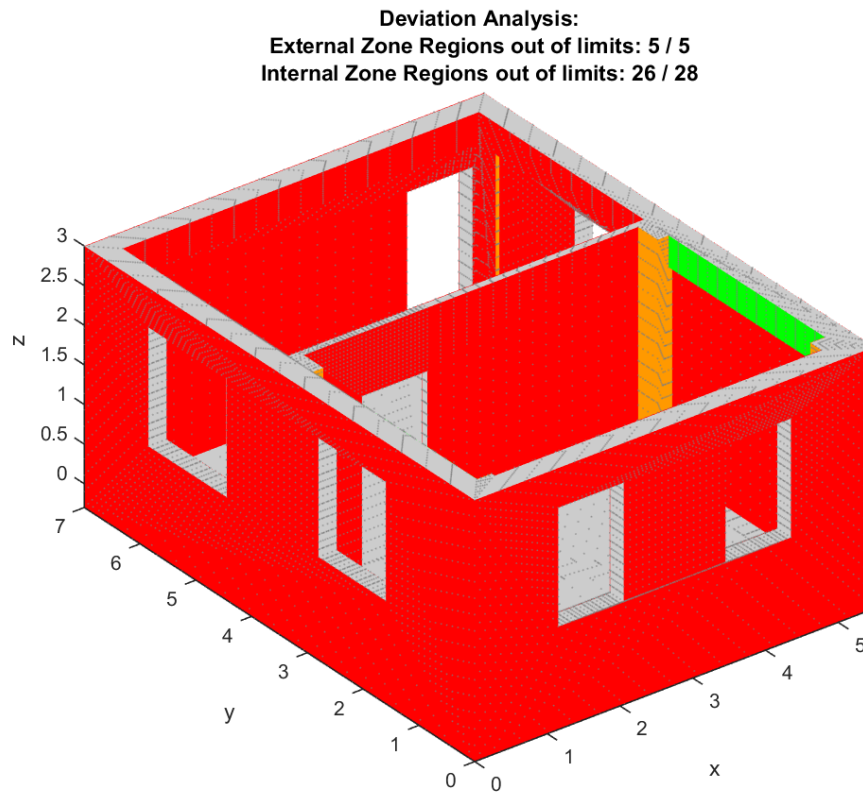


Figure 4.36 Deviation Analysis Results, for the Case 4 AB model.

As to the compliance check of the AB model to the theoretical model the data processing, as shown in Figure 4.36, leads to the conclusion that the external dimensions are out of the limits imposed by regulation, a fact which corresponds to the truth.

Regarding internal dimensions, the As-Built model actually has 24 surfaces out of limits. The method calculated that 26 surfaces are out of regulation, more than the actual ones.

The erroneous calculation in 2 areas is accountable to a false measurement of dimensions due to bad alignment of the model.

The experimental results are summarized below:

Table 2 Segmentation results of the method. For each case the RMS Error is presented and the elapsed time for the alignment to be completed

ALIGNMENT (Iterative Closest Point Algorithm)				
a/a	Case 1:	Case 2:	Case 3:	Case 4:
Total Time for alignment [sec]	14,4	15,2	16,1	17,3
RMS Error [m]	0,070	0,071	0,075	0,178

Table 3 Segmentation results of the method. For each case it is compared the true surfaces the model contains, the coplanar regions that were detected after the segmentation and the difference between the true and calculated state.

SEGMENTATION (Coplanar Region Extraction)				
a/a	Case 1:	Case 2:	Case 3:	Case 4:
No. of Surfaces in Model	63	63	63	59
No. of Regions Detected	62	62	137	59
Difference	-1	-1	74	0

Table 4 Region matching results of the method. The number of regions that were identified from the detected regions of the AB is presented, as well as an analysis of how many were found in external or internal zones.

MATCHING - Retrieval Statistics				
a/a	Case 1:	Case 2:	Case 3:	Case 4:
Coplanar Regions in AD Model	63	63	63	63
Regions retrieved from AB Model	59	59	59	50
External Zone Regions in AD Model	5	5	5	5
External Zone Regions retrieved from AB	5	5	5	5
Internal Zone Regions in AD Model:	32	32	32	32
Internal Zone Regions retrieved from AB	28	28	28	26

Table 5 Deviation results of the Data analyzed by the method. For every case, the detected deviations are compared to the true state for both the external and internal model zones.

Deviation Analysis					
a/a		Case 1:	Case 2:	Case 3:	Case 4:
External Zone Regions out of limits	Real	0	0	4	5
	detected	0	0	4	5
Internal Zone Regions out of limits:	Real	0	0	20	24
	detected	4	12	20	26

5 CONCLUSIONS

5.1 Summary/Contributions

Automating part of, or all the inspection process of an existing building, as well as the legal check of that building on a level of accordance to building regulation would greatly benefit the speed, accuracy and credibility of the measurements, as well as the transparency of the whole procedure. The rapid evolution and popularity of laser scanning and BIM in the construction industry offers opportunities for new and effective ways to obtain the 3D model of a construction and compare it to the theoretical 3D project described within its BIM model.

This thesis presents an attempt to develop such an automated method for the assessment of compliance of a building with its design specifications. The proposed method takes advantage of an existing BIM model and calculates dimensional deviations from the scanned point cloud of the As-Built structure. Experimental results from the simulated scans of the As-Built model demonstrate that this completely automated approach is quite robust in calculating variations, with regard to the external dimensions of the building. The latter is an important factor for evaluating whether the constructed building is within legitimacy limits or not.

It is concluded that the proposed system is promising and could prove particularly effective in cases of automated building inspections. Nevertheless, future work remains necessary to address the following issues:

5.2 Future Work

During the calculation of the building's dimensions, as analyzed in chapter 3.6, the projections of coordinates on the respective axis are taken into consideration. Thusly, the precision of calculations directly depends on the correct alignment of the model according to the ICP algorithm. Registration in this method only takes place once, in the beginning of the process, which in some cases can lead to a problematic alignment of the two models. The possibility of a second stage of alignment -during the matching of the corresponding regions between the models, by using the information of the surfaces that have been recognized- needs to be taken into consideration.

During the conversion of the three-dimensional models, modeling errors were observed in the 3D meshes. The errors detected were mostly the creation of almost zero area faces and disjointed faces. What led to the creation of these errors is the technique of increasing the density of the initial model that had been created for the simulation needs. Thusly, the possibility of countering such errors with the use of an alternative technique must be researched.

The segmentation technique applied in this method has the ability to differentiate regions in accordance to structural elements, especially in case these elements are coplanar, leading to problematic regions during the computing of dimensions and deviations. In cases such as these, it is possible that the deviations' calculation technique might produce erroneous results. On this basis, two possible solutions might need to be taken into consideration:

- i. Regarding interior zones, the limits of the walls could be defined as the zone limits. Regions that belong to props or beams and protrude from the wall, could be projected on its level and merged in a grouped region (which contains walls, props and beams). This logic is based on the calculation of the surface of an area as applied by Construction Regulation.
- ii. To research the possibility of detecting structural elements from the AB model, and the splitting of the regions to be carried out, based on them.

Future work will also have to focus on confirming these results with actual structure scans. The impact of uncertainties or noise in point measurement values will have to be investigated, and methods for automatically estimating the required threshold parameters will have to be further tested.

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7 APPENDIX

The following slides were used in the presentation, during the examination of this thesis. They are included as an aid for the Greek reader.

ΤΕΧΝΟΛΟΓΙΚΟ ΕΚΠΑΙΔΕΥΤΙΚΟ ΙΔΡΥΜΑ ΚΡΗΤΗΣ
ΔΙΑΤΜΗΜΑΤΙΚΟ ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ:
ΠΡΟΗΓΜΕΝΑ ΣΥΣΤΗΜΑΤΑ ΠΑΡΑΓΩΓΗΣ,
ΑΥΤΟΜΑΤΙΣΜΟΥ ΚΑΙ ΡΟΜΠΟΤΙΚΗΣ

Αυτόματη Αναγνώριση Τρισδιάστατων Μοντέλων Κτηρίων από Νέφη Σημείων για Οικοδομικό Έλεγχο

Φοιτητής: Γιώργος Παχάκης

Εισηγητής: Δρ. Αλέξανδρος Μακρής

ΗΡΑΚΛΕΙΟ 2015

Ελληνική Πραγματικότητα – Κίνητρα Εργασίας

- Υποχρεωτικοί έλεγχοι για κάθε έργο που εκτελείται με άδεια δόμησης, με αυτοψία και έλεγχο της εφαρμογής των μελετών βάσει των οποίων εκδόθηκε η άδεια δόμησης

ΥΠΕΚΑ, Ν. 4030/2011 «Νέος Τρόπος Έκδοσης Αδειών Δόμησης, Ελέγχου Κατασκευών και λουιές Διατάξεις»,

- Έλεγχος και καταγραφή των υπερβάσεων δόμησης για υπαγωγή στον νόμο τακτοποίησης αυθαίρετων

ΥΠΕΚΑ, "Ν.4178/2013: Αντιμετώπιση της Αυθαίρετης Δόμησης – Περιβαλλοντικό Ισοζύγιο και άλλες διατάξεις,"

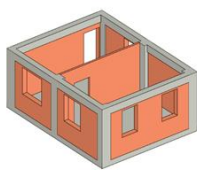
- Δημιουργία Ταυτότητας Κτηρίου με έλεγχο και καταγραφή της πραγματικής κατάστασης των ακινήτων της χώρας

ΥΠΕΚΑ, Ν. 3843/2010: «Ταυτότητα κτηρίων, υπερβάσεις δόμησης και αλλαγές χρήσης, μητροπολιτικές αναπλάσεις και άλλες διατάξεις.»



Προτεινόμενη Μέθοδος - Στόχος

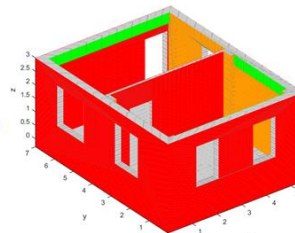
- Ανάλυση του 3D **As-Built** μοντέλου ενός κτηρίου με την βοήθεια του **As-Designed BIM**.
- Υπολογισμός διαστάσεων των κατασκευαστικών στοιχείων του As-Built.
- Έλεγχος αποκλίσεων και συμμόρφωσης με τα όρια που θέτει ο ελληνικός οικοδομικός κανονισμός.



Σχέδιο Οικοδομικής Άδειας
As-Designed BIM model



Σάρωση Κτηρίου
As-Built model



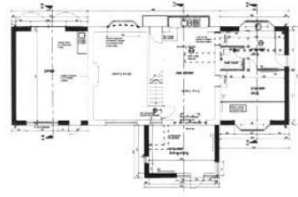
Έλεγχος Διαστάσεων

Ψηφιακή Σχεδίαση Κτηρίων

Computer Aided Design

Ηλεκτρονική σχεδίαση κτηρίου.

- Κυρίως 2D
- Απλή γεωμετρική αναπαράσταση (γραμμές, κύκλοι, τόξα)
- Ηλεκτρονική Σχεδίαση
- Στοιχειώδης Διαστασιολόγηση



Building Information Modeling

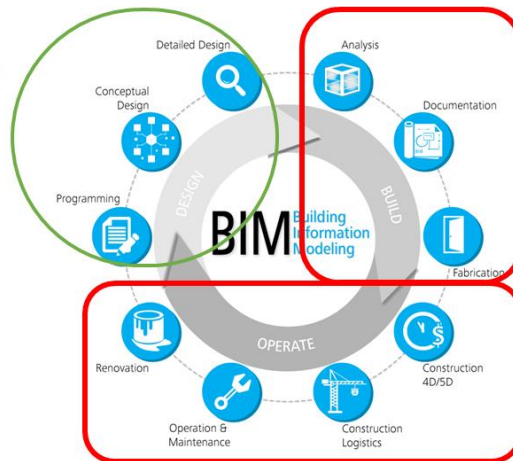
ολοκληρωμένη πηγή πληροφοριών για ένα κτίριο – υποδομή

- 3D, 4D, 5D, 6D, 7D
- Εξυπνα αντικείμενα (τοιχοί, πατώματα, πόρτες, υποστυλώματα)
- Εικονική Κατασκευή!



BIM – Building Information Modeling

Εξελιγμένος
Τομέας



Λίγες
Εφαρμογες BIM.
Πολλά υποσχόμενος
τομέας με
εξαιρετικές
Δυνατότητες

BIM vs As-Built

Φιλοσοφία: Κατασκευή όμοια με το Εικονικό Κτήριο



*Συγκρότημα Κατοικιών Με Pilotis & Υπόγειο,
Αγ. Ιωάννης Ηράκλεια, 2011*

BIM vs As-Built

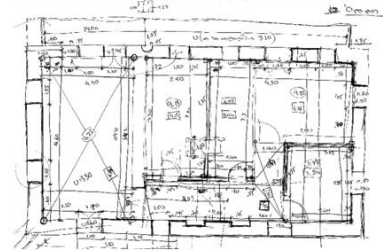


*Συγκροτημα Κατοικιων Με Pilotis & Υπογειο,
Μεσαμπελίες, Ηράκλεια, 2010*

.... ή σχεδόν όμοια....

Μέτρηση Διαστάσεων - Έλεγχος Κτηρίου

- Συλλογή δεδομένων χειροκίνητα
- Χρονοβόρες
- Δύσκολες
- Επιρρεπείς σε ακρίβεια



Τρισδιάστατη Σάρωση Κτηρίων



«Διερεύνηση μεθόδων αποκατάστασης του ιστορικού κτιρίου της Θεολογικής Σχολής της Χάλκης», Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης, 2013

Χρήση σε αποτυπώσεις:

- αρχαιολογικών χώρων
- παραδοσιακών κτιρίων
- τεχνικών έργων (πχ σήραγγες)

Πλεονεκτήματα

- ταχύτητα
- αξιοπιστία
- ακρίβεια
- περισσότερη Πληροφορία
- παρέχει συνολική αποτύπωση των 3D αντικειμένων

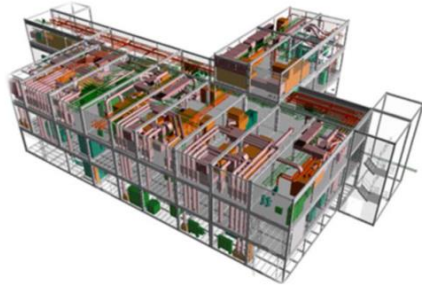


Μειονεκτήματα

- υψηλό κόστος εξοπλισμού

<https://www.youtube.com/watch?v=V1o1Tu2n0IE>

Scan Vs BIM



Θεωρητική κατάσταση
As-Designed Model
3D ΠΛΗΡΟΦΟΡΙΑ



Πραγματική κατάσταση
As-Built Model
3D ΔΕΔΟΜΕΝΑ

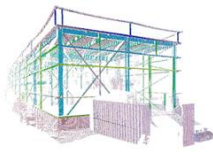
Σχετικές Ερευνητικές Εργασίες



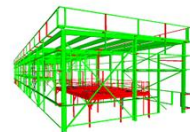
(a) Scan 4.



(b) CAD Model.



(c) Object Recognition (in point cloud).



(d) Object Recognition (in CAD model).

Αυτόματη Αναγνώριση Αντικειμένων CAD και Υπολογισμός Κατασκευαστικών Διαστάσεων

Bosche, 2009

- Χειροκίνητη αρχική ευθυγράμμιση μοντέλων
- Αντιστοιχισμός Σημείο-Σημείο
- Απόρριψη σημείων που δεν πέφτουν σε επιφάνεια,

Σχετικές Ερευνητικές Εργασίες



Ανάλυση Αποκλίσεων Για Τον Ποιοτικό Έλεγχο Σαρωμένων Κτηρίων *Burak Anil et al., 2013*

- Ελάχιστες ευκλείδειες αποστάσεις.
- Οι αποκλίσεις υπολογίζονται μόνο κάθετα στο επίπεδο της επιφάνειας
- Χειροκίνητη ευθυγράμμιση των δύο μοντέλων

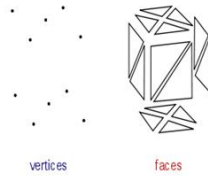
Προτεινόμενη Μέθοδος - Υλοποίηση

Το σύστημα αποτελείται από τα ακόλουθα βήματα:

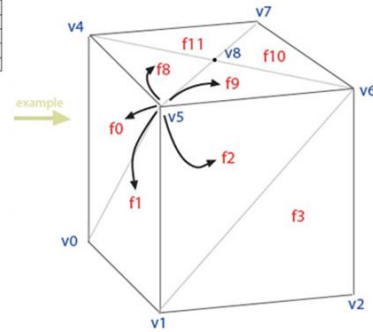
1. Πλήρως Αυτόματη Καταχώριση και ευθυγράμμιση του As-Built με το BIM
2. Διάσπαση σε συνεπίπεδες επιφάνειες
3. Αναγνώριση μέσω της Αντιστοίχισης Επιφανειών
4. Υπολογισμός Διαστάσεων & Αποκλίσεων σε όλες τις διευθύνσεις
5. Έλεγχος Υπερβάσεων

Τύπος Μοντέλων Εισόδου

- τριγωνικά μοντέλα επιφανειών (triangular meshes)
- 3D Mesh Model Format: OBJ
- Περιγράφεται από:
 - Σημεία (Vertices)
 - Τριγωνικές επιφάνειες (Faces)

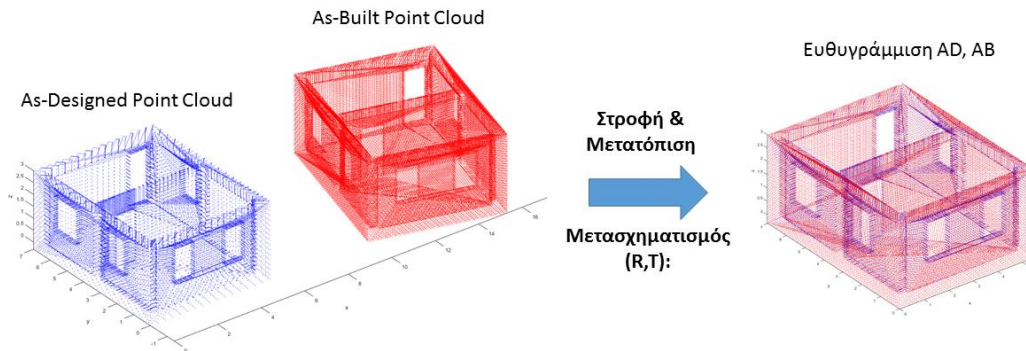


Face List	Vertex List
f0	v0 v4 v5
f1	v0 v5 v7
f2	v1 v5 v6
f3	v1 v6 v2
f4	v2 v6 v7
f5	v2 v7 v4
f6	v3 v7 v4
f7	v3 v4 v0
f8	v8 v5 v4
f9	v8 v6 v5
f10	v8 v7 v6
f11	v8 v4 v7
f12	v9 v5 v4
f13	v9 v6 v5
f14	v9 v7 v6
f15	v9 v4 v7



Βήμα 1: Ευθυγράμμιση AB και AD μοντέλων

- Αρχικά τα δύο μοντέλα πρέπει να εγγραφούν στο ίδιο σύστημα αξόνων και να ευθυγραμμιστούν (registration/alignment)



Βήμα 1: Ευθυγράμμιση AB και AD μοντέλων

Iterative Closest Point Algorithm (ICP)

Ορισμός:

- «Βρες μετασχηματισμό μεταξύ 2 νεφών σημείων»

Είσοδος:

- Νέφος αναφοράς,
- Νέφος που θα ευθυγραμμιστεί

Έξοδος:

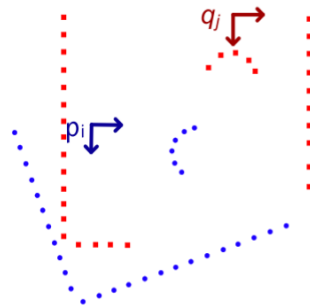
- Μετασχηματισμός μεταξύ των νεφών (R,T):

Βήμα 1: Ευθυγράμμιση AB και AD μοντέλων

Iterative Closest Point Algorithm (ICP)

Loop:

1. Αντιστοιχίες
2. Βάρη – Απόρριψη
3. Σφάλμα
4. Ελαχιστοποίηση
5. Μετασχηματισμός

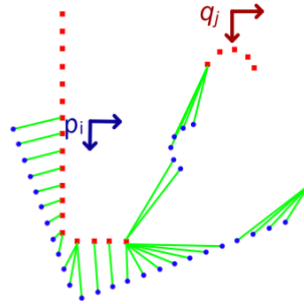


Βήμα 1: Ευθυγράμμιση AB και AD μοντέλων

Iterative Closest Point Algorithm (ICP)

Loop:

1. Αντιστοιχίες
2. Βάρη – Απόρριψη
3. Σφάλμα
4. Ελαχιστοποίηση
5. Μετασχηματισμός

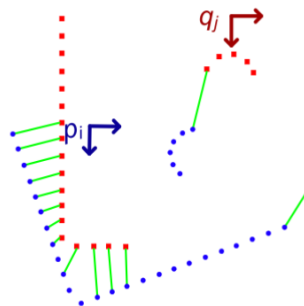


Βήμα 1: Ευθυγράμμιση AB και AD μοντέλων

Iterative Closest Point Algorithm (ICP)

Loop:

1. Αντιστοιχίες
2. **Βάρη – Απόρριψη**
3. Σφάλμα
4. Ελαχιστοποίηση
5. Μετασχηματισμός

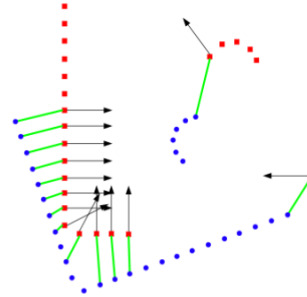


Βήμα 1: Ευθυγράμμιση AB και AD μοντέλων

Iterative Closest Point Algorithm (ICP)

Loop:

1. Αντιστοιχίες
2. Βάρη – Απόρριψη
3. **Σφάλμα**
4. Ελαχιστοποίηση
5. Μετασχηματισμός

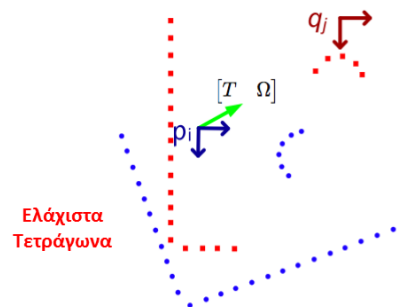


Βήμα 1: Ευθυγράμμιση AB και AD μοντέλων

Iterative Closest Point Algorithm (ICP)

Loop:

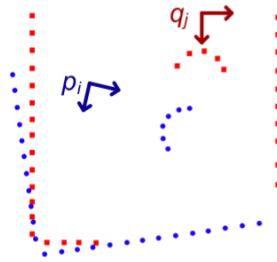
1. Αντιστοιχίες
2. Βάρη – Απόρριψη
3. Σφάλμα
4. **Ελαχιστοποίηση**
5. Μετασχηματισμός



Βήμα 1: Ευθυγράμμιση AB και AD μοντέλων

*Iterative Closest Point Algorithm (ICP)***Loop:**

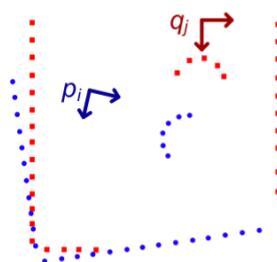
1. Αντιστοιχίες
2. Βάρη – Απόρριψη
3. Σφάλμα
4. Ελαχιστοποίηση
5. **Μετασχηματισμός**



Βήμα 1: Ευθυγράμμιση AB και AD μοντέλων

Iterative Closest Point Algorithm (ICP)

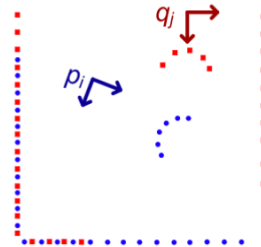
1. Αντιστοιχίες
2. Βάρη – Απόρριψη
3. Σφάλμα
4. Ελαχιστοποίηση
5. **Μετασχηματισμός**



Βήμα 1: Ευθυγράμμιση AB και AD μοντέλων

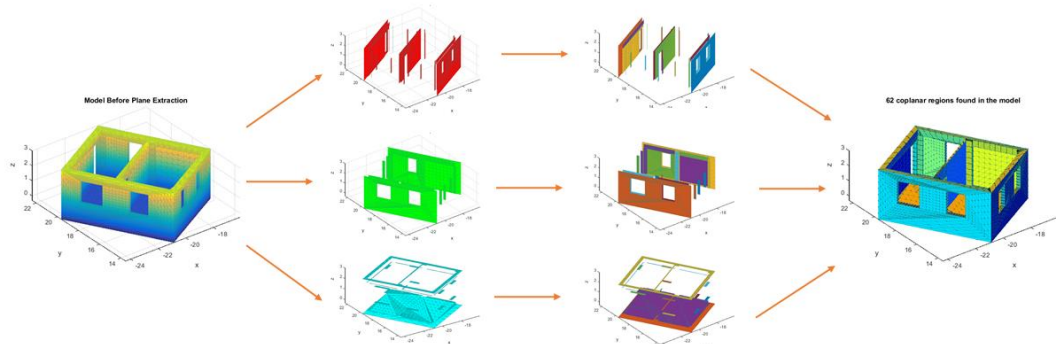
Iterative Closest Point Algorithm (ICP)

1. Αντιστοιχίες
2. Βάρη – Απόρριψη
3. Σφάλμα
4. Ελαχιστοποίηση
5. **Μετασχηματισμός**



Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διάσπαση μοντέλου σε παράλληλα επίπεδα
- Διαχωρισμός ομάδων σε συνεχείς περιοχές

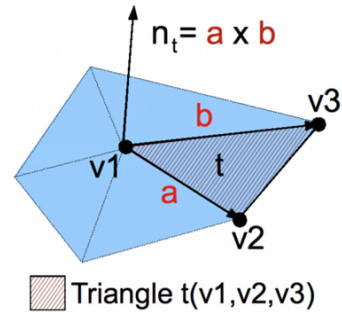


Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διάσπαση μοντέλου σε παράλληλα επίπεδα

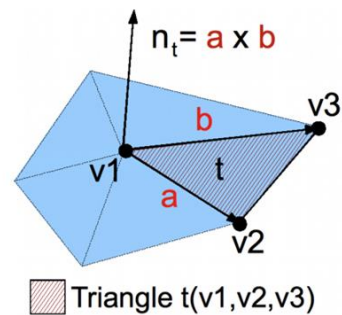
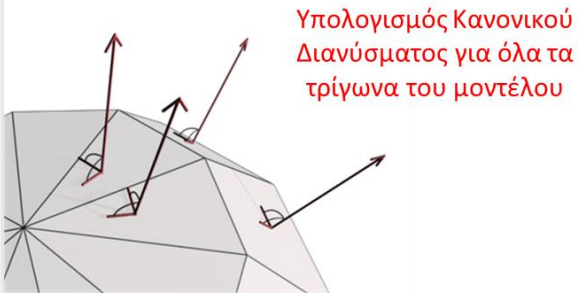
Κανονικό Διάνυσμα

$$\hat{N} = \frac{a \times b}{\sqrt{|a|^2|b|^2 - |a \cdot b|^2}}$$



Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

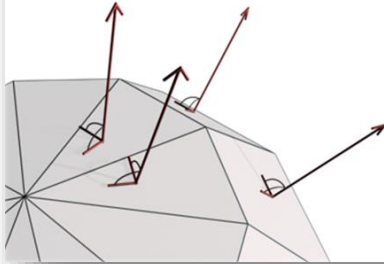
- Διάσπαση μοντέλου σε παράλληλα επίπεδα



Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διάσπαση μοντέλου σε παράλληλα επίπεδα

Υπολογισμός γωνίας μεταξύ normal vectors



$$\mathbf{A} \cdot \mathbf{B} = \begin{pmatrix} A_x \\ A_y \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix} \\ = A_x \cdot B_x + A_y \cdot B_y$$

$$\mathbf{A} \cdot \mathbf{B} = |\mathbf{A}| |\mathbf{B}| \cos(\text{theta})$$

$$|\mathbf{A}| = \sqrt{A_x \cdot A_x + A_y \cdot A_y}$$

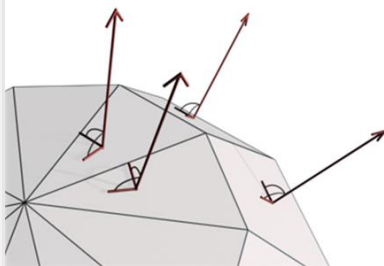
$$|\mathbf{B}| = \sqrt{B_x \cdot B_x + B_y \cdot B_y}$$

$$\text{theta} = \cos^{-1} \left(\frac{\mathbf{A} \cdot \mathbf{B}}{|\mathbf{A}| |\mathbf{B}|} \right)$$

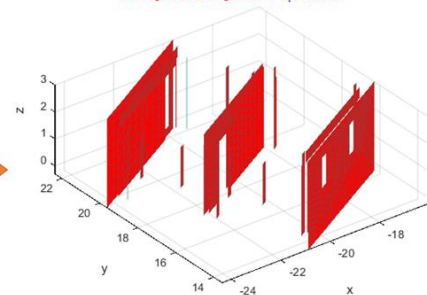
Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διάσπαση μοντέλου σε παράλληλα επίπεδα

Υπολογισμός γωνίας μεταξύ normal vectors



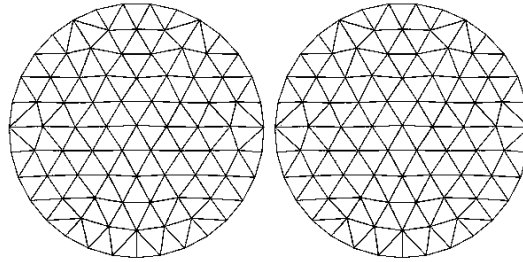
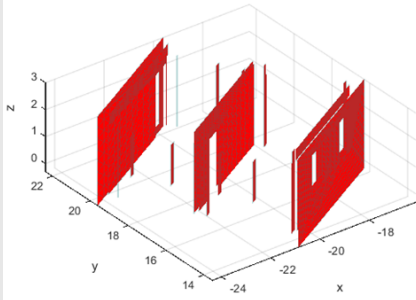
Ομαδοποίηση παράλληλων normal vectors → ομαδοποίηση παράλληλων faces



Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διαχωρισμός ομάδων σε συνεχείς περιοχές

Ομάδα παράλληλων faces



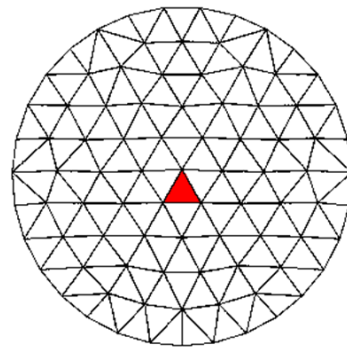
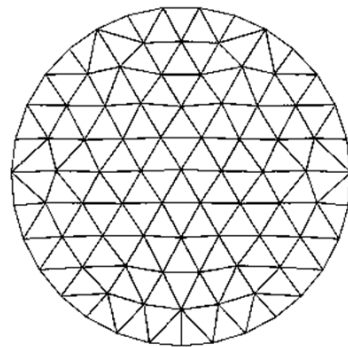
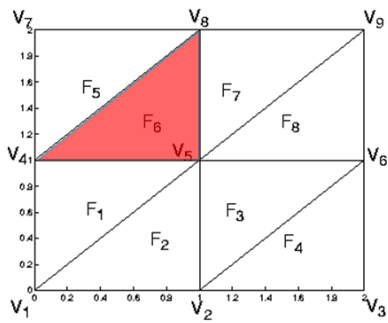
Ομάδα παράλληλων faces

Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διαχωρισμός ομάδων σε συνεχείς περιοχές

Ξεκινάω με ένα τριγωνο

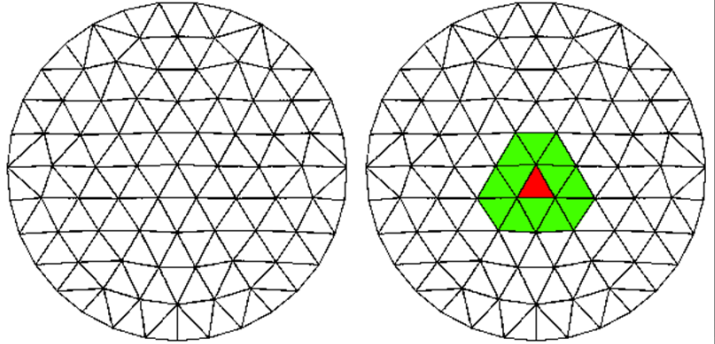
ZOOM



Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διαχωρισμός ομάδων σε συνεχείς περιοχές

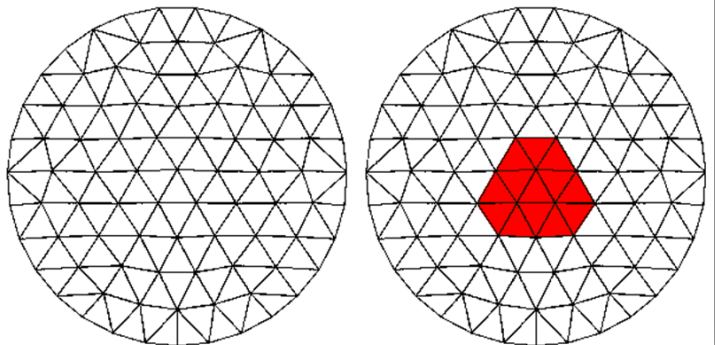
Βρίσκω γειτονικά



Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διαχωρισμός ομάδων σε συνεχείς περιοχές

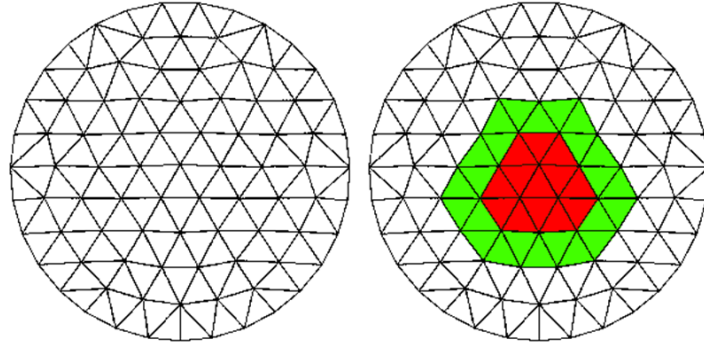
Ομαδοποιώ



Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διαχωρισμός ομάδων σε συνεχείς περιοχές

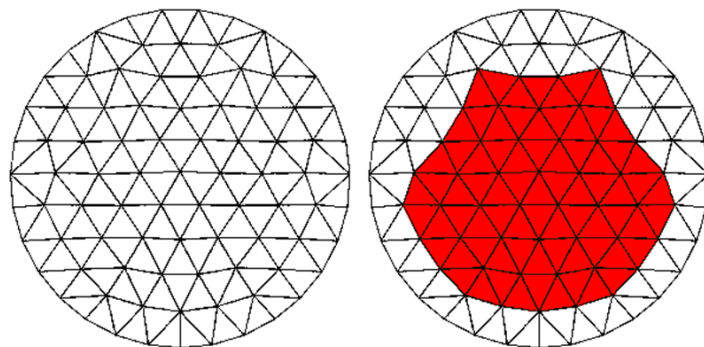
Βρίσκω γειτονικά



Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διαχωρισμός ομάδων σε συνεχείς περιοχές

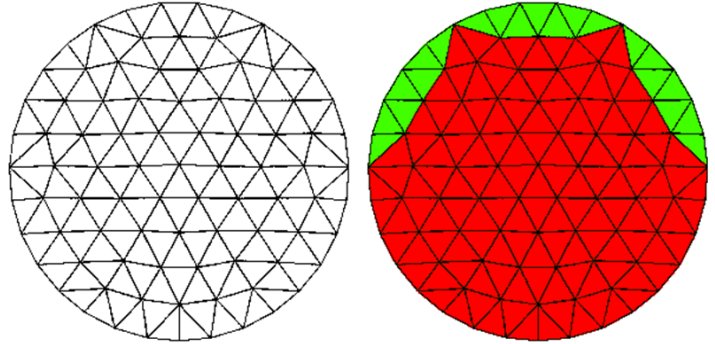
Ομαδοποιώ



Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διαχωρισμός ομάδων σε συνεχείς περιοχές

Βρίσκω γειτονικά



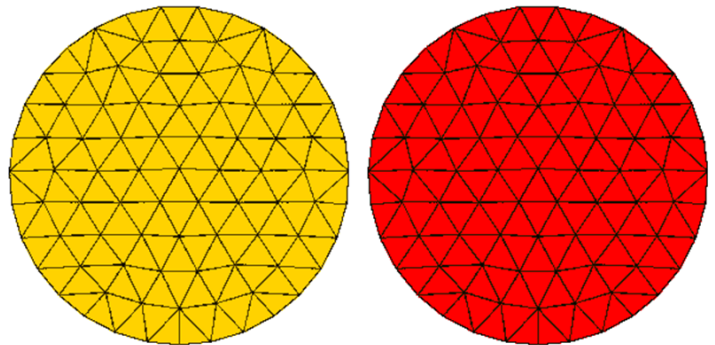
Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διαχωρισμός ομάδων σε συνεχείς περιοχές

Δημιουργώ νέα περιοχή

ΠΕΡΙΟΧΗ 2

ΠΕΡΙΟΧΗ 1

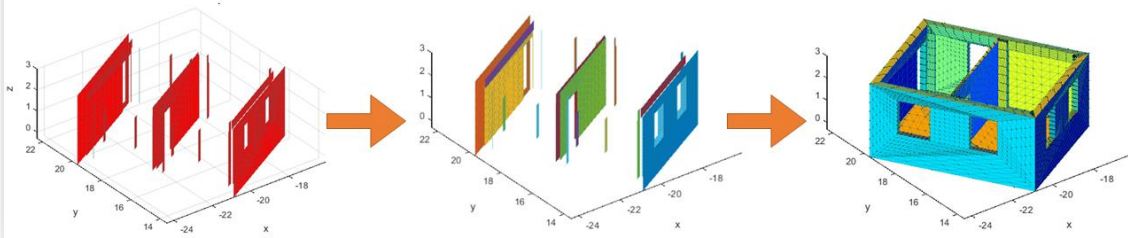


Βήμα 2: Διάσπαση σε συνεπίπεδες επιφάνειες

- Διαχωρισμός ομάδων σε συνεχείς περιοχές

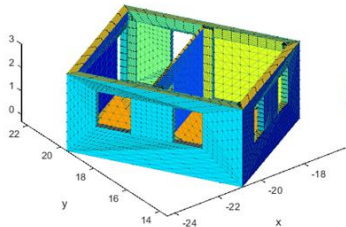
Ομάδα παράλληλων faces

Συνεχείς Επίπεδες Περιοχές

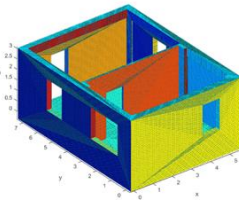


Βήμα 3: Αντιστοίχιση επιφανειών

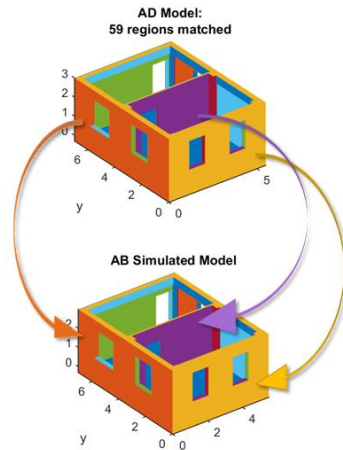
Μοντέλα με Συνεκτικές Περιοχές



AD model



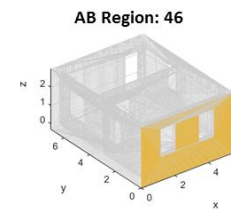
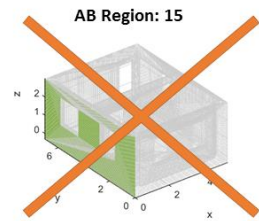
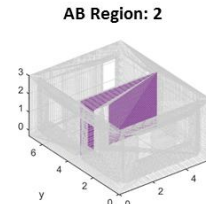
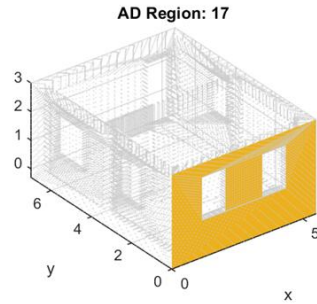
AB model



Βήμα 3: Αντιστοίχιση επιφανειών

Βασική ιδέα, για κάθε AD περιοχή:

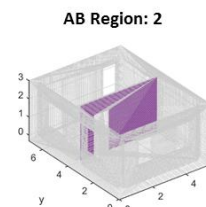
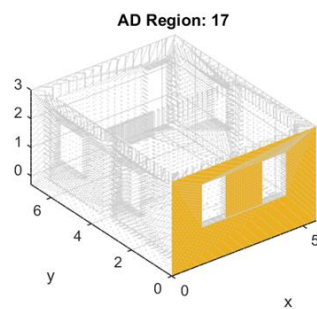
1. Έλεγχος παραλληλίας με AB



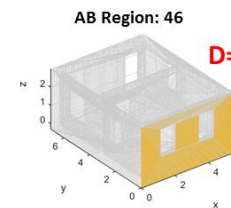
Βήμα 3: Αντιστοίχιση επιφανειών

Για τις παράλληλες περιοχές:

2. Υπολογισμός απόστασης μεταξύ περιοχών



D= 4,075

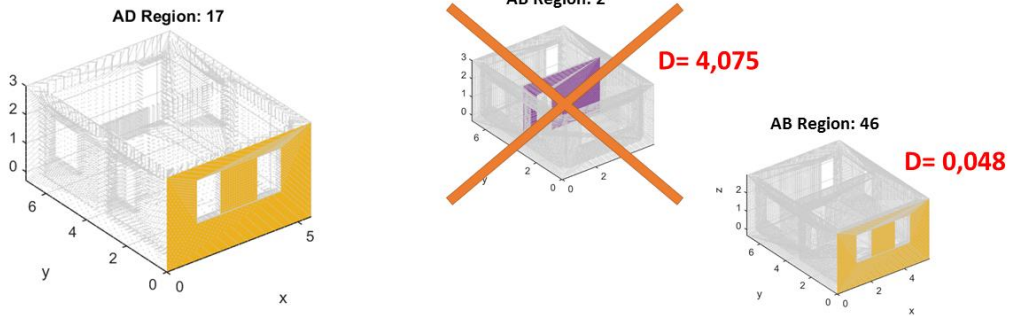


D= 0,048

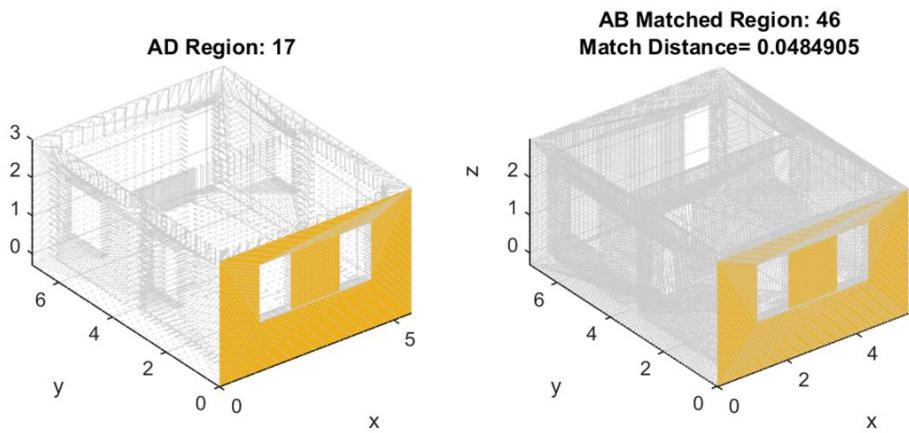
Βήμα 3: Αντιστοίχιση επιφανειών

Βασική ιδέα:

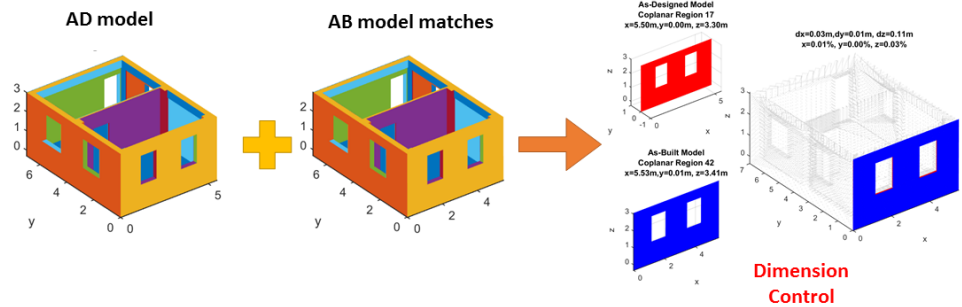
3. Κράτα την μικρότερη απόσταση



Βήμα 3: Αντιστοίχιση επιφανειών



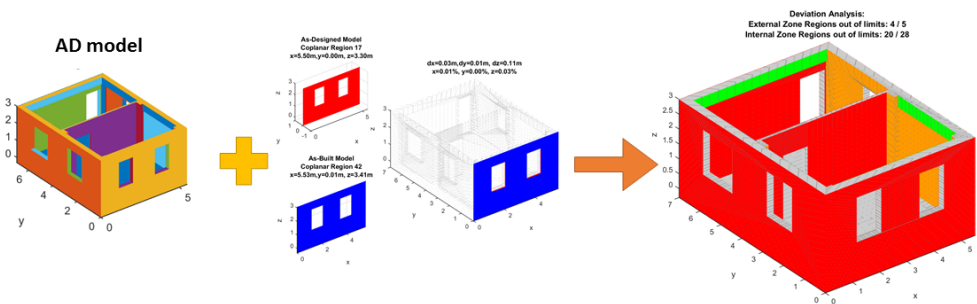
Βήματα 4 & 5: Έλεγχος Διαστάσεων & Υπερβάσεων



- Για κάθε αντιστοιχία AD-AB υπολογίζονται οι διαστάσεις.
- Υπολογίζονται οι διαφορές και ελέγχεται αν είναι εντός ορίων

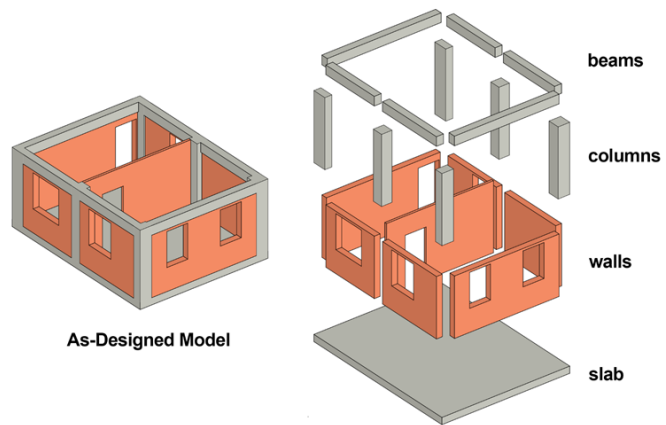
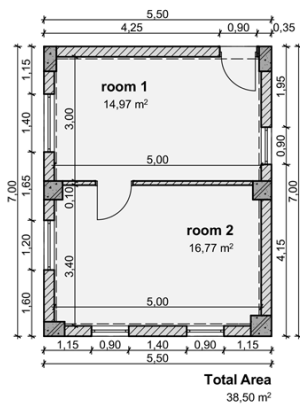
Βήματα 4 & 5: Έλεγχος Διαστάσεων & Υπερβάσεων

- Εμφάνιση θεωρητικού μοντέλου με ανάλυση υπέρβασης διαστάσεων



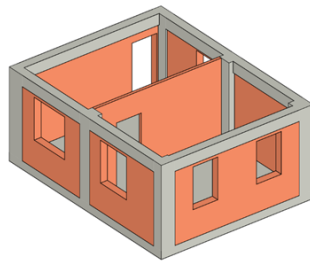
Πειράματα

Σχεδίαση BIM Μοντέλου αναφοράς (AD)

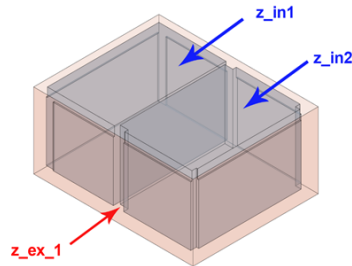


Κωδικοποίηση & Εξαγωγή Μοντέλου AD

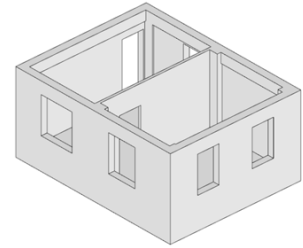
- Εξαγωγή πολυγωνικών μοντέλων (MESHER) για σύγκριση με τις παρατηρήσεις



1. Μοντέλο BIM



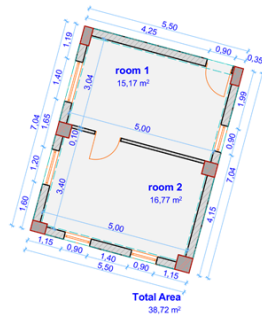
2. Μοντέλο Χώρων



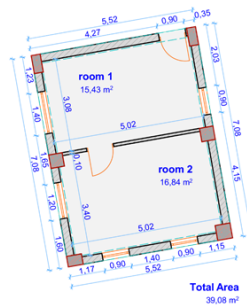
3. Μοντέλο Κέλυφος

Δεδομένα Προσομοίωσης

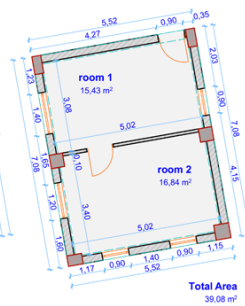
4 παραλλαγές πραγματικού Μοντέλου (AB)



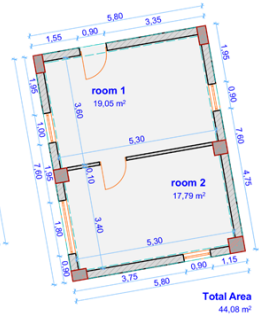
1. Μεγαλύτερο μήκος



2. Μεγαλύτερο μήκος, πλάτος



3. Μεγαλύτερο μήκος, πλάτος, υψος

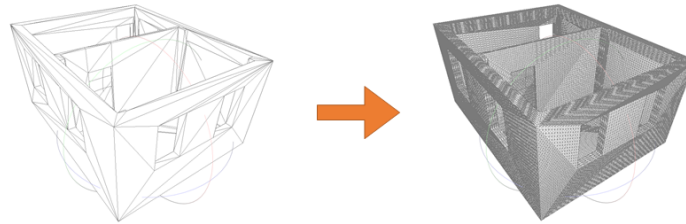


4. Εκτός ορίων υπερβάσεις

Πειραματικό Μέρος

Εξαγωγή από σχεδιαστικό πρόγραμμα:

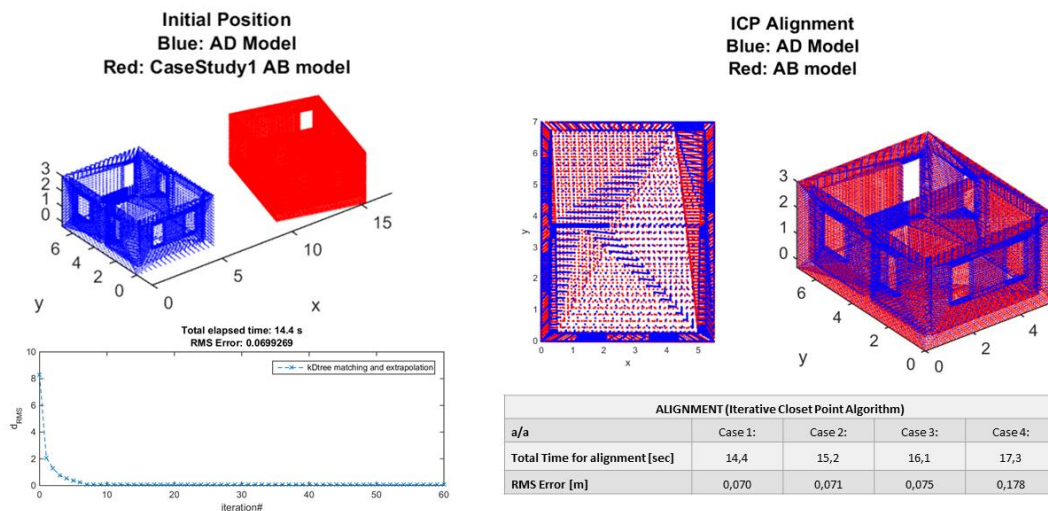
- Πολυγωνικό μοντέλο (Triangular Mesh)
- Περιγράφεται από τρίγωνα & σημεία (Face-Vertex Mesh)
- Τύπος αρχείου .OBJ



Λίγα σημεία κατά την εξαγωγή

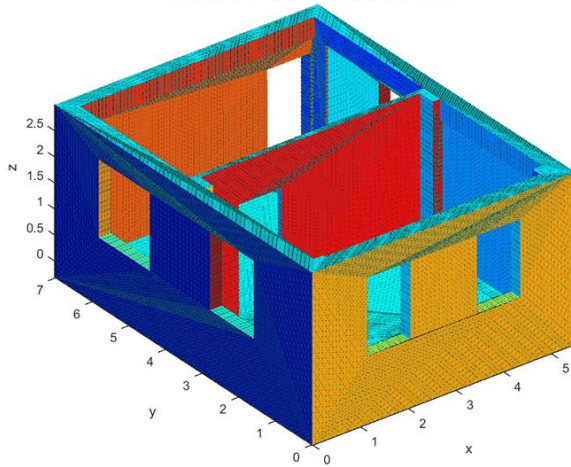
Επεξεργασία και πολλαπλασιασμός νέφους σημείων

Αποτελέσματα - Ευθυγράμμιση



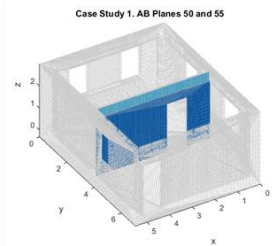
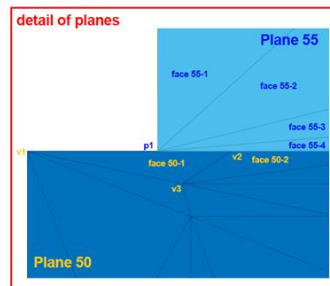
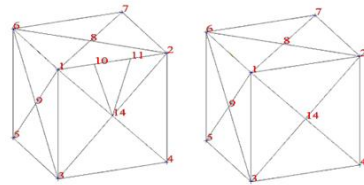
Αποτελέσματα - Συνεπίπεδες Επιφάνειες

As-Built Model: 62 Coplanar Regions found



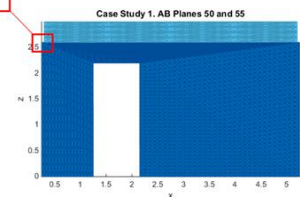
SEGMENTATION (Coplanar Region Extraction)				
a/a	Case 1:	Case 2:	Case 3:	Case 4:
No. of Surfaces in Model	63	63	63	59
No. of Regions Detected	62	62	137	59
Difference	-1	-1	74	0

Αποτελέσματα - Συνεπίπεδες Επιφάνειες

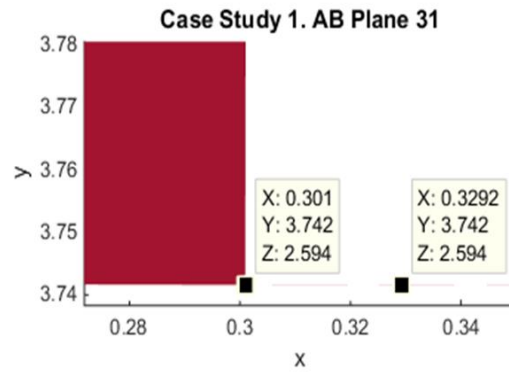
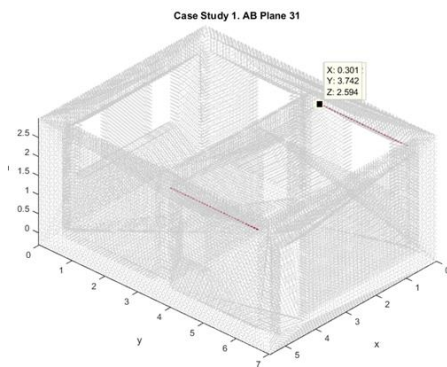


Λανθασμένος διαχωρισμός μιας συνεπίπεδης επιφάνειας σε περισσότερα regions.

- Λόγω εσφαλμένης μοντελοποίησης τριγώνων (mesh inconsistency)



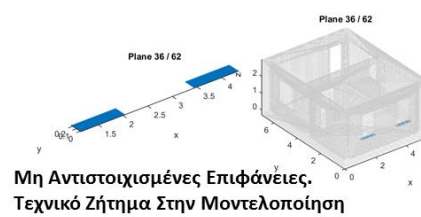
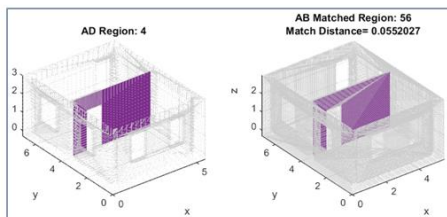
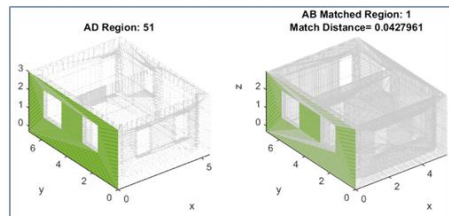
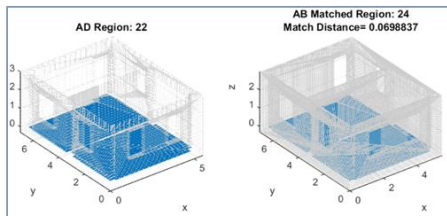
Αποτελέσματα - Συνεπίπεδες Επιφάνειες



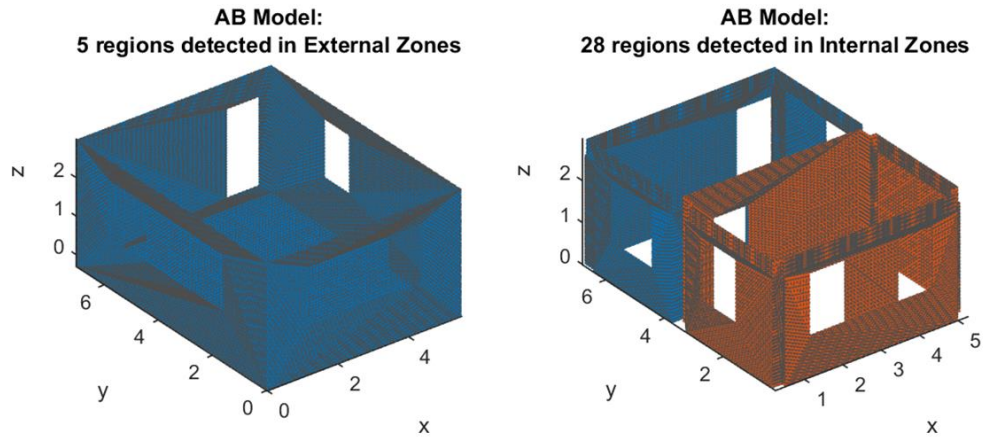
Λανθασμένη ενοποίηση δύο επιφανειών σε ένα region.

- Λόγω ύπαρξης τριγώνων μηδενικού εμβαδού (zero-area faces)

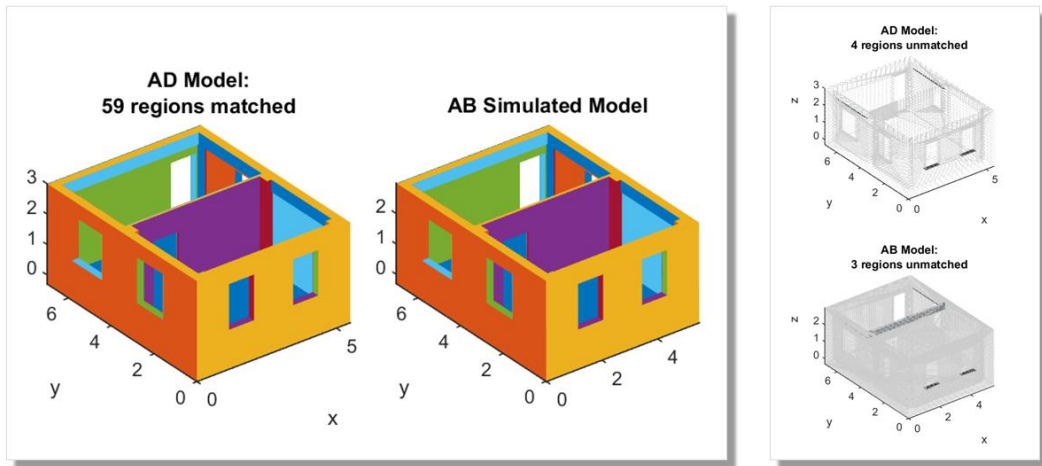
Αποτελέσματα - Αντιστοίχιση



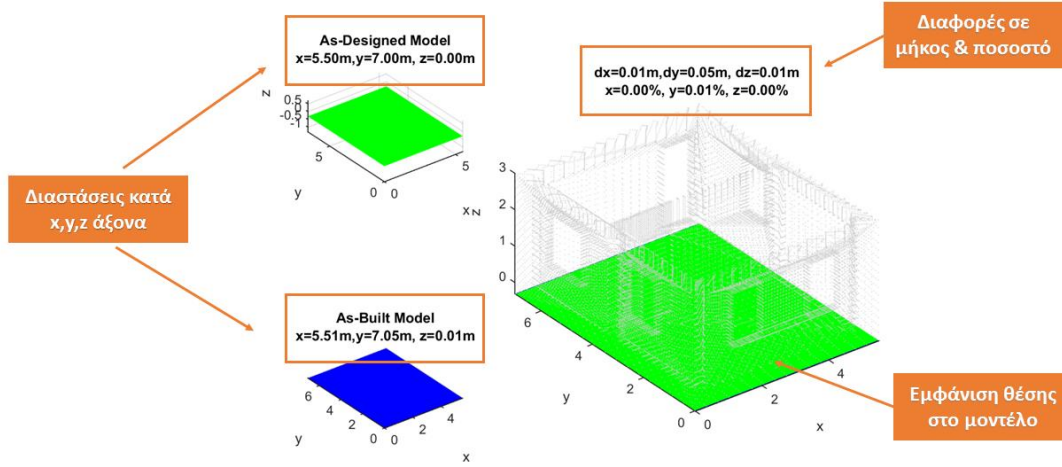
Αποτελέσματα - Αντιστοίχιση



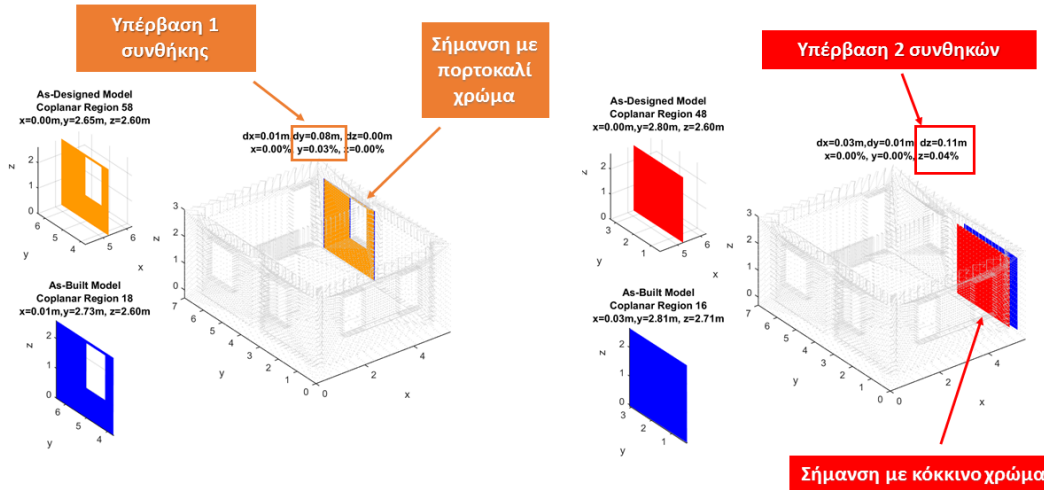
Αποτελέσματα - Αντιστοίχιση



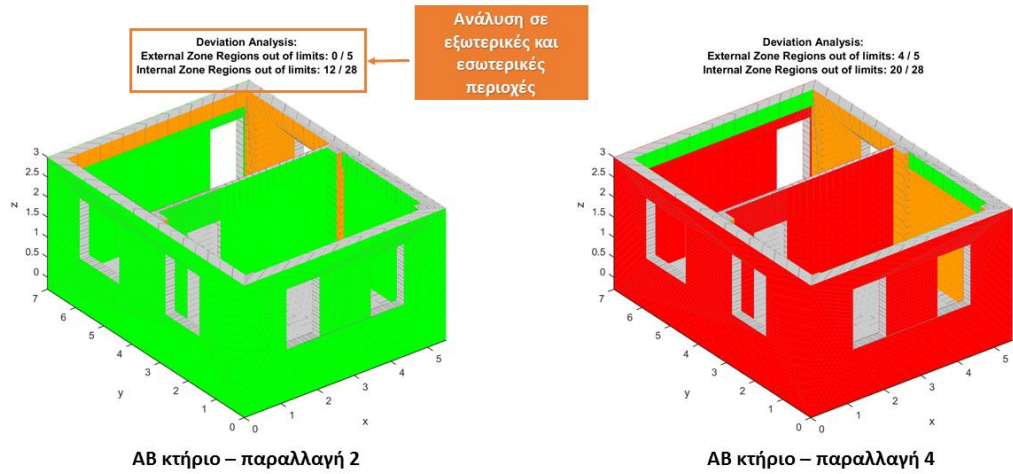
Αποτελέσματα – Έλεγχος Διαστάσεων



Αποτελέσματα – Έλεγχος Διαστάσεων



Αποτελέσματα – Έλεγχος Υπερβάσεων



Επίλογος

Αυτοματοποίηση Ελέγχων:

- ταχύτητα
- Ακρίβεια
- Αξιοπιστία
- Διαφάνεια

Σάρωση Κτηρίων και BIM Τεχνολογία

- Μεγάλη εξάπλωση
- Νέες μέθοδοι και τεχνικές καταγραφής
- Ενσωμάτωση πληροφορίας κατά σχεδιασμό
- Αξιοποίηση πληροφορίας για ανάλυση δεδομένων σάρωσης



Μελλοντική Εξέλιξη

- Πειράματα με πραγματικά δεδομένα
- Έρευνα για ακόμα αποδοτικότερο registration
- Αναγνώριση Κατασκευαστικών Στοιχείων
- Εξαγωγή As-Built BIM κτηρίου



ΤΕΧΝΟΛΟΓΙΚΟ ΕΚΠΑΙΔΕΥΤΙΚΟ ΙΔΡΥΜΑ ΚΡΗΤΗΣ
ΔΙΑΤΜΗΜΑΤΙΚΟ ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ
ΠΡΟΗΓΜΕΝΑ ΣΥΣΤΗΜΑΤΑ ΠΑΡΑΓΩΓΗΣ,
ΑΥΤΟΜΑΤΙΣΜΟΥ ΚΑΙ ΡΟΜΠΟΤΙΚΗΣ

Ευχαριστώ για την
προσοχή σας!

